Test Results with a Binary Actuated Parallel Manipulator

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Abstract

This paper reports experimental results of a newly built BAPAMAN1 (Binary Actuated PArallel MANipulator). This is a 3-DOF (Degree Of Freedom) modular spatial parallel manipulator with low-cost and easy-operation design features. BAPAMAN1 is driven by SMA (Shape Memory Alloy) at its flexure joints. Several experimental tests have been carried out with the aims to validate the proposed mechanical design and to evaluate the practical operation performances and characteristics of the built prototype. Experimental results show that the tested prototype can perform eight binary configurations and it has a suitable reachable workspace for the prescribed applications.

Keywords: Flexure Joints, Binary Actuators, Parallel Manipulators

1 Introduction

Traditionally, robotic manipulators are designed as continuously actuated systems. Although they can work well with applications in industry [1], service [2], and humanoids [3], they are very complex and expensive systems for non-expert users.

Since 1990, a research line has been devoted to the design of low-cost and easy-operation robotic systems at LARM (Laboratory of Robotics and Mechatronics). One efficient way for reducing the cost and complexity of a robotic system is to include as few actuators as possible. Alternatively, as proposed in [4]-[5], replacing continuous actuators with binary ones can also be an ideal solution. In fact**,** binary actuators can be controlled by simply triggering two states (on and off). Although a binary manipulator has limited motion capability, as the number of binary actuator increases, it can approach to conventional manipulators with continuous actuators.

In a previous work [6] at LARM, a binary parallel manipulator named BAPAMAN has been presented, which is a milli-scaled design with flexural joints actuated by SMA. Workspace performance of BAPAMAN has been analyzed theoretically in terms of position and orientation capabilities in [6]. However, the

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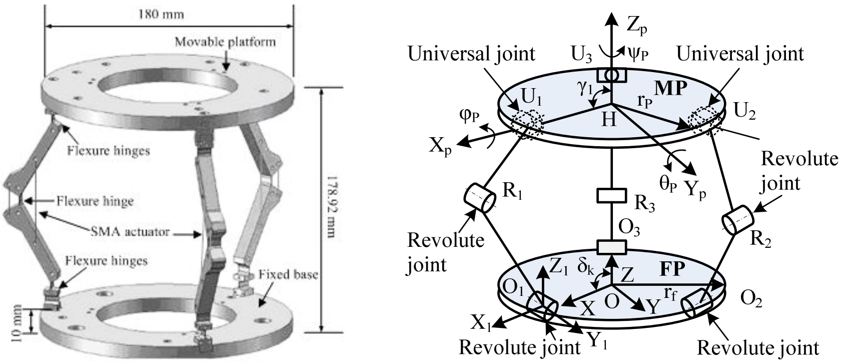
results are not validated by experimental tests, and, especially, the practical motion characteristics of the SMA actuated leg mechanism of BAPAMAN is still unknown.

Cooperating research has been carried out between LARM and IWF, aiming to design a novel version of BAPAMAN whose name is BAPAMAN1. In this paper, the operation performance of BAPAMAN1 has been characterized by using an experimental layout that has been specifically developed.

2 The BAPAMAN1

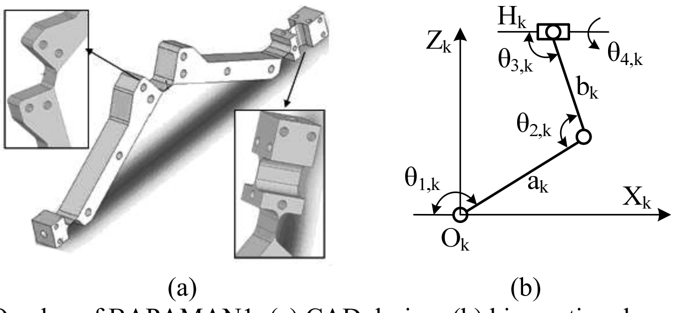
As illustrated in Figure 1), BAPAMAN1 is composed of a fixed platform (FP), a movable platform (MP), and three legs with identical structures which are assembled on the FP and MP with equilateral triangle configurations. As shown in the kinematic scheme in Figure 1b), the sizes of MP and FP are given by r_p and r_f respectively, where H is the centre point of the MP, O is the centre point of FP. δ_k and γ_k are deflection angles between the fixed points of two legs on the platform.

As in Fig. (2), the leg is composed of one actuated revolute flexure joint, one passive revolute flexure joint and one 2-DOF passive flexure joint. The 2-DOF flexure joint can be treated as a universal joint. Thus, each leg mechanism can be considered as an URR kinematic chain as in Fig. (1b).



(a) (b)

Figure 1: The proposed design of BAPAMAN1: (a) CAD design with main dimensions; (b) kinematic scheme.



(a) (b)

Figure 2: One leg of BAPAMAN1: (a) CAD design; (b) kinematic scheme.

In the kinematic scheme of Fig. (2b), design parameters of the k-th leg mechanism (k=1, …,3) can be identified through the link lengths a_k and b_k. The kinematic variables are $\theta_{i,k}$, (i=1,…, 4; k=1, …,3). In particular, $\theta_{3,k}$ are the input joint angles which are determined by the output displacements of the SMA actuators. H_k is the articulation point at which the k-th leg mechanism is fixed on the MP. The MP is driven by the three-leg mechanisms through the corresponding articulation points H_1, H_2, and H_3.

The MP can be obtained by investigating the coordinate of point H. The main dimensions of the above kinematic parameters for BAPAMAN1 are listed in Table 1.

Table 1: Geometry dimensions of the BAPAMAN1

a_k *(mm)*	b_k *(mm)*	r_f *(mm)*	r_p *(mm)*	δ_k *(deg)*	γ_k *(deg)*
100.0	*100.0*	*90.0*	*90.0*	*120.0*	*120.0*

Polyoxymethylene material has been selected for the construction of BAPAMAN1, which can achieve elastic strain up to 4% with more than one million stress cycles, and they are light-weight and quite cheap [7]. SMA wires are used as binary actuators for the operation. Since a powered SMA wire is slow to cool down for returning to its initial state, an additional SMA wire is assembled on the external side of the leg mechanism for pulling the internal one back to the initial state in an agonistic-antagonistic manne.

As a binary manipulator, BAPAMAN1 can be operated by on/off switching signals easily. The different actuator configurations for the three legs allow 8 operation modes, which are named OP0-OP7 as listed in Table 2. Furthermore, the number 1 means a leg is activated while the number 0 means deactivated, as shown in Fig. 5. In particular, OP0 is a stationary mode, in which all the legs are deactivated. Within OP1, OP2, and OP4, only one leg is activated; within OP3, OP5, and OP6, two legs are activated; within OP7, all legs are activated.

BAPAMAN-1 was built to evaluate the primary design and validate the proposal, so as to provide guidance for the design of next generation. Finally, a suitable ‘‘BAPAMAN-n’’ will be built and used as a module to design multi-module robot, e.g. snake robot, robotic arm (like trunk).

Table 2: Operation modes for the BAPAMAN1

Operation mode	*OP0*	*OP1*	*OP2*	*OP3*	*OP4*	*OP5*	*OP6*	*OP7*
Leg 1	*0*	*0*	*0*	*0*	*1*	*1*	*1*	*1*
Leg 2	*0*	*0*	*1*	*1*	*0*	*0*	*1*	*1*
Leg 3	*0*	*1*	*0*	*1*	*0*	*1*	*0*	*1*

3 The Experimental Layout

A suitable measuring system has been used to measure the position of the end-effector of BAPAMAN1. This system has been developed at LARM, whose name is Milli-CaTraSys (Cassino Tracking System) [8]-[10], as shown in Fig. (3). It is a cable-based architecture which can be used to measure the position and orientation of the end-effector of robotic systems. The Milli-CaTraSys design is based on a parallel manipulator configuration with 3-2-1 Gough-Stewart architecture. The kinematics of this measuring system has been solved in a closed form as a result of its architecture by applying the trilateration technique. Moreover, Milli-CaTraSys can be used to apply a known wrench on the end-effector of a robotic system and, simultaneously, to measure the corresponding end-effector displacements.

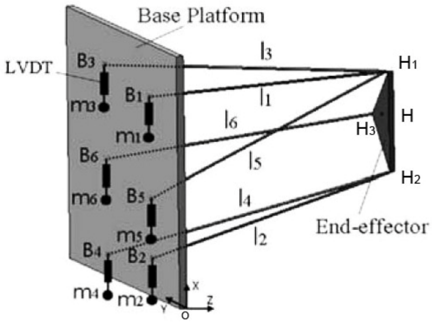


Figure 3: 3D scheme of Milli-CaTraSys with the reference frame O-XYZ

Milli-CaTraSys consists of a fixed platform and an end-effector with six cables. A set of six LVDT transducers is fixed at the end of each cable to determine the length change. Data acquisition and elaboration are executed by a NI DAQ PCI 6024 card and a program in LABVIEW environment. By measuring the length of the cables and using trilateration technique, the position and orientation of the end-effector can be determined in Cartesian space. This technique is based on suitable algebraic manipulations of distances l_i as function of the Cartesian coordinates x_{H1}, y_{H1}, and z_{H1} of point H_1 with respect to a fixed frame O-XYZ in the form

$$l_i^2 = (x_{H1} - x_{Bi})^2 + (y_{H1} - y_{Bi})^2 + (z_{H1} - z_{Bi})^2, (i = 1,3,5) \qquad (1)$$

where x_{Bi}, y_{Bi}, and z_{Bi} are the Cartesian coordinates of fixed points B_i at the Milli-CaTraSys base, as shown in Fig. (3). After some algebraic manipulation, the position of H_1 can be computed through its components as

$$\begin{aligned} x_{H1} &= H_x(-B_2 - \sqrt{B_2^2 - 4B_1B_3})/2B_1 + E_x \\ y_{H1} &= H_y(-B_2 - \sqrt{B_2^2 - 4B_1B_3})/2B_1 + E_y \\ z_{H1} &= (-B_2 - \sqrt{B_2^2 - 4B_1B_3})/2B_1 \end{aligned} \qquad (2)$$

in which

$$\begin{aligned} &E_x = (A_1 + A_2 - E_yY_{21})/X_{21}; E_y = (-A_1 + A_2)/Y_{32}X_{21}; B_1 = H_x^2 + H_y^2 + 1 \\ &B_2 = 2H_x(E_x - x_3) + 2H_y(E_y - y_3) - 2z_3; B_3 = E_x^2 + E_y^2 + A_3^2 - 2E_xx_3 - 2E_yy_3B_1) \\ &H_x = -(Z_{21} + H_yY_{21})/X_{21}; H_y = (Z_{21}X_{32} - Z_{32}X_{21})/(Y_{32}X_{21} - Y_{21}X_{32}) \end{aligned} \qquad (3)$$

In which

$$\begin{aligned} &A_j = l_i^2 - x_i^2 - y_i^2 - z_i^2; \quad X_{ij} = x_i - x_j \\ &Y_{ij} = y_i - y_j; \quad Z_{ij} = z_i - z_j \end{aligned} \qquad (4)$$

with (i, j=1,2,3), ($i \neq j$), and (x_i y_i z_i) is the coordinate of H_i.

Eq. (2) and Eq. (3) express a general formulation of the trilateration scheme of Fig. (3). Using expressions similar to Eq. (2) to Eq. (4) for measured length l_2, l_4, and l_6, it is possible to determine the position of point H_2 and H_3 through their components x_{H2}, y_{H2}, z_{H2}, x_{H3}, y_{H3}, and z_{H3}, respectively.

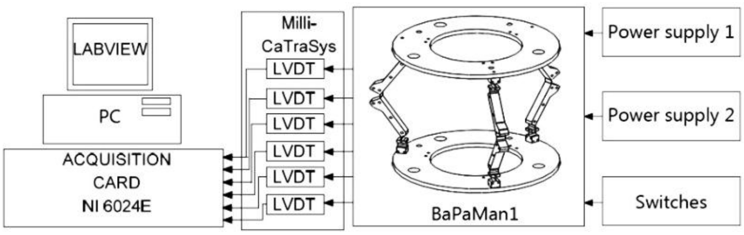
A built prototype of BAPAMAN1 is shown in Fig. (4b). For easy assembling and testing, BAPAMAN1 has been fixed on a cantilever beam reversely with MP upward and FP downward. NiTinol SMA wires with a diameter of 0.2mm have been set to be spring shapes as actuators for BAPAMAN1. There are two pairs of actuators for the leg mechanism: a pair of internal SMA actuators and a pair of external ones, which can overcome the slow cooling nature of SMA.

A scheme of the experimental setup for measuring the position of BAPAMAN1 is shown in Fig. (4). Six cables of Milli-CaTrasys are fixed on the MP through three articulation points H_1, H_2, and H_3. Particularly, three cables have been attached to H_1, two have been attached to H_2, and one has been attached to H_3. These points on the MP define an equivalent triangle. H is the center point of equivalent triangle $H_1H_2H_3$. Orientation of the MP has not been considered in the experiment.

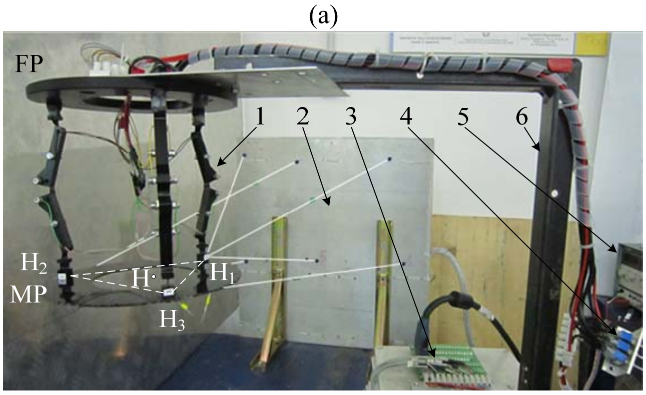
Preliminary tests have determined that the normal working current for the selected SMA wire is around 1A, and its resistance is proportional to its length. Since the length for the internal and external SMA actuators are different, two power supplies are needed for powering the internal and external actuators separately. The contraction of each wire is about 33% when switching on.

Figure (5) illustrates a scheme for the actuator wiring for BAPAMAN1. Power supply I (1.5V) and II (0.5V) are used for internal and external actuators respectively.

SMA_I_i (i=1, 2, 3) is the internal actuator for Leg_i, while SMA_E_i is the external actuator for Leg_i. K_i is two-state switch, whose 1 and 0 states are used for actuating SMA_I_i and SMA_E_i respectively. BAPAMAN1 can be operated manually by changing the configurations of switches K_1, K_2, and K_3. Certainly, for further applications with more modules, switches can be replaced by PLC (Programmable Logical Controller) for automatic operation. Nevertheless, for the experimental of BAPAMAN1, the proposed wiring system of Figure (5) can be used.



(a)



(b)

Figure 4: The experimental system: (a) Scheme for the experimental system; (b) The experimental layout (1-CAPAMAN1; 2-Milli-CaTraSys; 3-data acquisition device; 4-switches; 5-power supplies; and 6-cantilever).

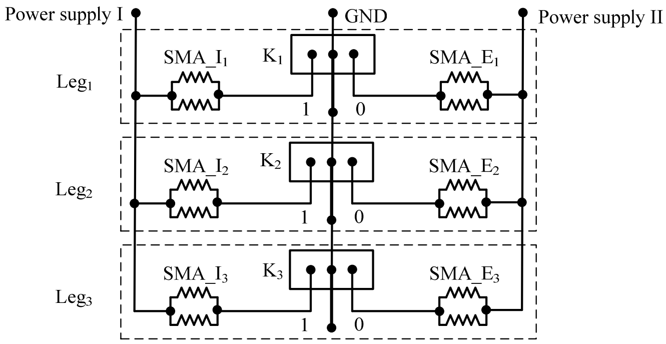


Figure 5: Scheme of the actuator wiring.

Calibrations have been carried out in order to verify and to reduce the effects of systematic errors on accuracy. The calibration of Milli-CaTraSys has been carried out with LVDT B type transducers with a range of 100mm in [11].

4 Experimental Results

After the calibrations of Milli-CaTraSys and BAPAMAN1, experiment has been carried out. In the experiment, switches have been set to perform the 8 operation modes (OP0 to OP7) of BAPAMAN1 sequentially as shown in Fig. (6). The stated eight operating modes just show all the possible working modes that BAPAMAN1 has, which are useful for the robot to make movement in future applications.

Coordinates of point H have been computed by a program developed in MATLAB as in Fig. (7). Considering the small sizes of the manipulator, the workspace of BAPAMAN1 is good as can be seen in Fig. (7). The time axis show time duration of the experiment under the operation of BAPAMAN1 from OP0 to OP7 sequentially. In particular, maximum motion ranges have been 2.3mm, 0.1mm, 3mm in x, y, z directions, respectively. It was not big because of the symmetrical structure of the robot. Maximum orientation angle is approximately to 25 degrees.

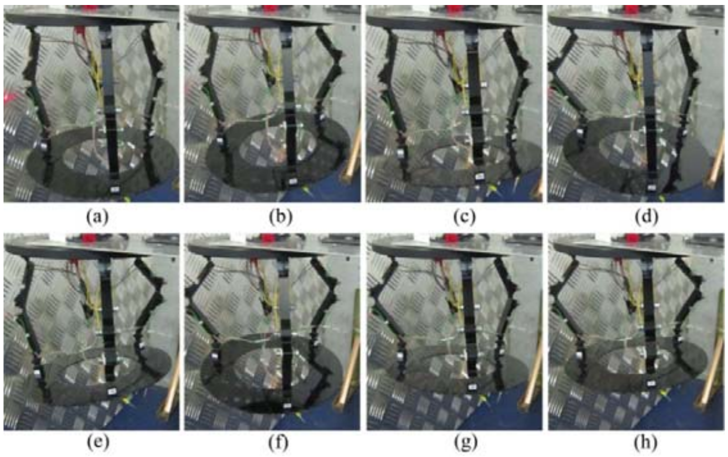
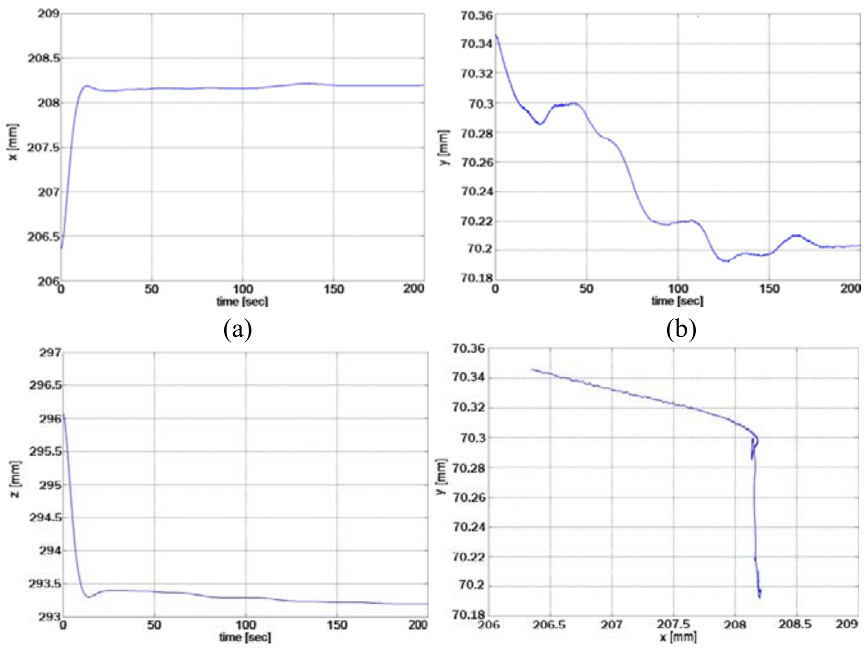


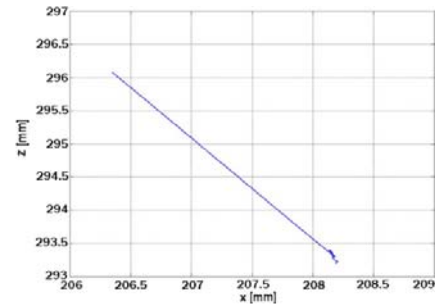
Figure 6: Snapshots of eight binary configurations of the tested prototype of BAPAMAN1: a-OP0; b-OP1; c-OP2; d-OP3; e-OP4; f-OP5; g-OP6; h-OP7.

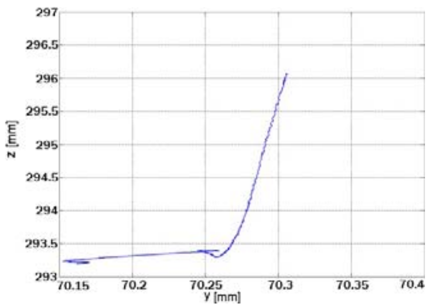
Time axis in Fig. (7a-c) show eight modes changing from OP0 to OP7 sequentially. Switching events couldn't be marked since the operation was operated manually, thus the exact switching time is hard to record.



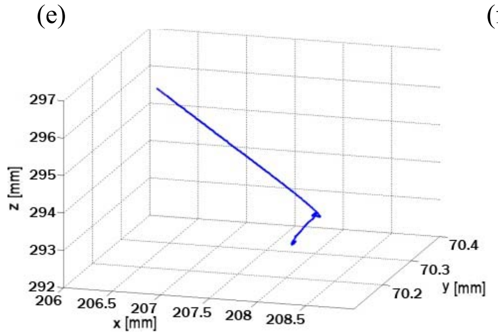
(a) (b)

(c) (d)





(e) (f)



(g)

Figure 7: Measured positions of the centre point H: (a) x_H; (b) y_H; (c) z_H; (d) y_H as function of x_H; (e) z_H as function of x_H; (f) z_H as function of y_H; (g) 3D trajectory.

5 Conclusions

In this paper, experimental tests have been carried out on BAPAMAN1 with the aims to validate the mechanical design and evaluate practical operation performances and characteristics. Experimental results show that BAPAMAN1 can perform eight binary configurations and has a suitable reachable workspace for the prescribed applications. Though the robot is not designed for the purpose of carrying high payload, stiffness is the key aspect that will be considered in the next generation design. Experimental results will be considered as the guideline for the design of an improved prototype BAPAMAN2, which has a half-size scale and multi-modules.

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