Biomimetic Approach in Developing Control Strategy for Shape Memory Alloy Legged Robot

Anca PETRISOR, Nicu George BIZDOACA, Mircea Adrian DRIGHICIU, Raducu PETRISOR
University of Craiova
Blv. Decebal nr.107, RO-200440 Craiova
apetrisor@em.ucv.ro, nicu@robotics.ucv.ro,adrighiciu@em.ucv.ro, raducu.petrisor@elprest.ro

***Abstract*— Control of legged robots can be inspired from the way in which biological systems (living creatures) control the movements. This paper deals with the problem of shape memory alloy spring based legged robot control in measurable but unpredictable environments. The paper structure consists of two sections: first section studies the use of shape memory alloy leg structure and the second section deals with the evolution performed using a causality structure with four free joints, with desired values for the centre position and for the body angle of the robot, codified as causality structure [motor 15 motor 25 4]. All the researches developed until now, for the robot represented as a variable causality dynamical system (VCDS), are kept and used for the causality structure approached in this paper. The results are implemented and verified in RoPa, a platform for simulation and design of walking robot control algorithms and some evolution examples are presented.**

***Index Terms*—causality structure, control algorithms, desired trajectories, shape memory alloy, legged robot**

I. INTRODUCTION

Recently, intensive studies have been focused on legged robots. Compared to traditional wheeled robots, walking robots will be able to handle uneven terrain and soft ground in difficult conditions where wheeled robots cannot go. Furthermore, one can take the advantages of biologically inspired control strategies and apply the control scheme to robots through observing how living creatures control their movements. Behavior of walking robots from the biped structure till the multileg structures is characterized by a specific type of movement called legged locomotion, [15], [6].

First of all, the robot leg has to offer not only a sure contact surface, but an adaptive damper coefficient in order to adapt the robot movement to unknown environment.

A simplified model for springy robot leg is assimilated with a pogo stick – Fig. 1. The variables in the model are positions and velocities, and the dynamic equations come from Newton’s laws of motion. When humans walk, feet never lose contact with the ground and alternate between having both feet on the ground and a swing phase in which one foot is on the ground and the second leg swings like a pendulum. When run, we alternate between a flight phase in which both feet are off the ground and a stance phase in which one foot is on the ground. Kangaroos hop with a flight phase alternating with a stance phase in which both feet are on the ground simultaneously.

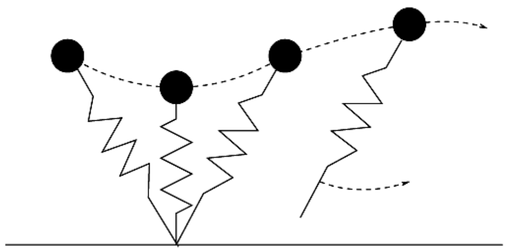


Fig. 1 A simple model for running and hopping leg

As an approximation, one can think of the springy leg as the tendons in the leg. By contracting muscles, the animal changes the force of the leg spring, enabling it to bounce off the ground. When in flight, we assume that the animal is able to swing the leg so that it will point in a new direction when the animal lands on the ground. At landing, the leg shortens, compressing the spring. The compressed spring exerts a vertical upward force that together with additional force exerted by the muscles propels the animal into its next flight phase. Simplifying, the hopping movement can be divided in hopping in place and hopping forward or backward.

Hopping in place and hopping forward/backward can both be divided into two different phases: an aerial phase (where the mass is airborne) and a ground phase (where the mass and spring are on the ground).

Control algorithms for legged locomotion are very different but all of them must assure a stable movement. From this point of view, there are two types of stable movements: dynamic stable movement and static stable movement.

Many control algorithms implemented on the existing walking robots, [7], are based on "state of the art" technologies to control the movements of articulated limbs and joint actuators. Some of them try to recreate the efficient yet very complex movements of biological insects and mammals, which effortlessly execute various types of periodic gait patterns and adaptive gaits at very high speed [6]. Usually, two-legged robots are designed according to the human skeleton and controlled according to human behaviors. This encourages many researchers to investigate the basic human movements and try to apply the human behavior to robots. Today, the notion of central pattern generator (CPG) has been developed based on living organisms to generate the human-like gait rhythm. The newest research of biologically inspired walking machine was presented by [3]. They used the oscillator originally proposed in [4], to generate oscillatory behavior, which possibly imitates mammal-like walking gait. A single leg control was described in [16] using a non-spiking neuron model as the first step in the process of modeling and building a fast and dynamically stable quadruped. In [17] it is used the Van Del Pol (VDP) oscillator as the gait rhythm generator for a two legged walking machine. There was a coupled neural-oscillator on the hip and knee joint. Taga (1995) used Matsuoka oscillator on a bipedal robot. The gait pattern was represented as a cyclic sequence of six states. In [5] it is made a comparison of three different oscillator models: the Stein neuronal model, the VDP model, and the FitzHugh-Nagumo model. However, their oscillators were used only for inter-limb control on a quadruped machine similar to that described in [13]. Most models have focused on either properties of the neural-oscillator or control architectures of inter-limbof walking machine. Few of them reported an intensive investigation on the human-like robot leg with hip, knee, and ankle joints. There are few applications of the gait rhythm generator on a human-like robot leg due to the lack of appropriate walking machine prototype and corresponding equation of motion (EOM).

This paper presents a systemic approach of a walking robot behavior and control in uncertain environments, with application to a hexapod robot. Taking into account a possible symmetrical structure, only the vertical xz-plane evolution is considered. The results can be extended to three-dimensional space. The mathematical model of the robot is determined considering all the points in the xz-plane as being complex numbers. The robot is characterized as VCDS "Variable Causality Dynamic System" [9].

II. ROBOT LEG STRUCTURES

II. 1. Hopping In Place

When the leg hops in place, the model is one of a spring, where the entire force of the spring is directed in the +y direction. The motion results from gravity trying to pull the mass toward the earth and the spring trying to push the mass away from the earth. In this case there is only one variable (y) because motion is only in one direction. As mentioned earlier, hopping in place has an aerial phase and a ground phase, with a different differential equation describing each.

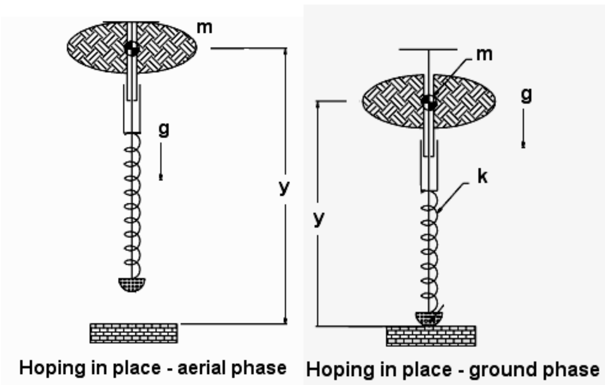


Fig. 2 Hoping in place positions

For hopping in place, the equations are:

$$m\frac{d^2y}{dt^2} = -mg \tag{1}$$

$$m\frac{d^2y}{dt^2} + ky = mg \tag{2}$$

For equation 1, while the mass is in the air, the acceleration of the object is equal to the acceleration due to gravity (9.8 m/s^2) in the -y direction, and therefore as the mass goes up, it starts to decelerate to zero m/s and then begins to accelerate as it falls down.

The evolution of this simplified hopping robot has no influence regarding the stiffness of the spring, or actuator nature.

Equation 2 shows that force of the spring subtracted from the force of gravity equals the mass multiplied by its acceleration. This equation describes the touch down moment. For this simple model, last equations, if we choose to experiment the influence of temperature, in case of using a SMA spring, we obtain the results exemplified in Fig.3.

From this simulation the advantage of using SMA spring is clear: a smart spring improve by reducing the touch-down time, and the energy losses.

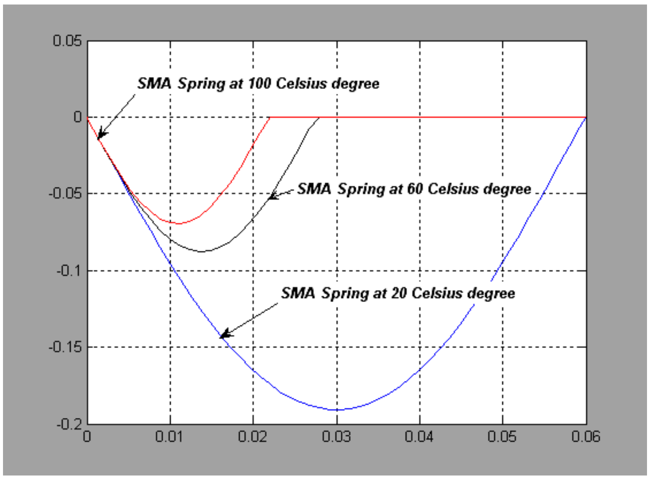


Fig. 3 Hopping in place for a SMA based robot

As one can easily observe, from the numerical simulations, the deformation of the contact terrain is up to 4 times reduced in case of a 100^0 C energized SMA spring.

II. 2 Hopping Forward

Modelling a leg hopping forward is more complicated than hopping in place and can be thought of as running. It can be assumed that the mass spring takes off at an angle (theta) against the ground, which means that it is very important to keep the vectors straight. Instead of one direction in which to move, there are two directions: vertical (x) and horizontal (y). This means that there must be two equations for both the ground and aerial phases. The equations for the aerial phase are:

$$m\frac{d^2y}{dt^2} = -mg \tag{3}$$

$$m\frac{d^2x}{dt^2} = 0 \tag{4}$$

The equation 4 means that there is no acceleration in the x direction, and equation 3 means the same thing it did in the example of hopping in place.

The ground phase is such that the leg lands at an angle ($-\theta$) to the ground, pivots on the ground while being compressed, and then decompresses as it pivots to angle $\tilde{\theta}$. At angle θ, the mass takes off into the aerial phase. The process repeats at the end of the aerial phase. The whole calculation assumes constant forward velocity (u) which is related to θ. The equations for the ground phases are:

$$\frac{d^2y}{dt^2}=\frac{ky}{m}\left(\frac{l}{\sqrt{x^2+y^2}}-1\right)-g \tag{5}$$

$$\frac{d^2x}{dt^2}=\frac{kx}{m}\left(\frac{l}{\sqrt{x^2+y^2}}-1\right) \tag{6}$$

$$l=\sqrt{x_0^2+y_0^2} \tag{7}$$

$$w=\sqrt{\frac{k}{m}} \tag{8}$$

$$l\sin(\theta)=u\frac{t_c}{2}\Rightarrow\theta=\arcsin\left(\frac{u\cdot t_c}{2\cdot l}\right) \tag{9}$$

$$\begin{aligned}\ddot{x}&=0\\ \ddot{z}&=-g\\ \ddot{\theta}&=\frac{k_{hip}(\theta_{hip}-\theta+\varphi)}{J_{leg}}\\ \ddot{\varphi}&=\frac{-k_{hip}(\theta_{hip}-\theta+\varphi)}{J_{body}}\end{aligned} \tag{10}$$

and the degree of freedom for stance stage are:

$$\begin{aligned}\ddot{r}&=-g\cos\theta+r\dot{\theta}^2+\frac{k_{leg}\left(r_0-r+p_{leg}\right)}{m}\\ \ddot{\theta}&=\frac{k_{hip}\left(p_{hip}-\theta+\varphi\right)-2mr\dot{r}\dot{\theta}+rmg\sin\theta}{J_{leg}+mr^2}\\ \ddot{\varphi}&=-k_{hip}\frac{p_{hip}-\theta-\varphi}{J_{body}}\end{aligned} \tag{11}$$

For equations 7, l is the initial, unperturbed length of the spring: x_0 and y_O are the coordinates of the mass at that length.

The coordinates (x_0,$y_{O)}$ are most likely given by:

$$y_0=l\sin(\theta);\qquad x_0=l\cos(\theta) \tag{12}$$

Equations 5, 6, 7 and 8 separate the ground phase into horizontal (*x*) and vertical (*y*) directions, which relates the accelerations in the *x* and *y* directions to positions *x* and *y*. In equations 9, t_c is the time the system is in contact with the ground.

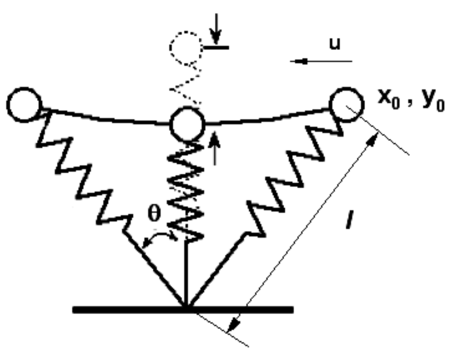


Fig. 4 Hopping forward schematically trajectory

If the scope of the experiment is to obtain the same forward velocity (u) the relation for ground time contact is:

$$t_c=\frac{2mg}{ku} \tag{13}$$

III. GEOMETRICAL STRUCTURE OF THE WALKING ROBOT

It is considered a walking robot structure, presented also in [11], [12] as depicted in Fig.1, having three normal legs L_k, k=1:3, and a head equivalent to another leg L4 containing the robot center of gravity G4=G, placed in its foot. The robot body RB is characterized by two position vectors O^0, O^1, and the leg joining points denoted R_k, k=1:4, so the robot body RB is univocally characterized by the set

$$\mathrm{RB}=\{\mathrm{O}^0,\mathrm{O}^1,\lambda^1,\lambda^2,\lambda^3,\lambda^4\} \tag{14}$$

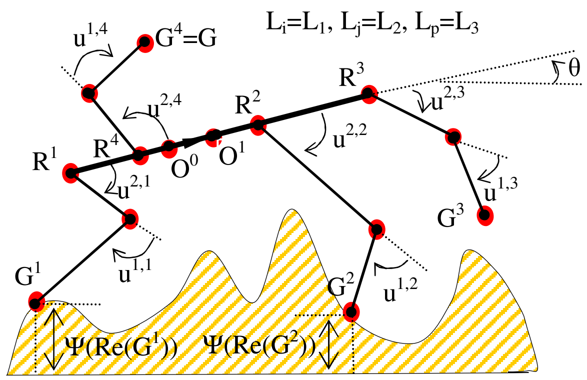


Fig. 5 The robot geometrical structure

The robot has a rigid body if the three scalars (λ^i, λ^j, λ^k) are time constants. The geometrical structure of the PWR is defined by

$$O^1-O^0=e^{j\theta} \tag{15}$$

$$R^i=O^0+\lambda^i\cdot e^{j\cdot\theta} \tag{16}$$

$$R^j=O^0+\lambda^j\cdot e^{j\cdot\theta} \tag{17}$$

$$R^p=O^0+\lambda^p\cdot e^{j\cdot\theta} \tag{18}$$

$$R^0=O^0+\lambda^0\cdot e^{j\cdot\theta}=O^0 \tag{19}$$

from which

$$R^i - R^j = (\lambda^i - \lambda^j)\cdot e^{j\cdot\theta} \tag{20}$$

$$R^p - R^j = (\lambda^p - \lambda^j)\cdot e^{j\cdot\theta} \tag{21}$$

$$R^i - R^p = (\lambda^i - \lambda^p)\cdot e^{j\cdot\theta}\,. \tag{22}$$

The robot position in the vertical plane is defined by the pair of the position vectors O^0, O^1 where $|O^1 - O^0| = 1$, or by the vector O^0 and the scalar θ, the angular direction of the robot body. Each of the four robot legs L^i, L^j, L^p, L^0 is characterized by a so-called Existence Relation $ER(L)$ depending on specific variables as in [11], [12].

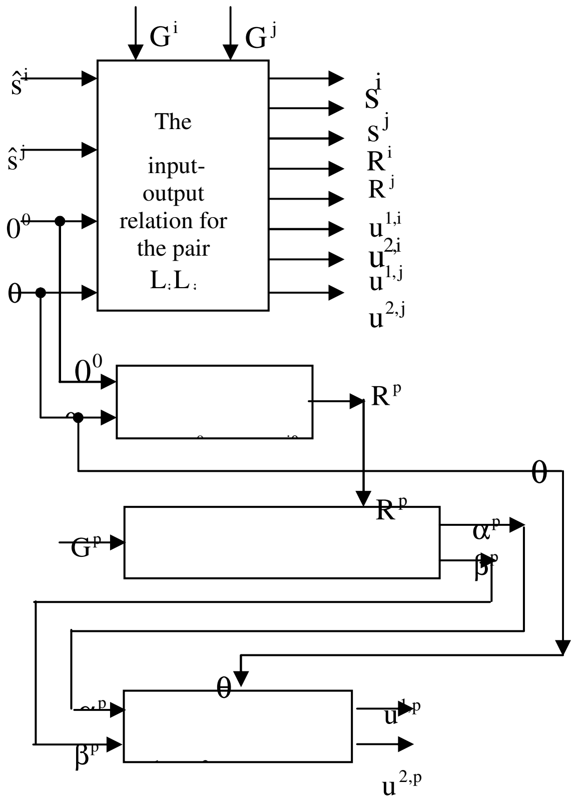
The mathematical model of this object is a Variable Causality Dynamic Systems VCDS [9] and it is analyzed from this point of view.

IV. CAUSALITY ORDERING WITH FOUR FREE JOINTS

A good description for the walking robot behavior is as a VCDS [11]. In such a system, all the variables that characterize its behavior (the terminal variables) are represented by a matrix X called the global variable of the system. In the case of the above robot, the matrix X is a 16x5 matrix. The first four columns of this matrix contain variables related to legs L_k k=1:4 and the fifth variable related to the robot body or other useful information.

Fig. 6 Block diagram of the causality structure [motor15 motor 25 4]

For example, the k-column contains



X^k=[$u^{1,k}$, $u^{2,k}$, R^k, G^k, s^k, α^k, β^k, a^k, b^k, λ^k], k=1:4

where s^k expresses the state of the k leg L_k and the fifth column contains

X^5=[O^0, θ, ε^{12}, ε^{23}, ε^{31},...]

where ε^{12}, ε^{23}, ε^{31} express the stability indexes [9].

In this causality structure with four free joints, the four degrees of freedom are used in the following way: one, to satisfy the kinematics restriction, another one, to assure the desired value for the angle θ of the robot and two degrees for the desired values O^0 (O_x^0, O_z^0) of the robot body.

Because O^0=X(1,5) that means the control variable O^0 is placed on the first row and on the fifth column in the matrix X of the system, it is noted by *motor 15*. Similarly, by *motor 25* it is codified the angle θ of the robot body because the control variable $\theta = X(2,5)$. In this case, it is external controlled, as input variable, the position of the passive leg G^p (G_z^p and G_x^p). Because the passive leg is placed on the fourth row of the matrix X, it is codified by *4*, finally resulted: cz=[motor 15 motor 25 4]. As a consequence, the angles $u^{1,p}$ and $u^{2,p}$ are output variables, that is free angles of the passive leg.

The following relations are used:

$$R^i = O^0 + \lambda^i \cdot e^{j\cdot\theta} \tag{23}$$

$$(\alpha^i, \beta^i, s^i) = f_{\alpha\beta}(R^i, \hat{s}^i, a^i, b^i) \tag{24}$$

$$u^{1,i} = \alpha^i - \beta^i \tag{25}$$

$$u^{2,i} = \beta^i - \theta - \pi \tag{26}$$

$$R^j = R^i + (\lambda^j - \lambda^i)\cdot e^{j\cdot\theta} \tag{27}$$

$$(\alpha^j, \beta^i, s^j) = f_{\alpha\beta}(R^j, G^j, \hat{s}^i, a^j, b^j) \tag{28}$$

$$u^{1,j} = \alpha^j - \beta^j \tag{29}$$

$$u^{2,j} = \beta^j - \theta - \pi \tag{30}$$

$$R^p = O^0 + \lambda^p \cdot e^{j\cdot\theta} \tag{31}$$

and further on it is calculated:

$$(\alpha^p, \beta^p, s^p) = f_{\alpha\beta}(R^p, G^p, \hat{s}^p, a^p, b^p) \tag{32}$$

$$u^{1,p} = \alpha^p - \beta^p \tag{33}$$

$$u^{2,p} = \beta^p - \theta - \pi \tag{34}$$

The position of the robot head is given by the relations (35)÷(39)

$$R^0 = O^0 + \lambda^0 \cdot e^{j\cdot\theta} \tag{35}$$

$$\lambda^0 = u^{1,0} + u^{2,0} + \theta + \pi \tag{36}$$

$$\beta^0 = u^{2,0} + \theta + \pi \tag{37}$$

$$S^0 = R^0 - b^0 \cdot e^{j\cdot\beta^0} \tag{38}$$

$$G^0 = S^0 - a^0 \cdot e^{j\cdot\alpha^0} \tag{39}$$

and it is controlled by the angles $u^{1,0}$ and $u^{2,0}$ and the neck position G^0 is fixed and rigid given the body. For controlling the head position it can be implemented procedures such as a maximum of stability be assured, when the robot evolves with bigger angles θ or in difficult ground conditions. The point R^i has a constant value in respect of the angles of the passive leg but it changes with the robot body position. In the walking process, the point G^p evolves towards the ground and tests it to trace the pits and the walls. The position of the point G^p is generated by the walking algorithm. It is obvious that the angles $u^{1,p}$ and $u^{2,p}$ are effects depended of these values G^p and of the position of the point Rp that, in its successions, depend on: O^0, θ, G^i, G^j, $\hat{s}^i$, $\hat{s}^j$.

V. EXPERIMENTAL RESULTS

It has been conceived an experimental platform for walking robots simulation and control, called RoPa, using the Matlab environment. The package of control and simulation programs has two basis structures: the test achievement and the results interpretations, going until the achievement of simple or multiple figures, in Cartesian coordinates or evolution kinograms. The program allows easy selection of desired dependence types to be analyzed. These dependences of different causality orderings are very important in practice because they are used as components of the family of inverse models that perform the control of the walking robots.

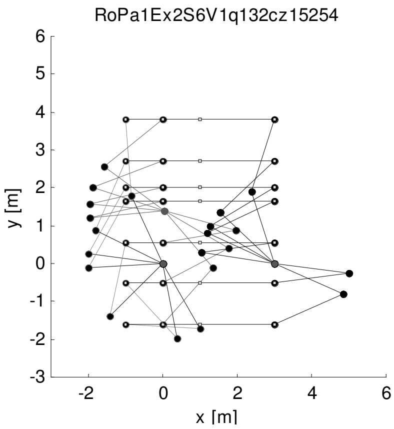


Fig. 7 The robot kinematics evolution in causality structure [15 25 4]

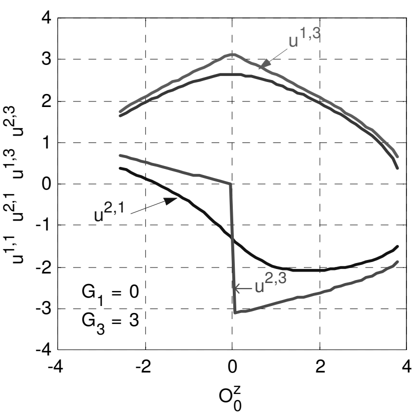


Fig. 8 Controlled angles with respect to the input position O_0^z

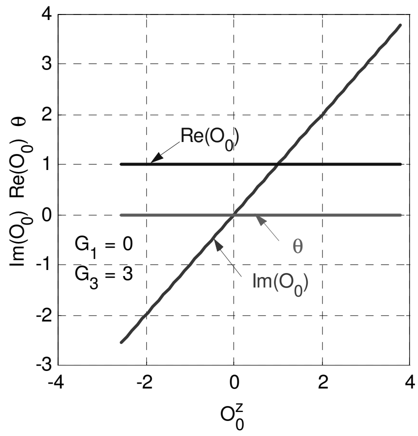


Fig. 9 Robot body position with respect to the input position O_0^z

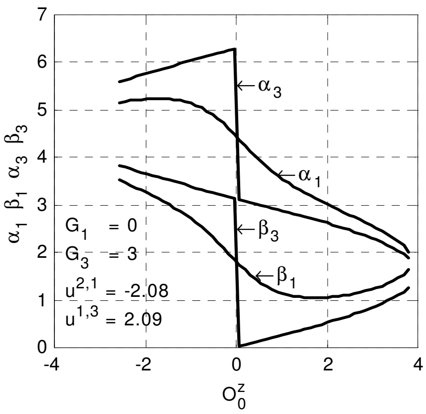


Fig. 10 Legs angular coordinates with respect to the input position O_0^z

VI. CONCLUSION

One important problem in controlling a walking robot to evolve in unpredictable environments is to assure avoidance of ground collision. The contact with ground can be actively controlled if every robot leg has individual control capabilities. A simple and realistic solution can be developed using a shape memory alloy spring based robot leg structure. Heating/cooling the SMA spring offer to entire robot structure an adaptive controlled damper system.

The causality structure is very useful in evolution on the trajectory because the values O^0 and θ are generated by the trajectory planner xyTrd and thTrd and the robot evolves with (O^0, θ) having G^i and G^j as fixed points.

In the reconstruction process it is possible that the foot of the passive leg has sensors that allows the evolution on the ground and in this way are generated the angles $u^{1,p}$ and $u^{2,p}$, from which are extracted the information (the height of the ground related to a fixed or mobile reference).

The experiments performed on RoPa platform reveal the advantage of this causality for walking robots control.

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