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On the Design and Test of a Prototype of Biped Actuated by Shape Memory Alloys

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ABSTRACT
In this paper the design of a biped robot actuated with Shape Memory Alloy (SMA) springs with minimum degrees of freedom is presented. SMA springs are a class of smart materials that are known for their high power to mass and volume ratios. It was shown that utilizing spring type of SMAs have many advantages as large deformation, smooth motion, silent and clean movement compared to ordinary type of actuators. In this work a Biped robot actuated through SMA springs with four DOFs is modeled and designed. Walking trajectory is generated validating the Zero Moment Point (ZMP) Criteria and the number of DOFs is modified accordingly. To verify the design, acomplete model of the biped actuated with SMA is modeled through computer simulation in MATLAB and Visual Nastaran. Finally to validate the results, a prototype is manufactured and tested. Experimental results showed reasonable agreement with simulation results.

1. Introduction

Most of biped walking robots consists of actuators (heavy servomotors), transmission systems (gearbox) and many DOFs to locomotate ([1, 2, 3]), resulting in relatively heavy (and large) walking robots.
Recently, miniaturization and simplification of robots has received increasing attention for multi-purpose use. In particular, the simplification of biped walking robots is an interesting and challenging problem. The first step of simplification is to delete extra parts or unnecessary DOFs. As we know, none of the existing biped walking robots is under 7 DOFs. In this paper, we present a walking robot that locomote through only5 DOFs. Further, to reduce the size and weight of the robot, we decided to use the SMA based spring materials to actuate the legs of the biped.SMA composites are class of smart materials that are known for their high power to mass and volume ratios. These actuators have many advantages as large deformation, smooth motion, silent and clean movement. These types of actuator don’t need any lubrication or protection from dust.
Son and Bum in 2001 introduce a quadruped robot with SMA wire actuators, SMAs is used in rack and pinion mechanism to transfer force to speed [4]. Liu and Liao in 2004 used SMAs in a snake robot able to change in length with several modules [5]. Nishida in 2006 tested first prototype of biped robot with SMA actuators. In fact, this robot sliding on surface and can't to locomate [6]. Esfahani in 2007 designed joint actuated by SMAs, suitable for biped robot, but never manufacturing a prototype [7]. Urata and Yoshikai studied on a joint that suggested for quadruped [8]. According to previous works, up to now, no biped robot actuate by SMAs that able to locomate not introduced. However, the controls of the SMAs are a big challenge specially for walking robot applications. In this work, the on/off (switching) method is implemented for the control purposes. The method utilizes the angular position of the joints and compensates the errors of the SMA position to move the legs of the biped.

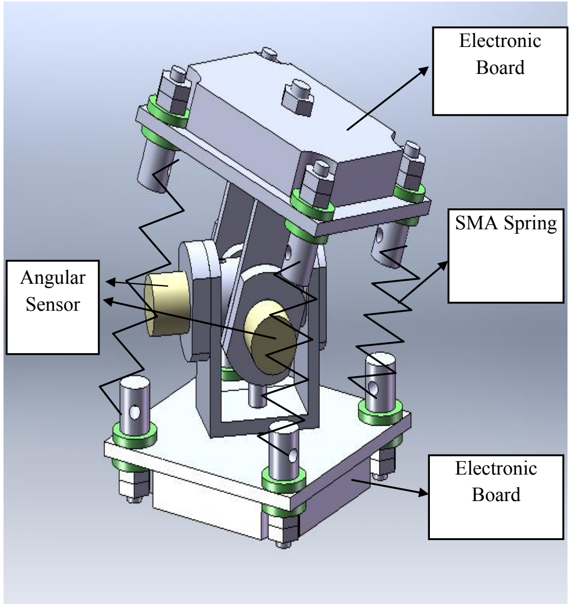

Fig. 1: Module parts

2. The Robot Design

The design of the robot consists of two parts: mechanical design and electrical design. The mechanical design is divided to two parts by itself: the module and the body design.

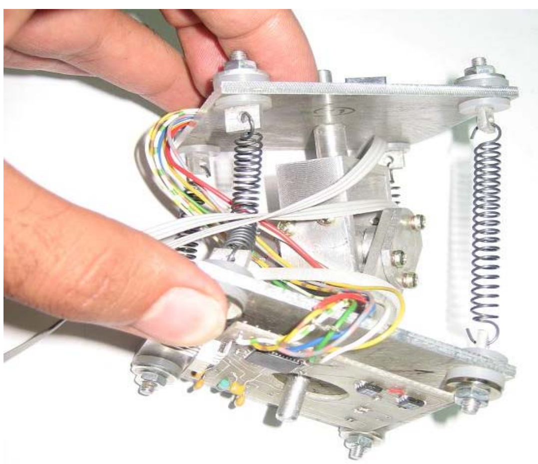

Fig. 2: The manufactured module

2.1. The Module Design

There are some studies on SMA module (joint), [5, 9]. Liu and Liao introduce a module with one DOF, [5]. This module is very simple but the deflection is limited and it has just one DOF, but locomotion needs at least two DOFs. Ying and Wang presented a two DOFs module that revolved in to plane [9], this module has high lost of energy because of friction in contact of SMA winding on disk. To provide two DOFs, large deflection and reduce friction, Hadi developed the Felexibot which is shown in Fig.1, [10]. Fig.2 shows the manufactured module.

This module consist of 7 parts, two flat plate, two U parts that make universal motion, two angular sensor to detect position, SMA connections and reserved space for electrical boards. This module has space work between + 30 deg to -30 deg in each revolution plan. Double couple of Hadi's module was used in this biped as hip joints. Each joint has 2 DOFs and 6 SMAs.

2.1.The Body Design

At first a mechanism of locomotion with just four DOFs was proposed, but it was found that a mechanism with less than five DOFs is not appropriate to locomate the system . Adding a sliding part on top of the 4DOFs robot, the drawbacks of the motion was solved. The robot consists of six parts, two modules, two legs connected to the modules, a slider and few SMAs. The slider weight is used to transfer the center of the gravity of the biped. A rigid block sliding on a bar is used for this case, however, in practice it can be replaced with camera, battery pack, and other devices. Fig. 3 shows the biped including the actuator modules and the sliding weight COG compensator.

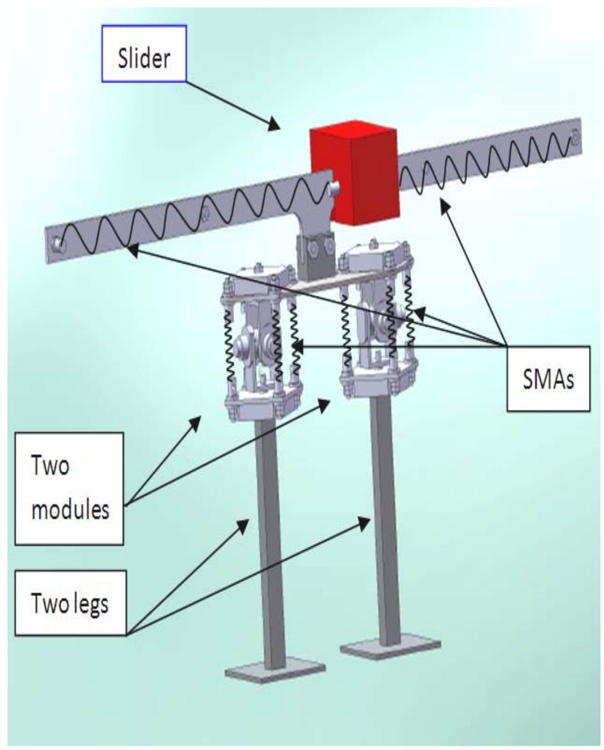

Fig. 3: Robot design

2.3 The Electrical Design

The block diagram of the module's electrical hardware is shown in Fig. 4. It includes a microcontroller (ATMEGA32), SMA drivers (Darlington transistors, TIP122), position sensors, and communication drives. The microcontroller is used to manage the driving of the SMAs, to handle the communication requirements, and to provide A/D conversion.

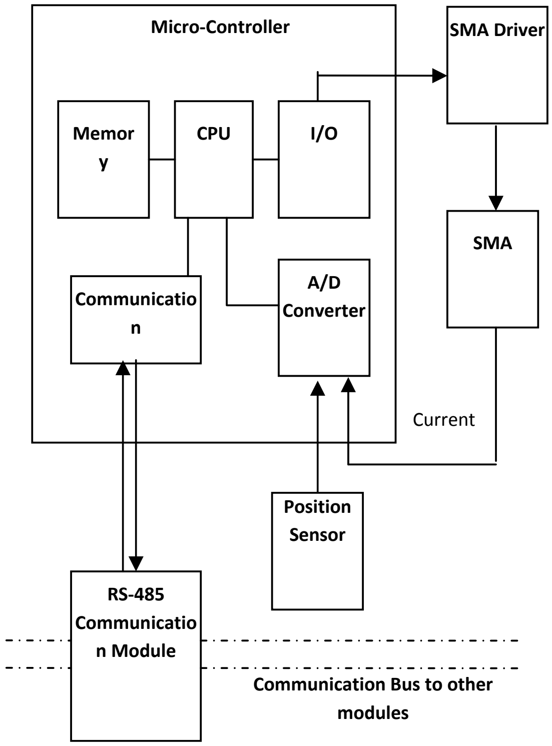

Fig. 4: Electrical board overview

3. Modeling

To model robot motion, we should develop kinematic model of robot body and model of SMAs actuator behavior.

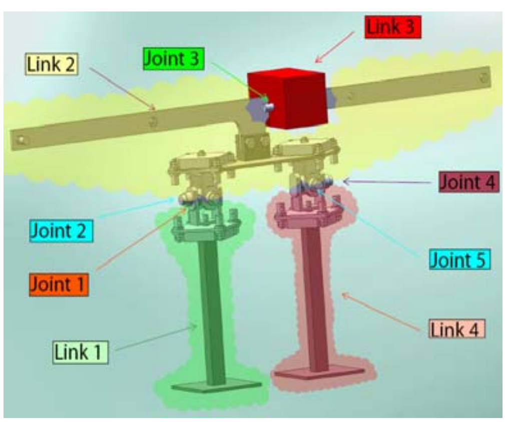

Fig. 5: Robot links and joint defenition

3.1. Kinematic Model

According to Fig. 5, robot is divided into 4 links and 5 joints. Refer to low reaction of SMAs actuators and ZMP criteria, acceleration terms is ignored, so ZMP criteria reduced to eq.1, describe kinematic model of robot and its stability region.

$$ {}^{0}R_{CG} = \frac{\sum_{i=1}^{4} m_i {}^{0}R_{CGi}}{\sum_{i=1}^{4} m_i} \quad (1)$$

Where, ${}^{0}R_{CG}$ is position matrix, in base coordinate system.

3.2. SMAs Behavior Model

According to [11]:

Deflection of shape memory alloys as function of force and the martensite fraction can be expressed as:

$$ y = \frac{8D^3N}{Gd^4}F - \frac{\Omega N \pi D^2}{\sqrt{3}Gd}\xi_s \quad (2)$$

Which y is deflection, F is force, G is the elastic shear modulus, Ω the phase transformation tensor (which can be calculated from $-E\varepsilon_L$ where E is the elastic modulus and ε_L the maximum recoverable strain), ξ_s is the stress induced martensite, D is outer diameter of shape memory alloys spring coil, d is wire diameter and N is number of winding.

In addition to the SMA spring model, the heat transfer model of the SMA is defined as:

$$ mc_p \frac{dT}{dt} = I^2R - h_c A_c (T - T_\infty) \quad (3)$$

$$ A_c = pi*d*L \quad (4)$$

Which m is the mass, c_p the specific heat constant of SMA, I current, R resistance of SMA, h_c convection heat transfer constant, A_c outer environment of SMA, *d* SMA spring wires diameter and T_∞ ambient temperature. Constant values are shown in Table 1.

Table 1: Constants value

Parameter	Value / Dimension
m	0.001182 kg
R_A	0.6 Ω
R_M	1 Ω
C_p	836.8 J/kg.c
h_c	50 J/mm^2.C.sec
T_0	23 °C
T_∞	23 °C
d	0.75 mm
L	*10 cm*

The final model of the system in Simulink Matlab is shown in Fig. 6.

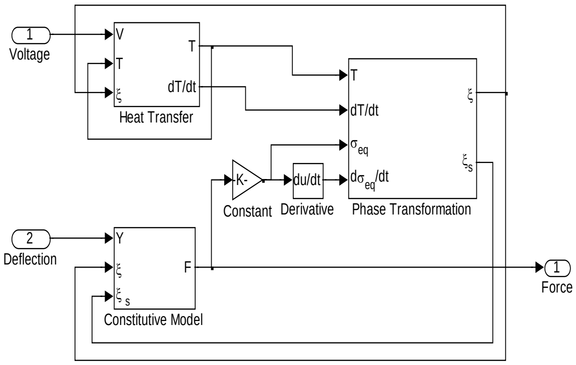

Fig. 6: SMA modeling in MATLAB software

4. Simulation

MATLAB and Visual Nastran software are used to simulate the locomotion of the robot. Actuators was are modeled in MATLAB environment and their actions are transformed to the Visual Nastran software to generate the biped body motion.

Both software are linked together in a range of 0.01s period. In doing so, inputs and outputs are defined in each software accordingly and the data in transferred through these for the communication purposes The input to the Matlab is the SMA's positions are input and the resulting forces of the SMA's based on their models are outputs to the V.N. software. Simulations are performed for a typical biped model and the results are shown in fig .7.

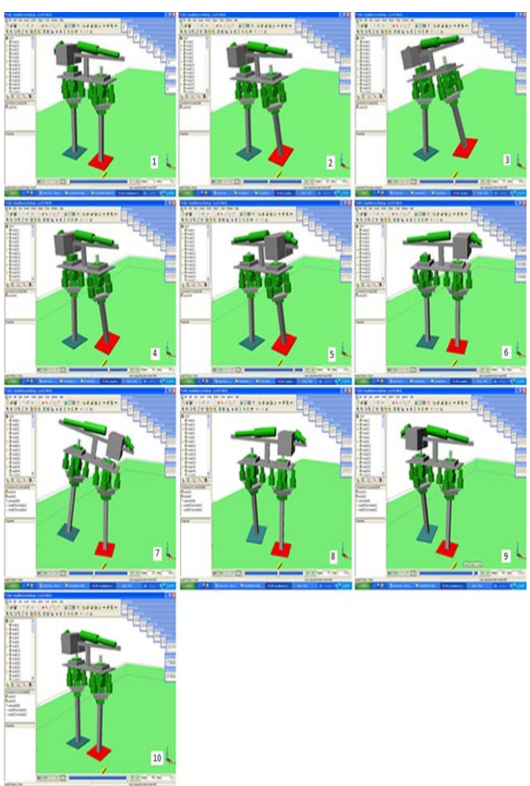

Fig. 7: Locomotion steps

As it shows, the locomotion consists of tenth parts: first, move the slider to left, second, take off the right leg of the ground, third, swing forward the suspended leg, fourth, put the right leg to the ground, fifth, move the slider to the right, sixth, take forward robot with get back right let to first position and robot repeats above steps but support on right leg, thus continues trajectory makes walking forward.

5. Trajectory Generation

Through simulation, walking trajectories are generated. Then, through kinematic modeling of the biped, desired motions of the robot's legs are calculated. It requires the motion of the modules that is actuated through SMA's. The SMA's are activated through two individual drivers. Fig .8 shows the simulation result.

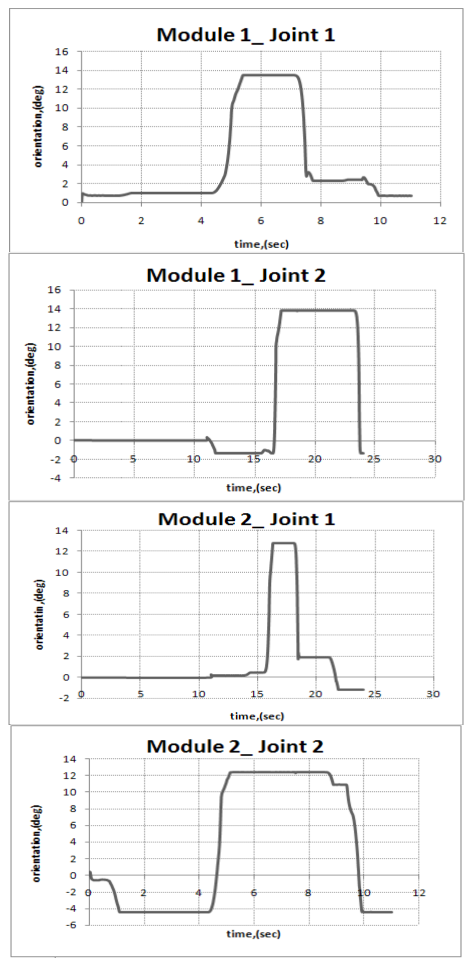

Fig.8: Simulation results

This curved shows position of each joint as function of time, clearly the path of joint 1 in module 1 is similar to joint 1 module 2, just joint 1 in module 2 has time shift. Other two joints are same as those ones. By using this result, the prototype of robot can move. Robot microcontroller should follow the curves and keep joints in correct position in time.

6. Experiments

A scaled version of the biped is designed and manufactured to verify the simulation results in practice. Fig.9 shows the experimental setup. Specification parameter of assembly robot is collected to Table 2.

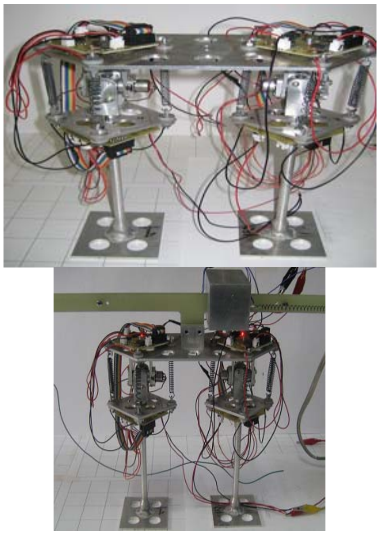

Fig. 9: Experimental setup

Table 2: Robot specification

parameter	quantity
mass	1483 gr
Total Height	30 cm
Leg Length	22 cm
Width	10 cm
Actuator	SMA
Number Of Actuators	14
DOF	5
Foot Dimension	70*80 cm^2
Supply	6 Amp- DC
Material	Aluminum
Microcontroller	ATMEGA32
Locomotion Speed	33 mm per min.

Fig.10 shows SMAs spring arrangement in module and robot. To take off robot weight, should use double SMAs spring in corner of each module.

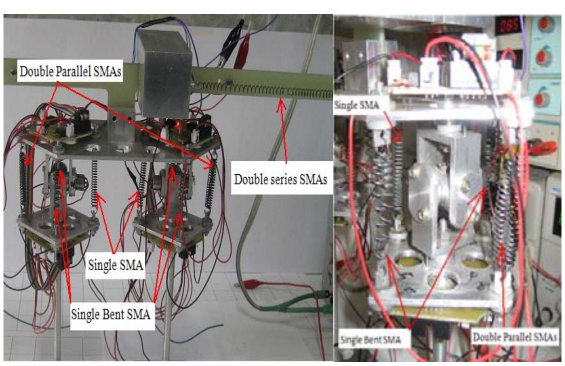

Fig. 10: SMA springs arrangement

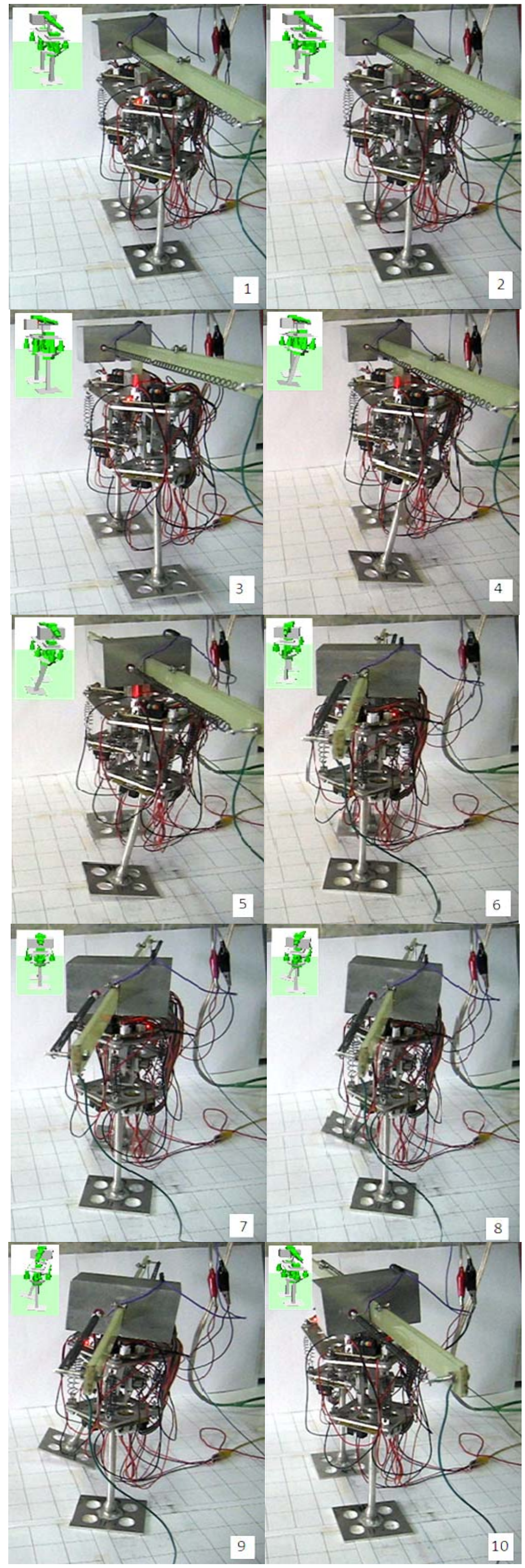

Fig. 11: Experimental results

A simple but complete walking pattern is designed and is fed to the system through a computer program. It is shown that the experimental results are close to the simulation results. Ten steps of motion pattern were generated automatically, and are repeated for a number of walking steps. Fig. 11 shows locomotion steps. It was found that the robot behaves stably, but due to the slow reactions of the SMA's the overall speed of the robot was very slow. However, the SMA's were shown to be properly strong to push the biped forward. Even though, the walking pattern was not very smooth in practice, but it proved that the motion can be generated through only 5 DOFs mechanisms.

7. Discussions

This paper presents the design of a biped robot actuated with Shape Memory Alloy (SMA) springs with minimum degrees of freedom. Modeling of SMAs and modeling of robot was shown, and the curved result used for experimental motion. So to simplify biped, extra DOF was deleted, therefore the biped moved with just 5 DOFs and actuated by SMAs. Finally a prototype of biped manufactured and locomate like simulation result. Experimental shows that SMA actuators in biped robot is useful, but apply this robot in corrosion surround, where other actuator will corroded, is suggested. Other advantage of this robot actuated by SMAs is maintenance free. This actuators work under water and in high duty conditions well.

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