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Output sliding mode controller to regulate the gait of Gecko-inspired robot

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Abstract: This paper describes the design of an output based controller to enforce the gait cycle of a bioinspired Gecko robot. This kind of robot represents a relevant system considering that it can be used to complete exploring, personal assistance, home professional medical care and surveillance tasks. The controller used the mixed structure based on twisting algorithm to solve the tracking trajectory problem and the super-twisting algorithm as robust observer/differentiator to recover the articulations velocity information. The controller was implemented as a class of decentralized structure where each articulation was fed with the corresponding reference trajectories. These trajectories corresponded to the angles observed in actual Gecko lizards and they were obtained by a biomechanical study. The concept of Bezier curves implemented as a combination of sigmoid functions was the keystone to design the reference states. Two reference trajectories were designed to represent the horizontal and vertical gait cycles. A set of numerical simulations was implemented to evaluate the controller performance in both scenarios, the horizontal and vertical gait cycles.

Keywords: Gecko robot; output based controller; super twisting algorithm; twisting controller; robust differentiator.

1. INTRODUCTION

Gecko inspired robot (GIR) is a particular example of the so-called surface climbing robots **?**, **?**. These devices have been used to develop complicated tasks in harmful environments such as vertical 3D-walls, ceilings, space shuttle outer surfaces and volcanoes among others **?**. The number of application where GIR can be used is growing everyday including applications such as inspection of devices in industrial plants, labelling oil tanks, cleaning, painting over vertical surfaces, surveillance, search and rescue, etc.

There are three GIR general configurations **?**. The first one uses adhesive material on the GIR foot surface. This is called the grasping technique which requires special and expensive materials specially designed for this problem **?**. The second one uses magnetic adhesion which is useful when the walking surface is metallic. This method is truly reliable but the number of applications is limited. Moreover, energy consumption could be unjustifiable. The third method uses suction adhesion concept **?**. These robots must carry on-board pumps for creating vacuum **?**. Even when this method is criticized because it can suffer large delays on gait cycle, it is still the most reliable and popular method of designing GIR **?**.

The suction adhesion GIR still has the advantage of carrying heavier loads than all other options **?**. However, there is still a challenging aspect regarding the controller design that forces the correct gait cycle in GIR leg joints **?**. In literature, the proportional derivative control form is the most recurrent solution proposed to regulate the GIR gait cycle **?**. However, the asymptotic nature of this controller does not match with the problem formulation of ensuring the tracking of reference leg joint trajectories. However, this control produces only limited locomotion, such as locomotion on a flat terrain or manoeuvring around very small obstacles.

Sliding mode theory has been used to construct robust finite time convergent controllers. This kind of control design seems to be a more adequate option for regulating the gait process of GIR. Considering that GIR obeys the regular second order structure which characterizes robotic systems, the second order sliding modes (SOSM) can provide better transient performances and they can force to reach the reference trajectories in finite time. The most popular control form emerged from SOSM is the so-called twisting algorithm **?**. This control scheme has proven to be very effective when the robotic system is uncertain or it is affected by external perturbations. However, this controller requires the simultaneous measurement of joint position and velocity.

The aforementioned negative fact of twisting controller was solved in a recent publication **?**. The twisting controller was complemented with a robust exact differentiator (RED) based on the so-called super-twisting algorithm (STA). This solution has offered a remarkable option for developing output based finite time robust controller. This specific kind of control form is considered in this study for solving the regulation of GIR gait cycle.

The aim of this work is to evaluate the application of the output based controller based on the mixed twisting and super-twisting structure over the GIR gait problem. The rest of the paper is organized as follows. The notation used in this manuscript is described in section 2. In Section 3, the generalization of GIR systems is introduced. After that, the problem formulation is presented in section 4. In the next section (5), the extended system that incorporates the STA to estimate the derivative of the error signal in closed loop with the twisting controller is given. In section 6 the numerical results are presented and finally, in section 7, some conclusions are given.

2. NOTATION

The following notation was used in this study: $\mathbb{R}^n$ represents the vector space with n-components. The symbol $\top$ is used to define the transpose operation. $\|z\|$ is used to define the euclidean norm of $z \in \mathbb{R}^n$. $\|z\|_H^2 := z^\top H z$ is the weighted norm of the real-valued vector $z \in \mathbb{R}^n$ with weight matrix $H > 0$, $H = H^\top$, $H \in \mathbb{R}^{n\times n}$. The matrix norm labelled as $\|D\|_2$, $D \in \mathbb{R}^{n\times n}$ is defined as the absolute value of the maximum eigenvalue of the matrix D. If two matrices $N \in \mathbb{R}^{n\times n}$ and $M \in \mathbb{R}^{n\times n}$, fulfils $M > N$ $(\geq)$, that means that $M - N$ is a positive definite (semidefinite) matrix. The symbol $\mathbb{R}^+$ represents the positive real scalars. The symbols $I_{n\times n}$ and $0_{n\times n}$ were used to represent the identity matrix $I \in \mathbb{R}^{n\times n}$ and the matrix formed with zeroes of dimension $n \times n$.

3. THE GECKO ROBOTIC SYSTEM

The electromechanical nature of GIR is used here to consider that a nonlinear system described by a feasible second order disturbed nonlinear differential equation can be used for representing it mathematically. Therefore, the following set of ordinary differential equations is considered to represent the GIR under study:

$$\begin{array}{c} \ddot{z}(t) = f(\dot{z}(t), z(t)) + g(z(t))\, u(t) + \\ \eta(\dot{z}(t), z(t), u(t), t) \end{array} \tag{1}$$

In the previous equations: $z(0) = z_0$ and $\dot{z}(0) = z_{d0}$ are the initial conditions and $z_0, z_{d0} \in \mathbb{R}^n$ are given vectors. The vectors $z \in \mathbb{R}^n$ and $\dot{z} \in \mathbb{R}^n$. The drift term $f : \mathbb{R}^{2n} \to \mathbb{R}^n$ is a Lipschitz function. The following assumption is considered valid in this study.

Assumption 1. The nonlinear system (1) is controllable.

Based on the previous fact, the input associated term $g : \mathbb{R}^n \to \mathbb{R}^{n\times n}$ satisfies.

$$0 < g^- \leq \|g(z)\|_F \leq g^+ < \infty, \quad \forall z \in \mathbb{R}^n \tag{2}$$

It is evident that matrix $g(z(t))$ is invertible $\forall t \geq 0$. The symbol $\|\cdot\|_F$ corresponds to the Frobenius norm.

The regular electronic instrumentation of GIR usually implies the possibility of measuring only the articulation angles. Then, it is usual to consider that the output signal $y \in \mathbb{R}^n$ is

$$y(t) = z(t) \tag{3}$$

The nonlinear function $\eta : \mathbb{R}^{2n} \times \mathbb{R} \to \mathbb{R}^n$ gathers the uncertainties of the nonlinear system. This function satisfies

$$\|\eta\|^2 \leq \eta_0 + \eta_1 \|Z\|^2 \tag{4}$$

The elements η_0 and η_1 are positive constants. The vector $Z \in \mathbb{R}^{2n}$ is formed by $Z^\top = [z^\top, \dot{z}^\top]$.

Considering the type of GIR, the system control action u is applied on every joint of the robot. Therefore, $u \in \mathbb{R}^n$.

The class of systems considered in (1) with the selection of $x_a = z$ and $x_b = \dot{z}$ can be represented as

$$\begin{array}{c} \dot{x}_a(t) = x_b(t) \\ \dot{x}_b(t) = f(x(t)) + g(x_a(t))u(t) + \eta(x(t), u(t), t) \\ y(t) = Cx(t) \end{array} \tag{5}$$

where $x^\top = \begin{bmatrix} x_a^\top & x_b^\top \end{bmatrix}$, $x \in \mathbb{R}^{2n}$ and $C = [I_{n\times n}, 0_{n\times n}]$.

Throughout the paper, the following assumptions are assumed to be fulfilled

Assumption 2. The nonlinear function $f(\cdot)$ is unknown but satisfies the Lipschitz condition **?**

$$\|f(x) - f(x')\| \leq L_1 \|x - x'\| \tag{6}$$

In the previous inequality, $x, x' \in \mathbb{R}^{2n}$ and $L_1 \in \mathbb{R}^+$.

The following assumption defines the type of controllers than can be applied over the GIR:

Assumption 3. The control input belongs to the set U^{adm} defined as

$$U^{adm} := \left\{ u : \|u(t)\|^2 \leq u_0 + u_1 \|x\|^2 \right\} \tag{7}$$

with u_0,$u_1 \in \mathbb{R}^+$. The previous condition allows to design an output feedback controller based on different techniques such as classical PD controllers ($u_0 = 0$ and $u_1 \geq 0$) or discontinuous controllers based on the sliding modes theory ($u_0 \geq 0$ and $u_1 = 0$).

4. PROBLEM FORMULATION

The problem considered in this paper was to complete the trajectory tracking between the states of (1) and the stable reference model given by z^* in finite time. The previous statement can be reformulated as to design an output feedback controller such that $\|e(t)\| = 0$ for all $t \geq T^*$ where T^* is the convergence time and $e = z - z^*$.

The reference trajectory z^* satisfies

$$\ddot{z}^*(t) = h(\dot{z}^*(t), z^*(t)) \tag{8}$$

with the the reference trajectory $z^* \in \mathbb{R}^{2n}$. In the previous set of second order differential equations, the initial conditions $z^*(0)$ and $\dot{z}^*(0)$ are given vectors. The function $h(z^*, \dot{z}^*)$ is a Lipschitz function. The system (8) can be transformed using the change of variables $x_a^* = z^*$ and $x_b^* = \dot{z}^*$.

The reference system (8) has a stable equilibrium point and by the converse Lyapunov theorem, one can ensure that the system in the new coordinates $[x^*]^\top = \left[(x_a^*)^\top \; (x_b^*)^\top \right]$ satisfies

$$\|x^*(t)\|^2 \leq X_+^*, \quad X_+^* \in \mathbb{R}^+, \quad \forall t \geq 0 \tag{9}$$

Due to the previous inequality is valid and considering that both functions f and h are continuous, then the following assumption can be straightforwardly verified:

Assumption 4. There is a positive constant h^+ such that the following inequality is valid:

$$\|f(x^*) - h(x^*)\| \leq h^+ \tag{10}$$

$\forall x^* \in \mathbb{R}^{2n}$ solution of (8).

5. CONTROLLER STRUCTURE

The problem of tracking trajectory between (1) and (8) can be solved by some well developed control schemes. The most common manner for solving the controller design is the so-called proportional derivative scheme. Another remarkable option for controlling the joints of GIR is the so-called twisting algorithm. However, both types of controllers consider that both x_a and x_b can be measured on-line and simultaneously. This condition is hardly fulfilled in real GIR due the necessity of setting up a big number of sensors and the wasting big amounts of energy. This problem has been solved using the so-called state observers. Despite the natural benefits offered by these observers, the estimation of velocity in the gait cycle of GIR requires the application of the so-called finite time observer. The most remarkable of these estimators is the STA which posses many relevant properties that can be useful to solve the tracking trajectory problem presented in this study.

Super-Twisting Algorithm In counterpart of some others second order sliding modes algorithms, the STA can be used with systems having relative degree one with respect to the chosen output **?**. The STA has been used as a controller **?**, a state estimator **?** and as a robust differentiator (RD) **?**.

In particular, the STA application as a RD is based on the following description: If $w_1(t) = r(t)$ where $r(t) \in \mathbb{R}$ is the signal to be differentiated, $w_2(t) = \dot{r}(t)$ represents its derivative and under the assumption of $|\ddot{r}(t)| \leq r^+$, the following auxiliary equation is gotten

$$\begin{aligned} \dot{w}_1(t) &= w_2(t) \\ \dot{w}_2(t) &= \ddot{r}(t) \end{aligned} \tag{11}$$

The previous differential equation is a state representation of the signal $r(t)$. The STA algorithm to obtain the derivative of $r(t)$ looks like

$$\begin{gathered} \dot{\bar{w}}_1(t) = \bar{w}_2(t) - \lambda_1 |\Delta_w(t)|^{1/2} \operatorname{sign}(\Delta_w(t)) \\ \dot{\bar{w}}_2(t) = -\lambda_2 \operatorname{sign}(\Delta_w(t)) \\ \Delta_w = \bar{w}_1(t) - w_1(t) \\ d(t) = \frac{d}{dt}\bar{w}_1(t) \end{gathered} \tag{12}$$

where $\lambda_1, \lambda_2 > 0$ are the STA gains. Here $d(t)$ is the output of the differentiator **?**. In this equation,

$$\operatorname{sign}(z) := \begin{cases} 1 & if \quad z > 0 \\ \in [-1, 1] & if \quad z = 0 \\ -1 & if \quad z < 0 \end{cases} \tag{13}$$

To apply the STA as differentiator, let us represent the uncertain system (5) as the composition of the following n second order systems

$$\begin{gathered} \dot{x}_{a,i}(t) = x_{b,i}(t) \\ \dot{x}_{b,i}(t) = f_i(x(t)) + g_i(x_a(t))u_i(t) + \zeta_i(x(t), u(t), t) \\ i = \overline{1, n} \end{gathered} \tag{14}$$

where $x_{a,i}$ and $x_{b,i}$ are the $i-th$ and $(n+i)-th$ states of (5), respectively.

The nonlinear functions $f_i(\cdot)$ and $g_i(\cdot)$ are the functions associated to the states $x_{a,i}$ and $x_{b,i}$.

Similarly, $\eta_i(\cdot,\cdot)$ is the corresponding uncertainty to the same subsystem.

Twisting controller based on STA implemented as RD
Before the STA can be applied, the dynamics of the tracking error also must be treated as in the case of (14). Then, the definition for the individual elements of the vector e is given by

$$\dot{e}_i = \dot{x}_{a,i} - \dot{x}^*_{a,i} \tag{15}$$

Based on the description of the GIR model presented in (1) and the model of the reference trajectories proposed in (8), one gets

$$\begin{gathered} \dot{e}_i(t) = e_{i+n}(t) \\ \dot{e}_{i+n}(t) = f_i(x(t)) + g_i(x_a(t))\, u_i(t) - \\ h_i(x^*(t) + \zeta_i(x(t), u(t), t)) \end{gathered} \tag{16}$$

The function $h_i(x^*(t))$ is the i-th component of the vector field $h(x^*(t))$. In this paper we assume that $g_i(x_a(t)) \neq 0$, $\forall x_a \in \Re^n$.

Using the STA structure and its approximation of the error derivative signal, the twisting control is selected as

$$u_i(t) = -k_{1,i}(t)\frac{e_i(t)}{|e_i(t)|} - k_{2,i}(t)\frac{d_i(t)}{|d_i(t)|} \tag{17}$$

The gains in the twisting controller are determined by

$$\begin{aligned} k_{1,i}(t) &= g_i^{-1}(x_a(t))\,\bar{k}_{1,i} \\ k_{2,i}(t) &= g_i^{-1}(x_a(t))\,\bar{k}_{2,i} \end{aligned} \tag{18}$$

with $\bar{k}_{1,i}$ and $\bar{k}_{2,i}$ are scalars that must be adjusted to solve the tracking trajectory problem. The following extended system describes the complete dynamics of the error signal in close-loop with an adequate implementation of (12)

$$\begin{gathered} \dot{e}_i(t) = e_{i+n}(t) \\ \dot{e}_{i+n} = f_i(x(t)) - h_i(x^*(t)) - \\ k_{1,i}\frac{e_i(t)}{|e_i(t)|} - k_{2,i}\frac{d_i(t)}{|d_i(t)|} + \eta_i(x(t), t) \\ \dot{\delta}_{1,i}(t) = \delta_{2,i}(t) - \lambda_{1,i}|\delta_{1,i}(t)|^{1/2} sign(\delta_{1,i}(t)) \\ \dot{\delta}_{2,i}(t) = -\lambda_{2,i} sign(\delta_{1,i}(t)) - \ddot{e}_i \end{gathered} \tag{19}$$

where $\delta_{1,i} = \bar{w}_{1,i} - e_i$ and $\delta_{2,i}(t) = \dot{\delta}_{1,i}(t)$. The term $d_i(t)$ refers to the approximation of e_{i+n} which is obtained by means of the second order STA presented in (12) applied over the dynamic of e_i.

Then, the variable $\bar{w}_{1,i}(t)$ is the first state of the corresponding STA implemented as differentiator. The constants $\lambda_{1,i}$, $\lambda_{2,i}$ are selected according to the rules described in the main theorem introduced below. A set of n

differentiators were used to reconstruct the information of e_{i+n}.

Output based controller form In the article of ?, a Lyapunov function was proposed to show that each extended system (19) has a robust finite time stable equilibrium point. For the problem tackled in this paper, the previous statement means that for every admissible perturbation η_i satisfying (4), and every initial condition $p_{0,i}$, there is a finite time $T_i(p_{0,i})$ so that a trajectory of system (19) starting at time $t = 0$ in $p_{0,i}$ converges to the origin in finite time, i.e. $p_i(t) = 0$ for $t_i > T_i(p_{0,i})$, despite of the perturbation. The aforementioned Lyapunov function has the form

$$V_i(\xi_i, e_i, e_{i+n}) = V_{ST,i}(\xi_i) + V_{T,i}(e_i, e_{i+n}) \quad (20)$$

The function $V_{ST,i}(\xi_i)$ is given by

$$V_{ST,i}(\xi_i) = \xi_i^\top P_{1,i}\xi_i \quad (21)$$

with $\xi_i^\top := \left[|\delta_{1,i}|^{1/2} sign(\delta_{1,i})\ \delta_{2,i}\right]$.

The matrix $P_{1,i} \in \mathbb{R}^{2\times 2}$ is a positive definite and symmetric matrix. Its specific form has been defined in (?).

Additionally, the function $V_{T,i}(e_i, e_{i+n})$ is given by

$$V_{T,i}(e_i, e_{i+n}) = \left(\pi_{1,i}|e_i| + 0.5e_{i+n}^2\right)^{3/2} + \pi_{2,i}e_ie_{i+n} \quad (22)$$

The constants $\pi_{1,i}$ and $\pi_{2,i}$ are positive values. The second of these values can be freely selected. On the other hand, the first value $\pi_{1,i}$ is connected to the constraints of the system.

In (20), the function $V_{ST,i}(\xi_i)$ justifies the convergence of the STA as RD, while the function $V_{T,i}(e_i, e_{i+n})$ is used to prove that twisting controller brings the trajectories of the e_i and e_{i+n} to the origin in a finite time $T_i(p_{0,i})$.

6. NUMERICAL RESULTS

Consider the GIR showed in the figure (1). This model was constructed in SolidWorks®software and exported to Matlab®using the SimMechanics Toolbox®. This simulation scheme is very useful because the mathematical model is truly unknown. The only certain fact is that GIR model produced by the SimMechanics Toolbox®is second order and it is always controllable. Then, the controller design proposed in this study is still applicable.

Figure (2) contains the graphical description of the angles associated to one leg of Gecko robot. These angles are labelled α, β and γ. The model GIR model showed in this figure is a simplification of the one already described. The degrees of freedom are same to the actual GIR evaluated in numerical simulations.

The angles considered in figure (2) are selected to show how the differentiator and the controller work.

6.1 RD performance

When the twisting controller is computed for the system, the derivative obtained by the STA brings some advantages. The robustness of STA applied as differentiator forced a better performance for any controller applied on second order systems when the only available information is the output signal.

Fig. 1. GIR model used to construct the numerical simulations of this study. This model is built in SolidWorks and then exported to Matlab. All the simulations are executed in the SimMechanics Toolbox®

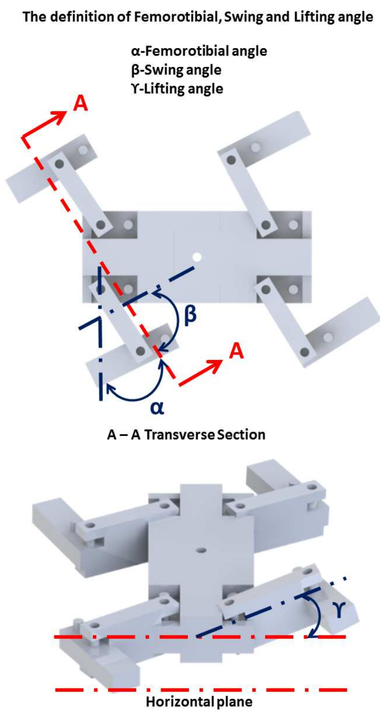

Fig. 2. Simplified model used to represent the angles of one GIR single leg evaluated in the numerical simulations of this study.

Then, the first part of the numerical simulations is devoted to evaluate the performance of the STA as RED. The derivative of tracking error is compared with the information provided by the measurements obtained directly from the simulation of the GIR and the derivative of reference signal. The differentiation of the error signal is shown in

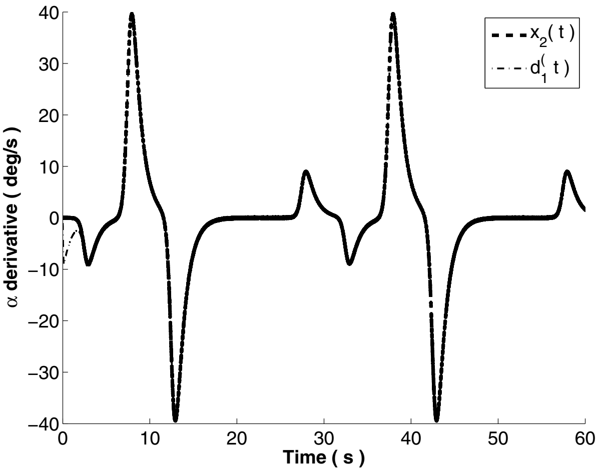

Fig. 3. Estimation of velocity for the angle $\alpha(t)$ based on the STA applied as STA. The estimated velocity is compared with the measured velocity obtained form the model exported to Matlab.

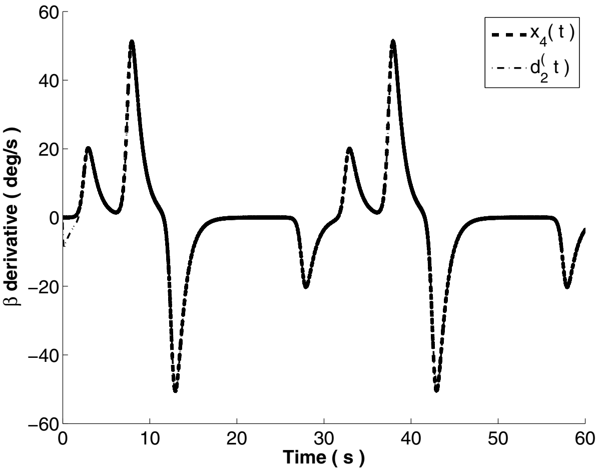

Fig. 4. Estimation of velocity for the angle $\beta(t)$ based on the STA applied as STA. The estimated velocity is compared with the measured velocity obtained from the model exported to Matlab.

Figure 3. In this figure, one can observe how the estimation process is accurate when the STA is applied to the velocity estimation of the first joint of the analyzed GIR leg. This figure is only showing the velocity estimated of one single joint (α).

A second confirmation of the RED performance appears in figure (4). This second estimation also shows how the RED estimates the velocity in finite time (less than 2 seconds).

6.2 Tracking trajectory controller

The simulation results for the tracking performance of the first, second and third links of the GIR are depicted in Figures 5, 6 and 7. In the three figures, the convergence of the all the GIR states tracks the reference trajectories formulated as result of the biomechanical study. The convergence between all the three states confirmed the performance of the controller proposed in this study. Moreover, the fast convergence obtained of the tracking

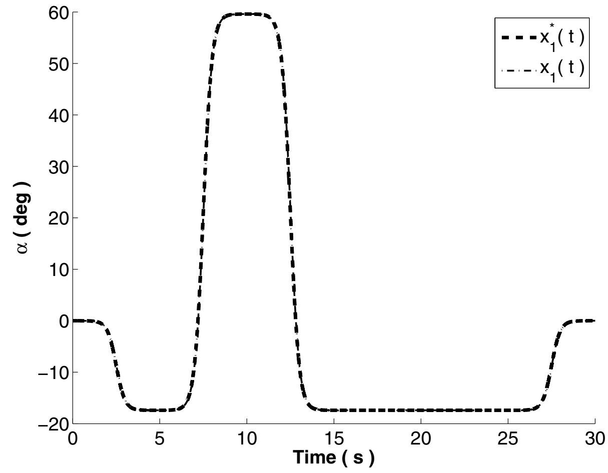

Fig. 5. Tracking trajectory of first link in the left rear leg of GIR. The solid line represents the reference trajectory and the dashed line corresponds to the trajectory of the actual joint angle.

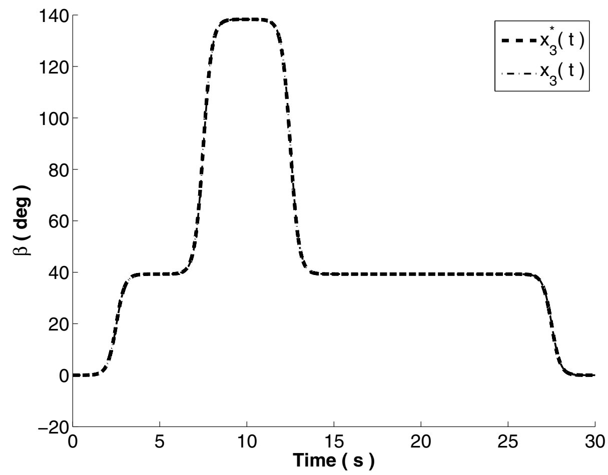

Fig. 6. Tracking trajectory of second link in the left rear leg of GIR. The solid line represents the reference trajectory and the dashed line corresponds to the trajectory of the actual joint angle.

error ensures the solution of regulation for the GIR gait cycle.

The first state converged within the first second of simulation. This condition was enforced to adjust the first angle of GIR leg because this first joint must ensure the adequate position of the whole biomechanical section of the robotic system. This condition appeared when both gait cycles are analysed: the vertical and horizontal.

The second and third joints track the corresponding reference trajectories (Figures 6 and 7) in less than two seconds of numerical simulation. This condition is obtained by the corresponding adjustment of controller gains. These gains can be adjusted without problem because the fast convergence obtained by the RED.

One of the control signals is demonstrated in Figure (8). The behaviour of this control action demonstrates that no so much energy is needed to complete the trajectory problem analysed in this study. This can be confirmed

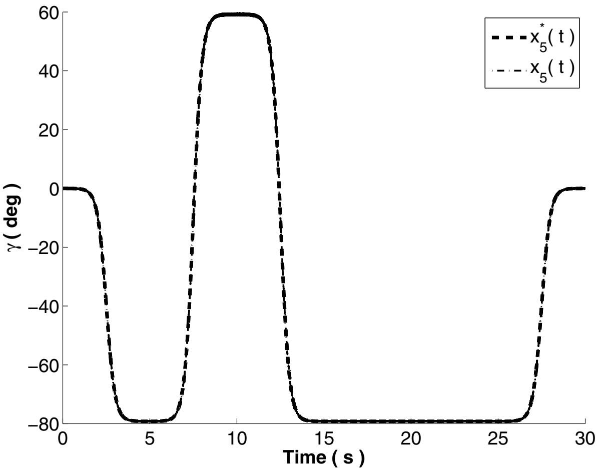

Fig. 7. Tracking trajectory of second link in the left rear leg of GIR. The solid line represents the reference trajectory and the dashed line corresponds to the trajectory of the actual joint angle.

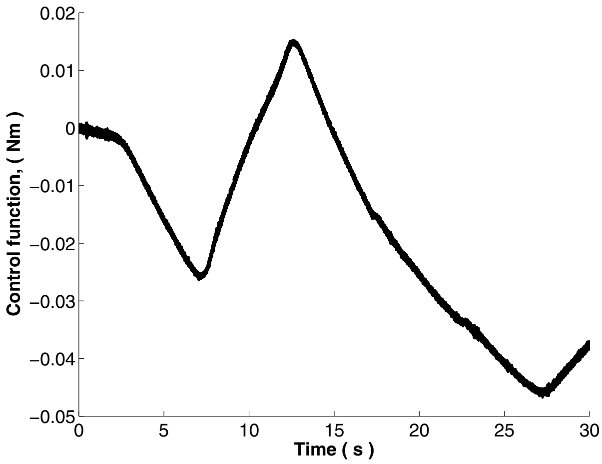

Fig. 8. Plot of control action produced by the twisting controller.

by the range where the control action evolves during the numerical simulations.

7. CONCLUSION

An output based controller using the twisting controller was implemented to regulate the gait cycle of GIR. The controller used the velocity information of a GIR estimated by a robust exact differentiator implementing the super twisting algorithm. The closed loop controller forced the finite time convergence of the tracking errors to the origin. The reference trajectories were generated as result of a biomechanical study. The controller was successfully implemented to force the GIR to follow horizontal and vertical orientated gait cycles.

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