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# Design and Modeling of Shape Memory Alloy Actuators for Intralogistic Applications

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## Abstract

Industrial engineering is conventionally dealing with the optimization of complex processes or systems. It is concerned with the development, improvement, implementation and evaluation of integrated systems of people, money, knowledge, information, equipment, energy, materials, analysis and synthesis, as well as the mathematical, physical, mechanical and social sciences together with the principles and methods of engineering design to specify, predict, and evaluate the results to be obtained from such systems or processes. Industrial engineers determine the most effective ways for an organization to use the basic factors of production, people, machines, materials, information, and energy to make or process a product or produce a service. As industrial engineering concerned with increasing productivity, improving quality and reducing costs. From this point, this paper presents alternative solutions and new driver technologies to solve some of industrial issues associated with internal systems, internal-logistics in factories like material handling and logistics especially linear actuators using smart material (shape memory alloys) to be an alternative to similar equipment. Shape memory alloys (SMAs) belong to the class of smart materials and have been used in numerous applications. Phase transformations induced by either stress or temperature are behind the remarkable properties of SMAs that motivate the concept of innovative smart actuators for different purposes. The SMA element used in these actuators can assume different forms and a spring is an element usually employed for this aim. In addition, it found that SMA actuator in reality could be employed to be alternative to other actuator and that is what this paper focused on.

## Keywords

Shape Memory Alloys, NiTi, Smart Actuators, Intralogistics

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## 1. Introduction

The Material Handling (MH) is a sub-discipline of mechanical engineering and deals with the conception, design, planning and execution of conveyors for conveying piece goods (pallets, boxes, packages, individual work pieces, etc.).

Furthermore, the internal transport systems are assigned for the conveyor system. It is referred meanwhile to as intralogistic systems. These include continuous conveyors such as roller conveyors, rotary valves, belt bucket elevators and belt conveyors, as well as discontinuous conveyors such as man-operated industrial trucks (forklifts, platform trucks, etc.), cranes, automatic truck loading systems, work piece conveyors and vertical conveyors such as lifting tables or belt lifters. In-house transport systems primarily have the task of transporting goods in the most efficient way from the delivery point to the delivery point [1-4].

An important step in the development of an autonomous control method for hybrid intralogistic systems (manual or automated) is the development of a generic new drive mechanism for intralogistic systems, which may represent the

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replacement of electric drives [5].

In a typical industrial facility, MH accounts for 25% of all employees, 55% of all factory space, and 87% of the production time [6]. Material handling is estimated to represent between 15 and 70% of the total cost of manufactured product. MH is one activity where many improvements can be achieved, resulting in significant cost savings. The ideal goal is to "totally eliminate" MH activities. Simply handling less, however, is not sufficient [7]. One can view MH as a means by which total manufacturing cost can be reduced through more efficient material flow control, lower inventories, and improved safety.

Therefore, an important step in the development of an autonomous control method for hybrid intralogistic systems (manual or automated) is the development of a generic new drive mechanism for intralogistic systems, which may represent the replacement of electric drives. For this purpose, the use of smart materials, namely NiTi shape memory alloys, is presented as a technical and economical solution.

## 2. Motivation

The material handling can be observed in the daily work by moving parts in a manufacturing system, transporting boxes and pallet loads in an industrial distribution system or mass transit system, and this is usually done by material handling equipment (MHE). In this paper, the goal is not the extension of the material handling itself, but the study of a similar machine, with new drive technology that works in a linear manner and the capability of the presented prototype to fulfill its function in the real world. The uses of the prototype as an alternative solution to other machines, leading to the improvement and use of new technologies in the industrial sector. This new technology could continue to expand in the future.

MHE is all equipment that relates to the movement, storage, control and protection of materials, goods and products throughout the process of manufacturing, distribution, consumption and disposal. This are designed such that they facilitate easy, cheap, fast and safe loading and unloading with least human interference. MHE can be classified into the following five major categories; Transportation, Positioning, Unit Load Formation, Storage and Identification and Control [8-9].

In this research contribution, the means of transport in general and conveyors in particular are taken into account, since they are most commonly used in industrial plants and account for most of the MHE costs.

According to the German Environment Agency (UBA), the mostly share of the industrial power consumption is caused to more than 60% by electric motors. Figure 1 shows this statement of the UBA in a diagram. Process heat, lightening or heating use proportionately less power, but should not remain unconsidered when talking about energy efficiency [10].

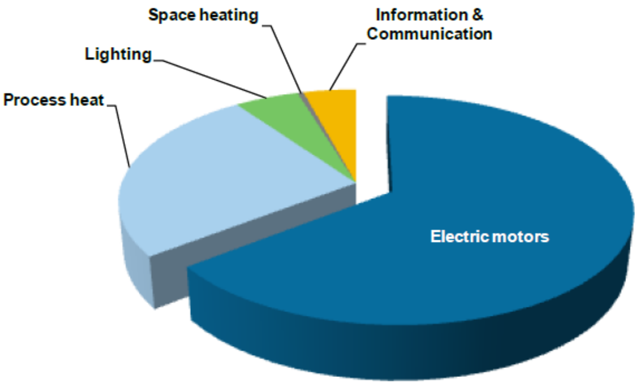

**Figure 1.** Electric power consumption in the German industry [10].

Therefore, an alternative solution, a replacement for electric motors, should be urgently sought, in order to protect the environment and to save operating costs. The only and very interesting alternative is the application of the intelligent materials. Because these materials, when designed as drive actuators, they can perform the required drive without power. In addition, they are quiet and generate no heat.

Thus, completely new solutions for transport systems are conceivable via functionalized component surfaces. In addition, such approaches to increase the life of the conveyor system and to increase the reliability.

## 3. Methodology

### 3.1. Designing with NiTi-Shape Memory Alloys

Shape memory alloys (SMA) made of nickel and titanium are materials with shape memory effect: If these materials are deformed at ambient temperature, they return to their original shape when heated. That's a kind of smart material. This shape memory effect can be used to generate movements, torques or forces. This means that the mechanical transmission elements between motor and belt (conveyor element) will be eliminated. This type of mechanism, the "direct drive" is very desirable in modern conveyor systems.

The NiTi shape memory alloys (NiTi-SMA) have become very important in the field of actuators in recent years, and the trend is rising. Compared to conventional drives such as electric motors, hydraulics and pneumatics, these SMA actuators have the advantages that they are designed with a simple design and thus the initial costs are reduced. In addition, they are also lighter in comparison, quieter and geometrically cheaper. SMAs have high energy-to-weight ratio, a SMA sheet (87×270×1 mm) so a SMA actuator can apply a force up to 600 N (60 kg) [11-13].

In addition, NiTi-SMA is biocompatible, has high wear resistance and the tribological behavior has been studied and compared with many conventional engineering materials such as Ni-based steels alloys [14-15].

For these many technical advantages of the SMA, NiTi-SMA is the obvious a choice for actuators that provide significant displacements and forces, and do not place critical demands on short response time or high efficiency. This makes NiTi- SMA an attractive candidate for a large number of industrial applications, intelligent structures and intelligent systems [16].

### 3.2. Design Concept

The idea of this design is simple, which is about the use of NiTi spring actuator as an upward/downward lift. This motion is based on the properties of NiTi-SMA, figure 2 shows a simple sketch, which illustrates the function of the prototype at different situations over a period of time through activate/inactivate the NiTi-SMA spring. As shown in this figure, when a load (weight) is set on the plate, NiTi spring will compressed to the solid length were all coils are touched (martensite phase) and the plate is moved downward. After that when the spring is activated (electrically or thermally) it will return to its original shape (Austenite phase) and in turn will lift the weight upward by transformation forces generated due to activation of NiTi spring. Then inactivation (cooling) is occurred by removing the source of heating that will return the NiTi spring to its deformable phase (martensite) which is compressed by the weight and so on.

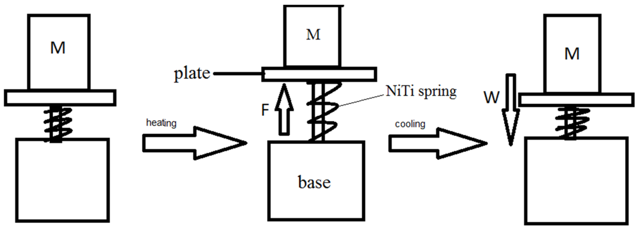

**Figure 2.** Schematic illustration of the prototype design concept.

## 4. Design and Fabrication of the Prototype

### 4.1. NiTi-SMA Spring Design

Waram first outlined the current design methodology for SMA coil springs in 1990 and again by Ohkata and Suzuki in 1998. This method is based on understanding of modulus behavior, which is obtained by approximating the slope of the linear portion of the material stress-strain response. Using this method, the modulus of a SMA in the martensite is found to be much less than the modulus of the material in the austenite, the difference of Young's Modulus between two phases is eight times for Nitinol shape memory alloy [17-18].

In this present actuator design, a straight NiTi wire of 100 cm length and 5.5 mm in diameter is used to form the spring. The shear modules in high and low temperatures are 23000 MPa and 8000 MPa respectively, other spring parameters are:

1. $L_s$=5cm, $L_f$=25cm, $D_m$=3.6cm, $D_w$=55mm, N=9 coils, P= 3cm, k=1.229, C=6.54
2. Stroke = 20 cm
3. Spring rate at low temperature is K= 2.45
4. Spring rate at high temperature is K= 7.04

whereby, the free length ($L_f$) the solid length ($L_s$), the wire diameter ($D_w$), the mean diameter ($D_m$), the spring index (C), the total number of coils (N), Pitch (P) and the spring rate (K).

Since, the desired spring will be of compression type made of NiTi wire that is 100 cm long and 5.5 mm in diameter, which mean that the stretched form will represent the parent phase (Austenite) at high temperature (HT), s. Figure 3, and the folded form represent the martensite phase at low temperature (LT).

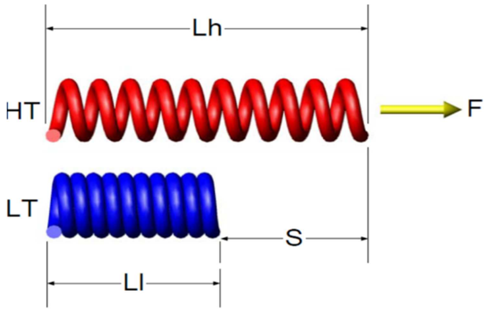

**Figure 3.** NiTi compression spring at low/high Temp.

The Shape setting of SMA is a thermally induced process that occurs when the alloy is heated to temperatures of approximately 500°C for 10 to 25 minutes. In most literatures, shape setting occurs in a furnace. Shape setting can be done over a wide temperature range from 300°C to 900°C. However, heat-treating temperatures for binary NiTi alloys are usually chosen in the narrower range of 325 to 525°C in order to optimize a combination of physical and mechanical properties. Heat treating times are typically 5 minutes to 30 minutes. Consideration must be given to the mass of the heat-treating fixture as well as the mass of the product.

### 4.2. Design of Complete Prototype-Model

Based on design concept, if a mass is set on the plate and electrical current passes through the NiTi spring (electrical activation), the spring will be heated and phase transformation occurs and therefore the spring will return to its original shape (stretched shape) which will move the plate upward. After that, the electrical current will be cut off to let the spring to cool (martensite phase). Then the plate weight contribute in the downward movement of the plate based on NiTi deformable phase that is created after cooling.

One of the advantages of 3D software design is the “rapid prototyping” in which allows making visual moving and testing associated with prototype function before going to real construction. Figure 4 shows the complete 3D Design of the prototype, made by AutoCAD.

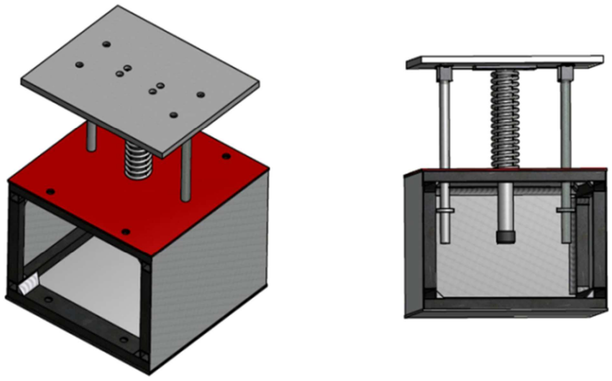

**Figure 4.** 3D design of the prototype.

After completion of CAD design and shape setting of the spring, physical construction of the prototype is the next step. The prototype construction was made based on the CAD design and previous calculations of SMA-spring as shown in Figure 5.

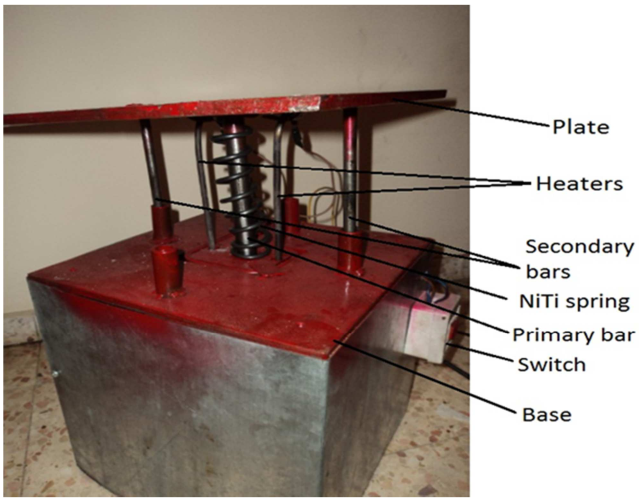

**Figure 5.** Manufactured prototype model.

Table 1 gives an overview of the components of the prototype model and their functions and dimensions.

**Table 1.** The components of the prototype.

| Components | Functions | Dimensions |
|---|---|---|
| NiTi spring | The most important part of the prototype, since it’s the source of actuation as discussed before. | the same as CAD design Ls=5cm, Lf=25cm, stroke = 20cm, Dm=3.6cm, Dw=55mm, Na=9 coils, P= 3cm |
| Primary bar (steel) | Control the spring movement during activation and ensure straight movement upward and downward. | D=1.5cm, L=30 cm |
| Secondary bars (steel) | Two bars subjected in both sides of the plate to control movement and avoid deflection of the plate. | D=1cm, L=32cm. |
| Plate (steel): | Represent the surface of the prototype in which objects would be placed on it. | 30×30×1 cm. |
| Heaters (tungsten): | Two heaters to provide the necessary heat for thermal activation. | L=30cm, D=0.5cm |
| Base (steel) | It’s the foundation of the whole prototype and each component is subjected on it. | 30×30×30 |

## 5. Results and Discussion

The evaluation of the manufactured model on basis of actual performance of this prototype. The performance measures of the prototype is obtained by determining the following measures, Cycle time, Power, Load and maintenance.

For this prototype, a cycle time is defined as the amount of time needed to actuate and relax a shape memory element and the cycle rate as the amount of cycles the actuator can perform per unit of time. The cycle time can be divided into two parts, heating or actuation time and relaxation or cooling time. Cycle time calculation of the prototype is found to be 2.5 minutes for heating and 5 minutes for cooling and recover back to be ready for the next cycle, then the whole cycle time = 7.5 min. and the cycle rate is the inverse of cycle time.

As far as the power calculation is concerned, the Power calculation of the prototype is the dissipated power in the two activation heaters. Each one of heaters consumes 3kW per hour.

so that the power per cycle = (3000w per hour*2.5min.*2Heaters)/60 = 250W per cycle. Note that the cycle time used in calculation is 2.5 min, which is the time between switch on/off the heaters.

Regarding the load (weights to be lifted), the maximum possible weight that the spring can carry is selected, and all the tests are carried out at this weight. Weights are 40 kg, 10 kg for the plate and 30 kg for each mass.

There is no need of maintenance in the prototype except the need of lubrication of the primary and secondary bars to minimize friction, one lubrication is enough for many number of cycles. It is important to consider the relationship between the NiTi spring and the recovery springs, when the NiTi spring is cooled, the recovery spring will force the NiTi spring to compress to its solid length.

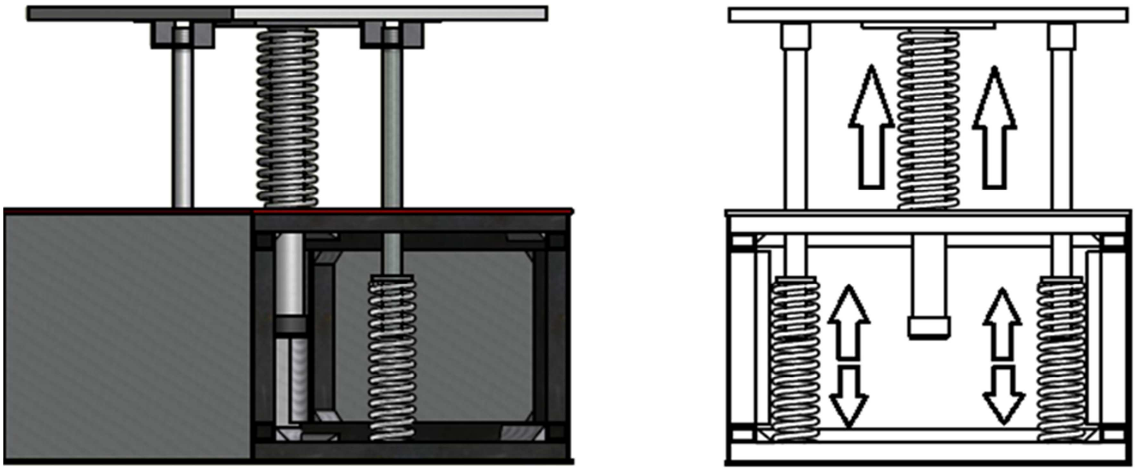

**Figure 6.** NiTi action during activation.

Then as the NiTi spring is activated (heated by means of heaters), the NiTi spring will return to its original shape and the recovery springs will stretched due to the force generated from NiTi spring as shown in figure 6.

To improve the performance of the prototype, some problems have to be solved without affecting the function of the prototype. These issues include the following items:

1. The steel plate is high in weight (10Kg) and able to conduct heat and electricity, this will make the plate more hazardous so that the plate type is unsuitable for the prototype.
2. As the secondary bars are fixed with the plate from one side and free from the other side, friction generates from the movement of the secondary bars through the base which will result in power dissipated due to this friction.
3. Cycle time is very high (7.5min.), in real world this will make the prototype unreliable because there is no reset force for new cycle to begin, and it found that more than half (5min.) of the cycle time is spent during the reset action done by the plate weight to compress the spring.

As mentioned above, a number of modifications have been added to the original prototype to improve its performance and solve the above problems. A redesign of the steel plate should be made. Thus, it is replaced by aluminum plate weights (2.5 kg) instead of (10 kg) to reduce the total weight of the plate and to use this difference between the two weights to increase the load weight by 7.5 kg. The problem of heat transfer is also solved by covering the bottom of the aluminum plate with heat insulation. In addition, two conventional tension springs should be added, one for each secondary rod, to control their movement through the base while holding the free side of the secondary rods to reduce friction. Another advantage of adding two tension springs (return springs) is the restoring force. After cooling the NiTi spring, the two tension springs push the NiTi spring to its full length.

## 6. Conclusion

The biggest benefit for the future researcher in this area is to show possible design strategies while avoiding some of the most time-consuming pitfalls. The implementation of SMA for large forces and for use in intralogistics is still far from being ready for series production. It is attractive to employ new technology such as the NiTi linear actuator as an alternative solution, hence the continuous improvement because there is no optimum solution. When uses a new driver technology, it must take into account other consideration like cost, environment of work, safety and efficiency to reach the main goal. Safety issue must be considered during shape setting process, since heat treatment is accomplished using high temperature furnaces. Furthermore, the activation method must be considered according to the SMA wire diameter because for large diameter electrical activation cannot be applied. It is preferred in SMA actuator design to use spring shape beside other shapes, because SMA springs offer an increased amount of stroke at the expense of a reduced actuation force. Regarding the Cycle time, it could be improved by effective cooling method applied on NiTi spring to reduce recovery time such as using Nitrogen gas to cool the spring.

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