Design and Operation of a Quadrupedal Robot

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***Abstract*-- QUADRO is a low cost QUADrupedal RObot, constructed mainly to test control algorithms concerning legged locomotion and guidance procedures for behaviorally autonomous walking robots. In this work, we describe the control architecture that has been developed for governing the robot and we discuss the performances obtained in actuating a series of basic movements. Since the mechanical structure of the robots presents imperfection due to the choice of keeping the cost of construction and assembling as low as possible, a key feature of the control architecture is that of employing an adaptation mechanism, based of fuzzy logic, for reducing errors in the execution of assigned movements. In addition, the adoption of a master-slave control architecture facilitates coordination and, up to an intrinsic negligible delay, synchronism of the different legs.**

***Index terms*— Walking robot, Fuzzy Control**

I. INTRODUCTION

The development of efficient walking robots is an interesting and actual problem in mobile robotics. Walking robots can in facts prove to be valuable tools in a number of applications, both outdoor ones and indoor ones, thanks to their versatility and ability to move on uneven terrain. However, from a mechatronic point of view, walking robots are much more complicated machines than wheeled robots and their realization still presents several problems (see, for a state-of-the-art and specific contribution to these general topics, [7], [8], [9], [10]).

In this paper, we consider a small, prototypal QUADrupedal RObot, called QUADRO, which has been constructed mainly to test control algorithms concerning legged locomotion and to develop guidance procedures for behaviorally autonomous walking robots (see [4], [5] and compare with [6]). A guideline of the QUADRO project has been that of keeping low the cost of mechanical components and to enhance, as much possible, the performances by implementing an efficient control. This has motivated the adoption of a flexible control architecture of master-slave type, split into different, hierarchically organized functional levels. The use of a master-slave structure, in particular, assures synchronism in the movements of the four legs, also when the given task is, possibly, poorly executed. In addition, in order to guarantee accuracy of execution with simple, low level PID controllers, the supervisor at the higher control level has been endowed with the ability to monitor the performances of the low level controllers and to modify accordingly their parameters. This adaptation mechanism has been realized by means of a simple fuzzy structure that acts on the gain of (some of) the low level controllers.

After describing briefly the robot structure and the control architecture, we present the results of two kinds of experiments concerning basic movements. In the first one, concerning leg bending, the robot performs the given task with a satisfactory accuracy, without requiring to enable the fuzzy supervisor for adapting the parameters of the low level controllers during the execution. In the second movement, as the center of mass moves horizontally, the effects of gravity on the robotic structure vary accordingly to the assumed configuration and this makes impossible to chose fixed, satisfactory values for the parameters of the low level controllers.

By enabling the fuzzy supervisor to modify some of those parameters, in order to adapt the controller action to the variable working conditions, it is possible to improve the performances of the robot in terms of accuracy and of reduction of oscillations. Results obtained in different experiments by measuring the behavior of the joint angles are used to show the validity of the proposed solution.

In conclusion, QUADRO proves to be a useful tool for studying and investigating construction and operation problems concerning legged robots. Next steps in the QUADRO project will be the implementation of more complex movements in conditions of static equilibrium and of dynamic equilibrium and of static and dynamic walk.

II. SYSTEM DESCRIPTION

The system configuration of QUADRO can be divided into two main parts: the electro-mechanical structure, consisting of the robot body, with sensors, actuators and on-board electronics, and the control unit, consisting of a PC-station, equipped with A/D-D/A boards. The two parts are connected by an umbilical, that is also used to supply the power to the actuators. This design, in which the mobile part, namely the body of the robot, is separate from the hardware component of the controller, allows us to simplify the mechanical component and to limit the cost of its construction, while fitting with our experimental objectives.

The mechanical structure of the body consists of four legs, connected to a central platform by a revolute joint (hip).

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Each leg has three links (thigh-bone, shin-bone, foot), connected by 2 revolute joints (knee, ankle). Only the hip and knee joints are actuated by a dc-motor with a 264:1 reduction gear. The joints angular positions at hips and knees are measured by means of incremental encoders. The onboard electronics generates, according to the control signal coming from the PC, the PWM signals for the eight actuators and it takes care of the encoders' signal treatment. The control unit generates the control signal pertaining to the robot motion on the bases of the sensors' measurements, so to make each leg follow a prefixed trajectory.

QUADRO is a prototypal system, whose structure has been realized in such a way to facilitate feasibility of performance tests. The choice of working in a LabVIEW environment, in particular, allows an easy and rapid implementation, integration and testing of software and hardware components.

Although the robot leg consists of three links, since the joint connecting shin-bone and foot is not actuated nor endowed with sensors, the third link is not considered in modeling the leg. Therefore, each leg is assumed to have two degrees of freedom, represented by the hip angle θ_1 and the knee angle θ_2. We denote by $P = (Px, Py)^T$ the position of the ankle in the planar coordinate system shown in Figure 1, while the lengths of the thigh-bone and of the shin-bone are denoted by d_1 and d_2 respectively. The direct kinematic model of the leg is described by the following simple equations:

$$\begin{cases} P_X = d_1 \cos\vartheta_1 + d_2 \cos(\vartheta_1 + \vartheta_2) \\ P_Y = d_1 sin\vartheta_1 + d_2 sin(\vartheta_1 + \vartheta_2) \end{cases}$$

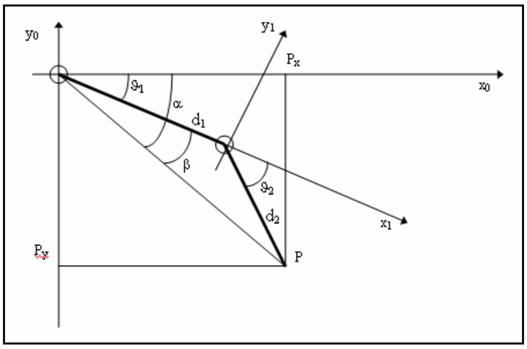

Figure 1: Robot's leg.

The working space of each leg in the realized mechanical structure is given by $-40^\circ \le \vartheta_1 \le 40^\circ$ and $-90^\circ \le \vartheta_2 \le 90^\circ$. After choosing a desired trajectories for the ankle, inverse kinematic equations are used for obtaining the joint angles. The solution of the inverse kinematic equations is not unique, but we choose the one that guarantees $\vartheta_2 \ge 0$, so that:

$$\begin{cases} \vartheta_1 = \alpha - \beta \\ \vartheta_2 = \cos^{-1}((P_X^2 + P_Y^2 - d_1^2 - d_2^2)/2d_1 d_2) \end{cases}$$

where

$$\alpha = tg^{-1}(P_Y / P_X)$$

$$\beta = \cos^{-1}((P_x^2 + P_Y^2 + d_1^2 - d_2^2)/2d_1\sqrt{P_X^2 + P_Y^2})$$

A dynamic model of the leg can be obtained using the Newton-Euler formulation (see e.g. [1]) as done in [4], [5].

III. Control Architecture

When QUADRO moves, in particular when it walks, links in different legs are required to move in a coordinated and synchronous way (see [2]), in order to guarantee equilibrium and to satisfy other specific requirements (like to avoid bending and/or vertical motion of the body). This motivates the adoption of a hierarchical control architecture that implements master-slave(s) control modalities. Low level controllers assure that each link follows a reference trajectory. A high level controller implements the master-slave(s) structures, grouping the links according to specific task. Given the reference trajectory for the master angle, the reference trajectories for the slave angles are computed as functions of the actual, measured position of the master. This solution provides coordination also in case the motion of the master is affected by significant tracking errors. Synchronism is achieved only up to the delay imposed by the chosen master-slave structure, in which the set point given to the slave at time *t* equals the position of the master at time *t-1*. Since the movements are smooth, such delay is made negligible by keeping the sampling time small and the velocities, in comparison, low. Low velocities are also preferred for avoiding problems due to the fact that the PC-station does not employ, in the current situation, a real time operating system.

Although in principle the control architecture described above can govern the robot motion in a satisfactory way, it performances are strongly influenced by those of the low level controllers, which are designed as PID controllers (see e.g. [3]). In order to overcome the difficulties due to possible poor performances of the controllers (mainly caused by disturbances due to mechanical imperfections, model approximations and parameter variations in different configurations), the high level controller has been given the ability to supervise their actions in terms of tracking errors and to modify accordingly their parameters. In particular, the tracking error and its variation are processed in a fuzzy way and the result is used to modify the gain of the PID low level controller at issue. In this way, the overall control architecture is endowed with a sort of adaptation mechanism, which enhances its overall performances.

QUADRO has been tested in various situations. Here, to describe the action of the control system, we consider two kinds of motion. In the first one, called leg bending, the body is required to move vertically, while remaining horizontal, with the four feet resting at a fixed position on the ground. In the second one, called back or forward swing, the body is required to move horizontally, remaining at a fixed height from the ground, with the four feet resting at a fixed position on the ground. In both movements, the robot is in a condition of static equilibrium, since the vertical projection of its center of gravity is kept inside the convex region defined by the positions of the feet.

In both situations we employ the control architecture described in Figure 2 below, in which one thigh is chosen as master. The corresponding shin acts as a direct slave, as well as the remaining thighs do. The other three shins act as (secondary) slaves of the corresponding thighs. The block denoted as Fuzzy Supervisor may be enabled or not, according to the necessity of adapting on-line the parameters of the low level controllers. Its action, in our implementation, will be described in Section V.

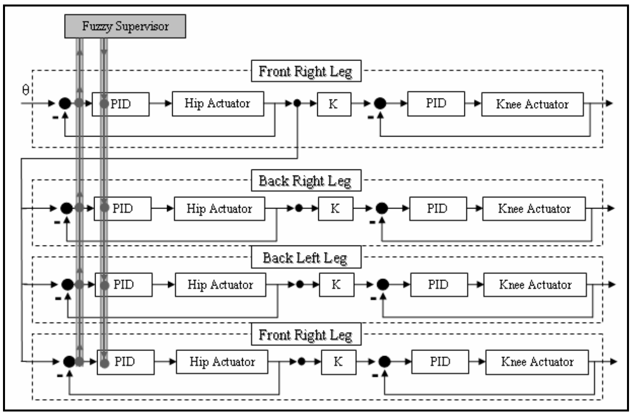

Figure 2: Control scheme.

The modularity of the control structure allows to change the robot's behavior simply modifying the reference trajectory θ and the mathematical low implemented in the block denoted by K in Figure 2.
In the case of leg bending, the movement is realized letting the legs assume an antisymmetric configuration (see Figure 3), so to ensures stability in front of possible overall oscillations that could cause the robot fall down.


Figure 3: Configurations taken into account for bending.

According to this we obtain the slaves' reference trajectories in the following way. Denoting by $\theta_{h,m}(t)$ the reference trajectory of the hip angle of the leg chosen as master, the trajectories of the remaining hip angles, specified by the index i for i = 1,2,3, are given by $\theta_{h,i}(t) = \boldsymbol{\theta}_{\boldsymbol{h,m}}(t-1)$ or $\theta_{h,i}(t) = -\boldsymbol{\theta}_{\boldsymbol{h,m}}(t-1)$, where $\boldsymbol{\theta}_{\boldsymbol{h,m}}$ denotes the measured value of the master hip angle and the plus or minus sign is chosen in order to get the antisymmetric configuration. The trajectory for each (slave) knee angle is computed as $\theta_k(t) = -2\boldsymbol{\theta}_{\boldsymbol{h}}(t-1)$, where $\boldsymbol{\theta}_{\boldsymbol{h}}$ denotes the measured value of the corresponding hip angle (see, for example, see Figure 11).

In the case of back or forward swing, it is required to keep the hips at a constant height *h* from the ground. Looking at Figure 4 it is easy to see that the trajectory for each (slave) knee angle can be computed as:

$$\theta_k(t) = \pm \arccos\left[\frac{h - l_1 \cos\left(\boldsymbol{\theta}_{\boldsymbol{h}}(t)\right)}{l_2}\right] + \boldsymbol{\theta}_{\boldsymbol{h}}(t) \qquad (1)$$

where $\boldsymbol{\theta}_{\boldsymbol{h}}$ denotes the measured value of the corresponding hip angle and the plus or minus sign is chosen according to the direction of the movement. In this case a symmetric configuration for the legs has been chosen.

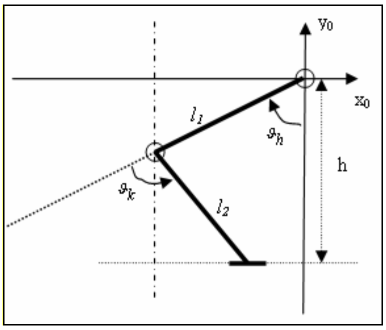

Figure 4: Geometric leg description.

From equation (1), it turns out that, fixed the desired height *h*, the master hip angle must be limited by the values:

$$\theta_{h,\inf} = -\arccos\left(\frac{h - l_2}{l_1}\right) \text{ and } \theta_{h,\sup} = \arccos\left(\frac{h - l_2}{l_1}\right).$$

For $\boldsymbol{\theta}_{\boldsymbol{h}} = 0$, we have a singular configuration (see Figure 5) and to avoid it we limit the master hip angle to positive values.

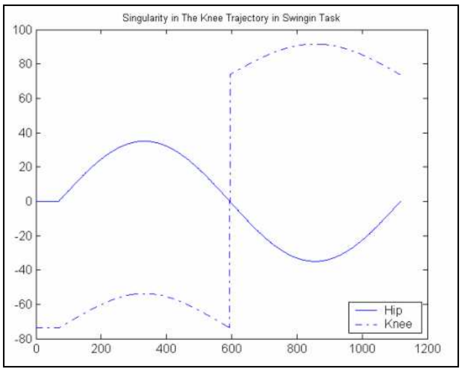

Figure 5: Trajectory in singularity case.

IV. Experiments and System Validation

In the following we report some results both in the case of leg bending and back or forward swing. In the leg bending, the chosen trajectory for the master hip angle is a sine waveform. The hip moves vertically between 0.54m and 0.4m from the ground. Figure 6 shows the legs configuration at different steps of the overall movement; Figure 11 shows the trajectory of the various angles.

In the back or forward swing (more influenced by gravity), the master leg follows a stepwise trajectory. Figure 7 shows the legs configuration at different steps of the overall movement.

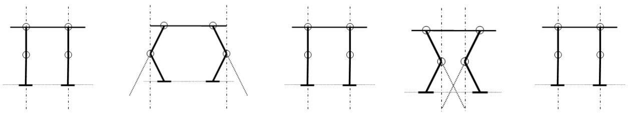

Figure 6: Leg bending main steps.

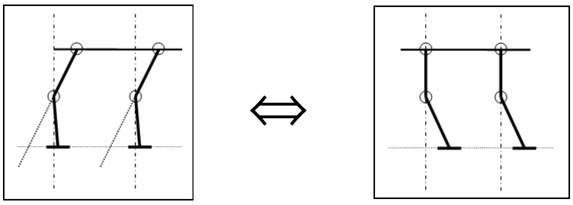

Figure 7: Back or forward swing main steps.

A. *Leg Bending Experiments*

In an ideally perfect execution, choosing suitable orientations, the trajectories of the four hip angle (the master and the three slaves) should coincide, so to keep the body horizontal, and they should follow the reference, so to perform the required movement. The Master-Slave control architecture has been successfully tested in several leg bending experiments, obtaining small tracking errors for each angle with respect to the corresponding imposed trajectory. In Figure 11, typical results are shown: in the higher window, the master measured trajectory (dotted line) is compared with the given reference (continuous line); in the lower window, slave hips' measured trajectories are compared with their reference signals (master's measured trajectory). The middle window shows the measured trajectory of one of the knees (dotted line) compared with its reference signal (continuous line) (compare with scheme in Figure 2).

B. *Back or Forward Swing Experiments*

In this case, the horizontal movement of the center of mass produces significant variations of the effects of gravity on the entire mechanical structure. Due to this, in some situations, the performances of the low level PID controllers, although carefully tuned, appear to be quite poor. Figure 12 shows a typical behavior of the robot .Remark that, in an ideally perfect execution, choosing suitable orientations, the trajectories of the four hip angle should coincide. Although the overall constraints are generally respected, large oscillations are present.

V. FUZZY SUPERVISOR

The solution chosen in order to overcome the execution problems described in the previous Section in the case of back or forward swing consists in endowing the control system with a fuzzy adaptation mechanism, that allows to modify on-line the proportional gains of the low level PID controllers. This action counteracts the variations of the effects of gravity on the mechanical structure due to variations of the configuration.

The fuzzy supervisor works separately on four of the low level controllers (those governing the hip angles) having, as inputs, the tracking error and its incremental variation and, as output, the proportional gain of the PID's. The structure of the fuzzy supervisor is of Sugeno type, with a limited number of rules.

Considering the module of the error signal $e(t) = |\boldsymbol{\theta_h}(t) - \theta_d(t)|$ and a linguistic variable that takes the values Zero, Small and Large, we characterize the situation as shown in Figure 8.

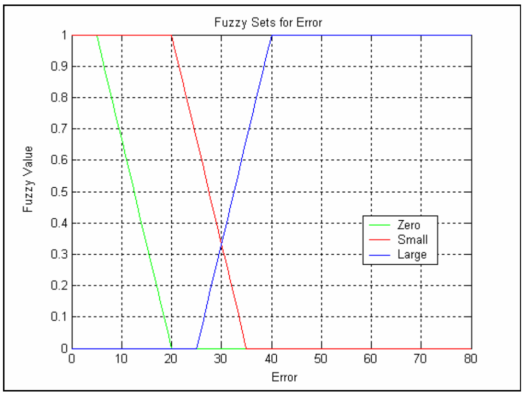

Figure 8: Fuzzy sets for the error variable.

Considering the variation $\Delta e(t) = e(t) - e(t\text{-}1)$ of the error signal (t counts the control cycles, whose duration is 125 ms)and a linguistic variable that takes the values Zero, Positive and Negative, we characterize the situation as shown in Figure 9.

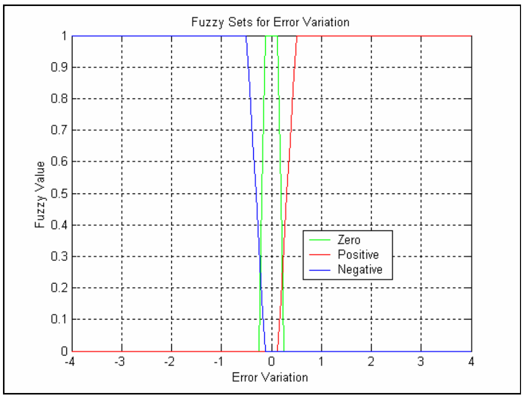

Figure 9: Fuzzy sets for the error variation variable.

The nominal value of the proportional gain in each one of the PID controllers that govern the hip angles has been set equal to 0.2. The fuzzy supervisor can act on each gain by making it Smaller than, Greater than or Equal to the nominal value, where the meaning of the linguistic variable we employ is described by the following Figure 10.

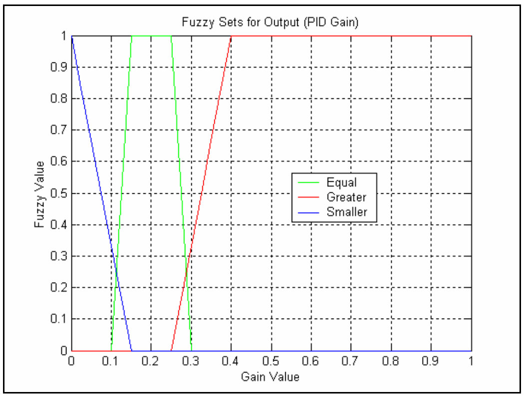

Figure 10: Fuzzy sets for the output variable.

The inferential rules applied by the fuzzy supervisor are summarized in the following table:

Derivative Error Signal				
	N	Equal	Smaller	Equal
	Z	Greater	Equal	Greater
	P	Greater	Greater	Greater
		S	**Z**	**L**
	Error Signal			

It has to be remarked that we chose to keep very simple the structure of the fuzzy supervisor and very small the number of fuzzy rules in order to limit the computation burden on the PC-station. By executing the back or forward swing after enabling the fuzzy supervisor, we obtain a more precise execution, as shown in Figure 13.

VI. Conclusion

In conclusion, the realized control architecture, whose main characteristics are the subdivision in different, hierarchically organized functional levels, the possibility of implementing, in a flexible way, master-slave control modalities and fuzzy-based adaptation, achieves the objective of governing the behavior of QUADRO in a satisfactory way. Further improvements are expected to come by employing a more powerful PC-station, so to have the possibility of extending the action of the fuzzy supervisor to all the low level controllers and of refining it by adding values for the linguistic variables. In addition, the adoption of a real time operating system will make possible to enhance precision and synchronism in task execution, allowing more complex movements in conditions of dynamic equilibrium.

VII. References

[1] H. Asada, J. Slotine, *Robot Analysis and Control*, John Wiley & Sons, New York, 1986

[2] M. H. Raibert, *Legged robots that balance*, The MIT Press, Cambridge Massachussets, 1986

[3] K. J. Astron, T. Hagglund, *PID controllers*, Instruments Society of America, 1995

[4] A. Pasqualini, *Modellazione e simulazione di un Robot mobile Quadrupede*, Dissertation, Università degli Studi di Ancona, 1996

[5] G. Conte, G. Grasso, *Improving leg coordination of a quadrupedal robot*, Proc. IASTED Int. Conf. on Modelling, Identification and Control, Innsbruck, Austria, (2001)

[6] A. Muraro , C. Chevallereau , Y.R. Aoustin, *Optimal trajectories for a quadrupedal robot with Trot, Amble and Curvet gaits for two energetic criteria*, Multibody System Dynamics, 9, 2003

[7] K.Tanie, *New trends of walking robotics research and its application possibilities*, Proc. Int. Conf. on Climbing and Walking Robots, Karlsruhe, Germany, 2001

[8] L.S. Martins-Filho, J.L. Silvino, P. Resende, T.A.Pizziolo, *QUADRUP: towards a prototype of quadruped walking robot*, Proc. Int. Conf. on Climbing and Walking Robots, Paris, France, 2002

[9] , Proc. Int. Conf. on Climbing and Walking Robots, Karlsruhe, Germany, 2001

[10] Proc. Int. Conf. on Climbing and Walking Robots, Paris, France, 2002

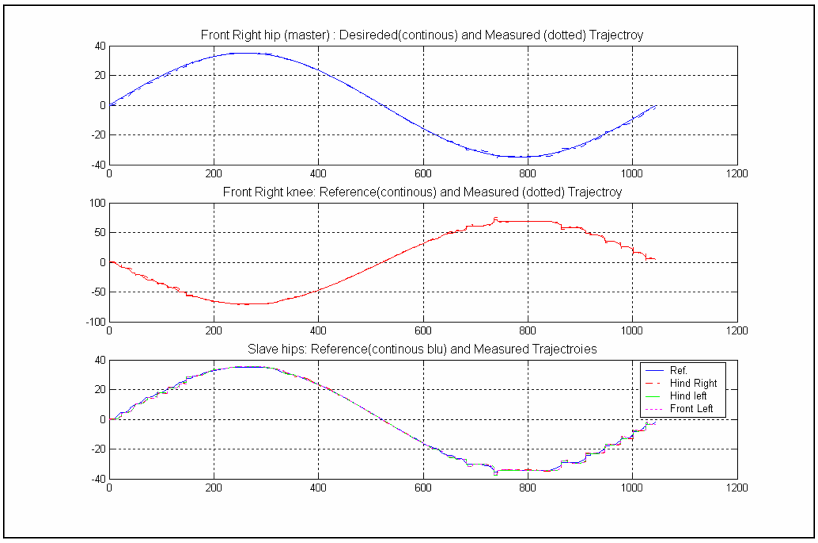

Figure 11:Legs bending: measured and reference angles trajectories (amplitude is in degrees, time is in control time cycles (25 ms)).

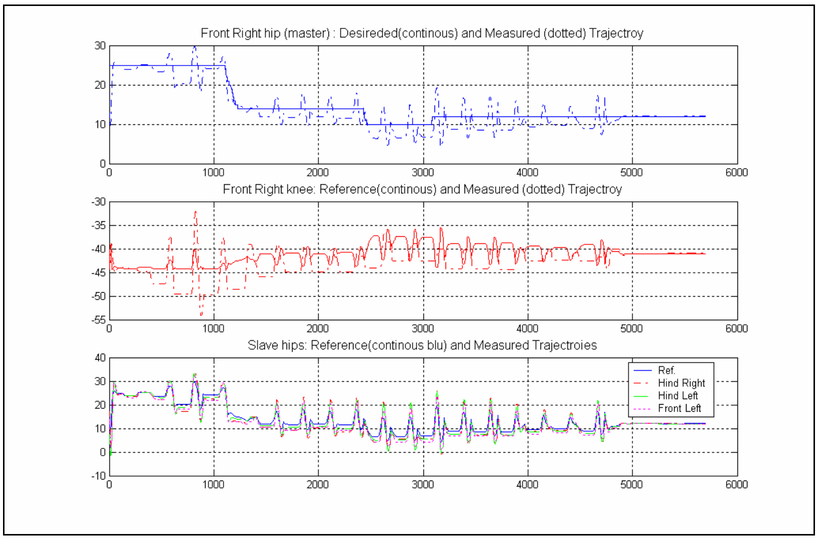

Figure 12: Back or forward swing: measured and reference angles trajectories when fuzzy supervisor is not active

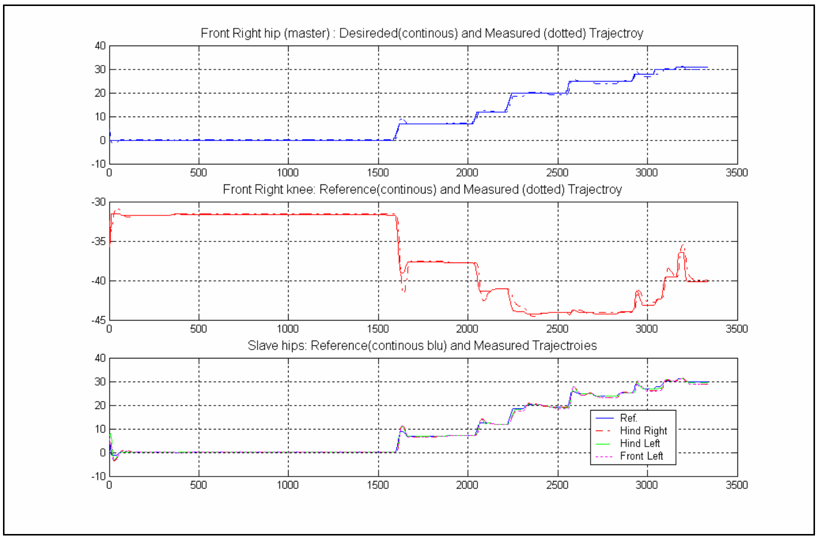

Figure 13: Back or forward swing: measured and reference angles trajectories when fuzzy supervisor is active