STABLE STATES TRANSITION APPROACH
A New Strategy for Walking Robots Control in Uncertain Environments

[*]Anca Petrişor, [**]Nicu George Bîzdoacă, [*]Adrian Drighiciu
[*]Faculty of Electromechanical Engineering, University of Craiova, Romania

[**]Ilie Diaconu, [*]Sonia Degeratu, [**]Gabriela Canureci, [*]Gabriela Petropol Serb
[**]Faculty of Automation,Computers and Electronics, University of Craiova, Romania

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Abstract: A new strategy for walking robots control in uncertain environments, called Stable States Transition Approach (SSTA), is proposed in this paper. All the controls, both the steps succession and the evolution inside each step are established by the evolution environment and by the objective proposed during the evolution. There are no predetermined types of legs movements; they are on-line determined during the robot evolution, irrespective of the ground shape. To apply this strategy it was necessary the robot interpretation as a Variable Causality Dynamic Systems (VCDS). Experimental results are implemented and verified in RoPa, a platform for simulation and design of walking robot control algorithms, to demonstrate the efficacy of the proposed control method.

1 INTRODUCTION

In the last years, many researches combine results from the fields of robotics and control systems, especially for wheeled and legged mobile robots (Fulgenzi, Spalanzani and Laugier, 2007), (Jung, Hsia and Bonitz, 2004).

Mobile robots control in uncertain environments represents still a challenge for real world applications. The robot should be able to gain its goal position facing the implicit uncertainty of the surrounding environment.

The walking robots, particularly the legged robots, allow many advantages with respect to the wheeled robots, especially regarding the autonomy in difficult environments. Unfortunately, a specific type of movement called legged locomotion, (Thirion 2001), (Cubero 2001), is characterized by strongly nonlinear mathematical models to allow describing both the fundamental aspects: leg movements and leg coordination. During the legged locomotion, the control algorithms must assure a stable movement that can be dynamic stable movement or static stable movement.

The problem of walking robots control in uncertain environments has been deeply studied in literature and several techniques have been developed.

Many control algorithms implemented on the existing walking robots, (CWR, 2003), are based on "state of the art" technologies to control the movements of articulated limbs and joint actuators. Some of them try to recreate movements of biological insects which execute various types of periodic gait patterns and adaptive gaits at very high speed, (Cubero, 2003). The walking control algorithms are often around some distributed architectures, (Schmucker, 1996), (Galt, 1999), by assembling a multitude of small processes which are executed concurrently.

Other approaches consider the robot having the necessary intelligence to operate in uncertain environments and use fuzzy logic or neural networks based techniques, (Thirion, 2001), (Gu 2001), (Nanayakkara, Watanabe, Izumi, and Kiguchi, 2001), advanced control schemas, genetic algorithms (Kiguchi, Watanabe, Izumi, and Fukuda, 2000), (Kumarawadu, Watanabe, Kiguchi and Izumi, 2002) etc., to develop the dynamic walking.

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In this paper it is developed a new concept of walking called SSTA "Stable States Transition Approach" based on the variable causality mathematical model of the walking robot. According SSTA both the leg coordination and individual leg movements are entirely dependent on the robot goal and the environments only.

The control structure of SSTA, presented in this paper, is proposed in order to apply the best control with respect to safety issues and convergence to the goal.

Simulation results show how the developed walking control algorithm allows the robot to navigate safely, in uncertain environments, toward the goal and to modify its behavior according to the SSTA control strategy.

The paper is structured as follows: in Section II the geometrical structure of the walking robot is described in detail; in Section III the variable causality mathematical model of the walking robot is described and discussed. In Section IV the general block diagram of SSTA walking robot control is proposed. In Section V the algorithm for walking robot control in SSTA strategy is presented. In Section VI simulation results are shown and discussed. Last section closes the paper with conclusions and purposes for future activities.

2 GEOMETRICAL STRUCTURE OF THE WALKING ROBOT

It is considered the walking robot structure as depicted in Fig.1, having three normal legs L^i, L^j, L^p and a head equivalent to another leg, L_0, containing the robot centre of gravity, 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^i, R^j, R^p. The joining point of the head, L^0, is the central point O^0, $R^0 = O^0$, so the robot body RB is univocally characterized by the set,

$$RB = \{O^0, O^1, \lambda^i, \lambda^j, \lambda^p, \lambda^0\} \tag{1}$$

where $\lambda^0 = 0$.

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.

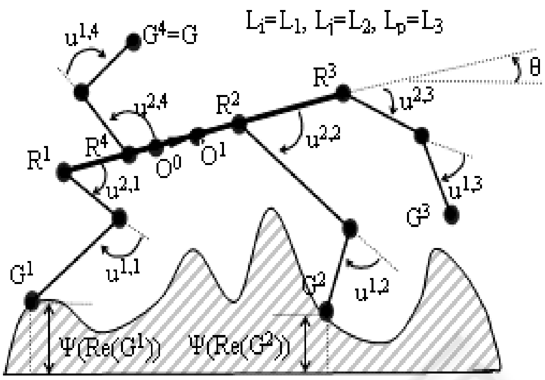


Figure 1: Geometrical structure of the robot.

The robot has a rigid body if the three scalars (λ^i, $i = 1:4$) are time constant. The variable θ determines the robot body angle in vertical plane.

The geometrical structure of the walking robot is defined by the relations

$$O^1 - O^0 = e^{j\cdot\theta} \tag{2}$$

$$R^k = O^0 + \lambda^k \cdot e^{j\cdot\theta} \tag{3}$$

from which,

$$R^{k_1} - R^{k_2} = (\lambda^{k_1} - \lambda^{k_2}) \cdot e^{j\cdot\theta}, k_1, k_2 \in \{1,2,3,4\} \tag{4}$$

The robot position in the vertical plane is defined by the pair of the position vectors O^0, O^1, where

$$|O^1 - O^0| = 1 \tag{5}$$

or by the vector O^0 and the scalar θ, the angular direction of the robot body.

Each of the four robot legs L_k, k=1:4 is characterized by an Existence Relation ER(L) depending on specific variables,

$$ER(L_k):\ R^k - G^k - A^k = 0 \tag{6}$$

$$A^k = a^k \cdot e^{j\cdot\alpha^k} = -a^k \cdot e^{j\cdot\theta} \cdot e^{j\cdot u^{1,k}} \cdot e^{j\cdot u^{2,k}} \tag{7}$$

$$B^k = b^k \cdot e^{j\cdot\beta^k} = -b^k \cdot e^{j\cdot\theta} \cdot e^{j\cdot u^{2,k}} \tag{8}$$

$$R^k - G^k + e^{j\cdot\theta} \cdot AB^k = 0 \tag{9}$$

$$AB^k = -e^{j\cdot u^{2,k}}[b^k + a^k \cdot e^{j\cdot u^{1,k}}] \tag{10}$$

From this point of view, the walking robot is an object containing five fundamental components,

$$WR = \{L_1, L_2, L_3, L_4, RB\} \tag{11}$$

This determines a system of equations where the unknown variables selection depends on the robot status. This system is called Existence Relation of the walking robot denoted ER(WR).

This means that in specific circumstances some variables are effects of the others but the causality ordering can be changed. For example, sometimes a junction is external controlled but it could become a free junction as the effect of the other causes.

The mathematical model of this object is a Variable Causality Dynamic Systems (VCDS) and will be analyzed from this point of view.

Irrespective of the leg numbers, any walking robot, evolving in a vertical plane with a rigid body, has only two legs as a support on the ground.

The ground, at the time moment t, is defined by an unknown equation.

$$z = \psi(x, t) \tag{12}$$

about which only some values are obtained

$$z^* = \psi(x^*, t^*) \tag{13}$$

as a result of feet testing at time instant t*.

A pair of legs $\{L_i, L_j\}, i, j \in \{1,2,3\}, i \neq j$ constitutes the so called Active Pair of Legs (APL) if the robot body position is the same irrespective of the feet position of all the other legs different of L_i (the prime-active leg) and L_j (the second-active leg).

A robot is a fixed robot on the ground (FRG) if its position is constant in time when both all its commands and the ground are time invariant

$$\psi(x, t) = \psi(x), \forall t \tag{14}$$

A robot containing N proper legs can have only N_a numbers of APL,

$$N_a = C_N^2 = N(N-1)/2 \tag{15}$$

In this case N=3 so N_a=3. All the other legs that at a time instant do not belong to APL are called Passive Legs (PL).

A label is assigned to each possible APL. The APL label is expressed by a variable q called Index of Activity (IA) that can take N_a values, numbers or strings of characters. For example the string of characters, q='ijp', points out that the pair $\{L_i, L_j\}$ is an APL and the leg L_p is a passive leg. Instead of strings of characters, the IA can take numerical values as for example,

$$q = 123 \Leftrightarrow i = 1; j = 2; p = 3, \Leftrightarrow$$
$$L_i = L_1; L_j = L_2; L_p = L_3;$$

3 VARIABLE CAUSALITY MATHEMATICAL MODEL OF THE WALKING ROBOT

A good description for walking robot behavior is as a VCDS. 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 the legs L_k k=1:4 and the fifth variable related to the robot body or other useful information.

For example, the k-column contains

$X^k=[u^{1,k}, u^{2,k}, R^k, G^k, s^k, \alpha^k, \beta^k, a^k, b^k, \lambda^k]$, k=1:4, where s^k expresses the state of the k leg L_k and the fifth column contains

$X^5=[O^0, \theta, \varepsilon^{12}, \varepsilon^{23}, \varepsilon^{31}, ...]$

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

A distinction has to be pointed out between the walking robot as a physical object, which has a mathematical model, and different systemic input-output representations generated by this mathematical model.

These different systemic input-output representations refer specially to different VCDS extensions of the walking robot model subsystems. VCDS representations are used in the SSTA control algorithm of the walking robot.

According to SSTA, all the control actions are closed loop performed. Both the sequence of different types of movements and evolutions inside of each specific movement, depend on the general walking robot behavior objective and the environment only.

Even if, as a physical object, the walking robot has some command parameters, it behaves as a VCDS because of the internal kinematics restrictions that determine mechanical locks of the rigid body. For example in this paper the variables

$$u^{1,I}, u^{2,I}, I = \{1,2,3,4\} \tag{16}$$

are the command parameters, as inputs to robot actuators, but discrepancies can appear between the values as desired values supplied by the control device and the realized values of these parameters. In addition, a physical robot can have the possibility of controlling its causal structure through a new variable cz. For example, the angle $u^{2,j}$ is set as free angle or other angles intentionally are set free. The values of the free variables depend on the kinematics restrictions or depend on the position parameters, intentionally some how modified. For example, it is possible externally to modify the position vector R^i or only its real or imaginary part $R^k = R^{k,x} + j \cdot R^{k,y}, k = 1:4$. All these justify the interpretation of the walking robot as VCDS.

In the framework of VCDS description, inputs and outputs do not exist. All the variables are terminal variables satisfying the System Existence Relation (SER). As long as the system exists, the SER is true according to a causality ordering specified by the variable cz which acts as a true input variable.

In the VCDS approach with discrete time evolution, the global variable X is represented by three instants: X_k^d, X_{k-1} and X_k which respectively express: the desired value at the current step, the previous value and the actual realized value.

Depending on the actual value of the ordering structure signal cz_k, and the actual value of the index of activity signal q_k, only some components of the matrix X_k^d are effectively realized.

The VCDS evolution equation of the WR is

$$X_k = F(X_{k-1}, X_k^d, q_k, cz_k) \tag{17}$$

The VCDS model of the walking robot is used in the SSTA control structure proposed by the authors. The behavior of the walking robot in different causal structure is analyzed in details in other papers.

4 SSTA CONTROL STRUCTURE

It is consider that the walking robot has to evolve in space along a direction Ox, which determines a vertical section in the plane xOz of the evolution environment as an unpredictable but measurable function, called also the ground,

$$z = \psi(x) \tag{18}$$

The evaluation of the curve $\psi(x)$ can be performed by using walking robot external tools or by using its legs for ground testing.

Evolution of the walking robot on unpredicted ground $\psi(x)$ implies performing very complex movements for walking robot legs. They must be coordinated in such a way to avoid ground collision during gaiting. Generally, in classical approaches, the legs movements are predetermined, specifically for different typical shapes of the ground.

The general block diagram of SSTA walking robot control is presented in Fig.2.

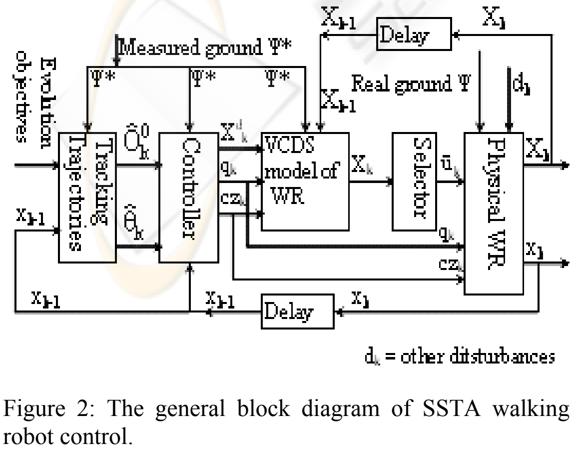


Figure 2: The general block diagram of SSTA walking robot control.

The evolution attitude refers, for example, to the forward or backward evolution, having some imposed fixed body angle, or variable body angle but with maximum stability.

As a physical object, at a time moment t=kT, the robot is controlled by the variables $\hat{u}_k, q_k, cz_k$, where $\hat{u}_k$ represents the matrix of the desired values command angles of the proper legs L_1, L_2, L_3, and of the head, assimilated as a leg, L_4. So,

$$\hat{u}_k = \begin{bmatrix} u_k^{1,1} & u_k^{1,2} & u_k^{1,3} & u_k^{1,4} \\ u_k^{2,1} & u_k^{2,2} & u_k^{2,3} & u_k^{2,4} \end{bmatrix} \tag{19}$$

The variables q_k, cz_k, represent the values of the activity index q and respectively the causal ordering cz at the time moment t=kT. By d_k there are equivalently represented all the other disturbances acting on the physical robot evolving in the environment expressed by the function Ψ. The desired values $\hat{u}_k$ are applied to the positioning systems, as a request, but they are not necessarily realized. This depends on the values of q_k, cz_k.

Applying to the physical robot the desired commands $\hat{u}_k$, under the conditions of q_k, cz_k, Ψ, d_k, the global variable X, takes the value X_k and the abscissa x of the robot centre point O^0 takes the value x_k.

The values X_k, x_k will be utilized by the control algorithm in the next time step. The real evolution ground, expressed by a function Ψ is externally or internally expressed by a function Ψ^*, known, at least, around the actual position of the robot.

5 IMPLEMENTATION OF THE WALKING ROBOT CONTROL ALGORITHM IN SSTA STRATEGY

By SSTA strategy is assured the walking robots evolution in uncertain environments subordinated to two goals:

- achievement of the desired trajectory expressed by the functions $O_z^0 = f(x)$ and $\theta = \theta(x)$, where x is the ground abscissa and $O_x^0 = x$; it is considered the evolution from left to right;
- assuarance of the system stability that is, in any moment of the evolution the centre of gravity has to be in the stability area.

Considering the walking robot as a variable causality dynamic system it is possible to realize this desideratum in different variants of assurance the steps succession. The steps succesion suposes a series of elementary actions that are accomplished only if the stability condition exists.

Continuously, by sensorial means or using the passive leg, the robot has informations about its capacity of evolving on the ground. Every time it is considered that the legs i, j are on the ground and the the system is stable ($\varepsilon_{ij}\in[0,1]$). The passive leg G^p is which realises the walking.

By testing the ground is realized its division in lots representing the fields on x axis which constitue the abscissas of some points that can be touched by the G^p leg. The leg will always touch the ground only on an admitted lot.

A next support point given by the free G^p leg, is chosen so that to existe a next stable state ε_{ip} or ε_{jp}, taking into account the actual state of legs activity. For example, if q=132, passive leg (which tests) is $G^p=G^2$ and assures $\varepsilon_{12}\in[0,1]$ or $\varepsilon_{23}\in[0,1]$. When the change of legs activity is realised (q=123 or q=321 or q=231 etc.), the present passive leg G^p will become the leg i or the leg j.

In this paper, a variant of mouvements succesion, composed by 12 steps, is proposed.

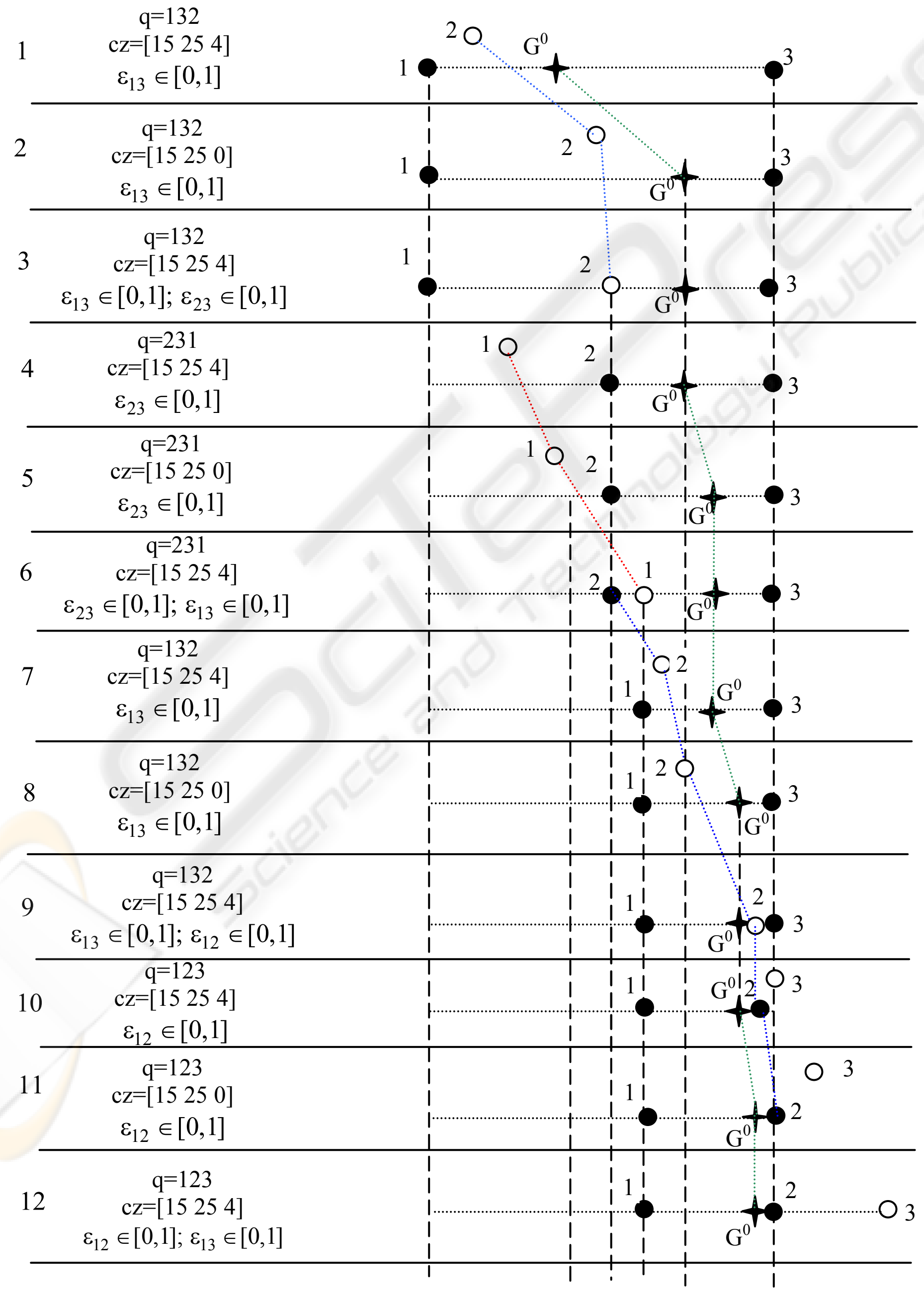


Figure 3: The graphical representation of SSTA walking strategy.

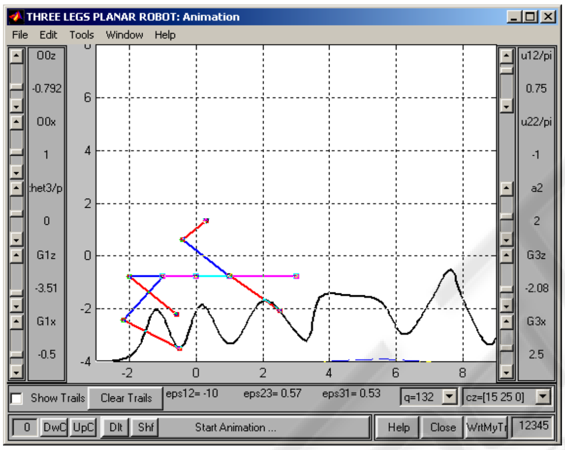
6 EXPERIMENTAL RESULTS

An experimental platform, called RoPa, has been conceived. The RoPa platform is a complex of MATLAB programs for simulation and control of walking robots evolving in uncertain environments according to SSTA control strategy.

A number of eight causality orderings of the robotic structure have been implemented on RoPa.

Figure 4 presents the interface of this application for the causality structure with four free joints. The four degrees of freedom are thus consumed: one to fulfil the kinematics restriction; one to ensure the desired value of the θ angle of the robot body and two for the desired values $\hat{O}^0(O_x^0, O_z^0)$ of the robot body.

The causal ordering is activated by selecting the causal variable cz=[15 25 0].



00z -0.792
00x 1
:het3/p 0
G1z -3.51
G1x -0.5
u12/pi 0.75
u22/pi -1
a2 2
G3z -2.08
G3x 2.5
eps12= -10
eps23= 0.57
eps31= 0.53
q=132
cz=[15 25 0]

Figure 4: RoPa Graphic User Interface.

The stability of this evolution is graphical represented by a stability certificate of the evolution. This certificate attests the stability index of the active pair of legs in any moment.

7 CONCLUSIONS

The experiments performed on RoPa demonstrate the efficacy and adaptability of the proposed method when the walking robots evolve in uncertain environments. All the causal orderings are perfectly integrated in RoPa structure proving the correctness of the theoretical results.

The mathematical model developed in the paper becomes an element of the VCDS walking robot model. The robustness of this mathematical model was proved by many experimental results.

Further investigations will be directed towards a hexapod robot performing a task in uncertain environment.

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