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Experimental Implementation of Lyapunov based MRAC for Small Biped Robot Mimicking Human Gait

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1. Introduction

The chapter presents an approach to control the biped humanoid robot to ambulate through human imitation. For this purpose a human body motion capturing system is developed using tri-axis accelerometers (attached to human legs and torso). The tilt angle patterns information from the human is transformed to control and teach various ambulatory skills for humanoid robot bipedalism. Lyapunov stability based model reference adaptive controller (MRAC) technique is implemented to address unpredictable variations of the biped system.

1.1 Background

The biped humanoid robot is one of the accelerated interests in many ongoing research projects. Biped walking is a flexible mechanism that can do dynamic maneuvers in any terrain. Yet, the walking dynamics is non-linear, has many degrees of freedom and requires the development of a complicated model to describe its walking behavior. Existing biped walking methods and control techniques based on Zero moment Point (Babkovic et al., 2007; Kim et al., 2005; Montes et al., 2005; Park, 2003; Kajita et al., 2003; Sughara et al., 2002) give precise stability control for walking robots. However these methods require precise biped walking dynamics and the biped is required to have its feet flat on the ground. Also, these methods may not guarantee a human like walking behavior.

CPG is one biologically inspired method (Kajita et al., 2002; Lee & Oh, 2007; Nakanishi et al., 2004; Righeti & Ijspeert, 2006; Ha et al., 2008; Tomoyuki et al., 2009) defined as the neurons of the nervous system that can generate rhythmic signals in different systems (ex: motors). CPG’s are applied to produce several rhythmic patterns or trajectories for biped walking. In these approaches, it is challenging to find appropriate parameters to achieve a stable gait. Most of the CPG’s are to be tailor made for specific applications. Moreover it is also important to develop an appropriate controller to meet with disturbances occurring in real-time.

Reinforcement learning (Benbrahim, 1996; Lee & Oh, 2007; Morimoto et al., 2004; Takanobu et al., 2005; Tomoyuki et al., 2009) is a method of learning in which the system will try to map situations to actions, so as to maximize a numerical reward signal. The system is not given any set of actions to perform or a goal to achieve; rather it should discover which actions yield a maximum reward. Reinforcement learning provides a good approach when the robot is subject to environmental changes, but since this method learns through trial and error, it is difficult to test the performance on a real time robot.

Virtual Model control technique uses simulations of virtual mechanical components to generate actuator torques (or forces) thereby creating the illusion that the simulated components are connected to the real robot (Hu et al., 1999; Pratt et al., 2001). Even so, this method still requires other controllers in conjunction to make the Biped stability reliable.

Intelligent control techniques such as Fuzzy Logic, Neural Networks, Genetic algorithm, and other intuitive controls are useful in making intelligent decisions based on their pre existing data patterns (Benbrahim, 1996; Kun & Miller, 1996; Lee & Oh, 2007; Manoonpong et al., 2007; Miller, 1997; Morimoto et al., 2004; Park, 2003; Takanobu et al., 2005; Tomoyuki et al., 2009; Wolff & Nordin, 2003; Zhou & Meng, 2003). Since these controllers may not guarantee robustness under parameter uncertainties, these methods are useful when combined with conventional control techniques.

In recent years, biped walking through human gait imitation has been a promising approach (Calinon & Billard, 2004; Chalodnan et al., 2007; Grimes et al., 2006; Hu, 1998; Loken, 2006), since it avoids developing complex kinematics and dynamics for the human walking balance and trajectories and gives the biped humanoid robot a human like walking behavior. However, these methods along with the conventional control techniques cannot adapt their behavior when the dynamic environment around the robot changes. Therefore adaptive controllers are useful to handle the changes with respect to the dynamics of the process and the character of the disturbances (Bobasu & Popescu, 2006; Chen et al., 2006, Hu et al., 1999; Kun & Miller, 1996; Siqueira & Terra, 2006; Miller, 1997).

1.2 Current work

In this chapter we show an approach to teach the biped humanoid robot to ambulate through human imitation. For this purpose a human body motion capturing system is developed using tri-axis accelerometers (attached to human legs and torso). The tilt angle patterns information is transformed to control and teach various ambulatory skills for humanoid robot bipedalism. Lyapunov stability based model reference adaptive controller *(MRAC)* technique is implemented to address the dynamic characteristics and unpredictable variations of the biped system (Vempaty et al., 2007, 2009, 2010).

An Adaptive Control system is any physical system that has been designed with an adaptive viewpoint, in which a controller is designed with adjustable parameters and a mechanism for adjusting those parameters. Basically, the controller has two loops. One loop is a normal feedback with the process and the controller. The other loop is the parameter adjustment loop. Due to this ability of changing its parameters dynamically, adaptive control is a more precise technique for biped walking and stability (Section 2).

In MRAC the presence of the reference model specifies the plants desired performance. The plant (biped humanoid robot) adapts to the reference model (desired dynamics). The reference model represents the desired walking behavior of the biped robot, which is derived from the human gait, which is obtained from the human motion capturing system

This chapter shows the design and development methods of controlling the walking motion of a biped robot which mimics a human gait. This process of robot learning through imitation is achieved by a human motion capturing system. In this work, a human motion capturing suit is developed using tri-axis accelerometers that are appended to a human body (Section 4).

In order to ensure precise control and stability, adaptive controller technique is applied. The control system applied for this process is based on Model Reference Adaptive Control (MRAC) with Lyapunov stability criterion. The process of learning to walk, through imitation with MRAC is applied to a real time Humanoid Robot (Robonova) with multiple servo motors (Section 5). This process is carried out by instructing the robot to follow human walking gait with the help of the human body motion capturing system and MRAC schemes (Section 6).

2. MRAC approach for biped walking

Consider the objective of controlling a biped robot so that it imitates the movements of a person. Fig. 1 shows the basic idea where the human movement is represented by $\mathbf{y}_d$ and the biped movement by $\mathbf{y}$. The biped motion is determined by the servo motors which are controlled by the inputs $\mathbf{u}_a$.

In the present problem, we will consider the case where the servo motor has uncertainties including nonlinearities, and unknown parameter values. The overall objective is to find the adaptive $\mathbf{u}_a$ such that $\mathbf{y} \to \mathbf{y}_d$.

In this chapter, we will focus on the adaptation scheme a servo motors (Ehsani, 2007).

Fig. 2 shows the adaptive the objective where the servo motor output angular displacement θ is made to follow a required θ_d, which will be computed from the desired requirement that $\mathbf{y}$ tracks $\mathbf{y}_d$.

Servo motor dynamics including nonlinearities and delays, which have not been widely addressed. The study presented in this chapter deals with the formulation and real-time implementation aspects of the MRAC for Biped imitating human walking motion.

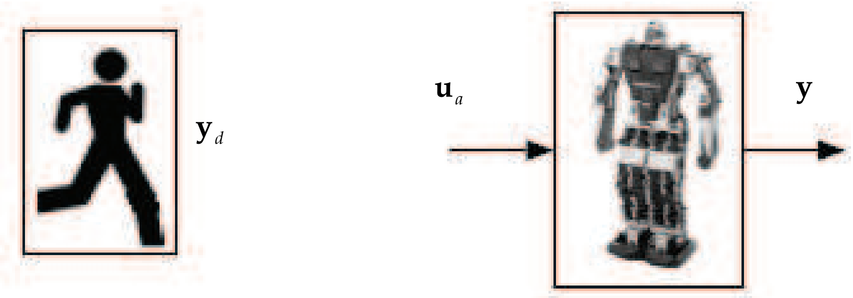

Fig. 1. Human-Robot movements interaction

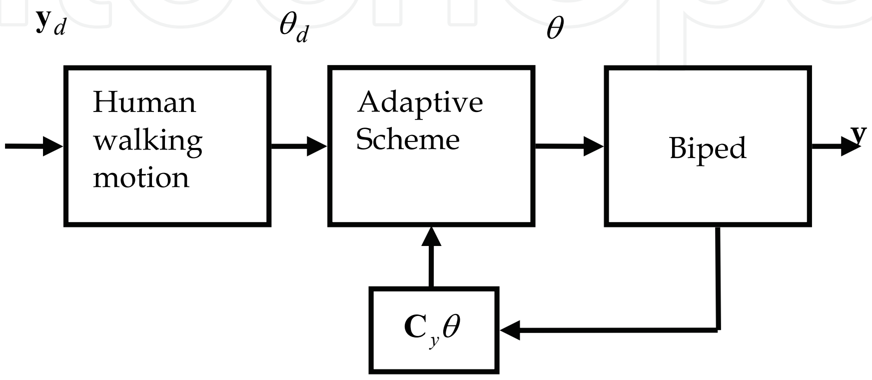

Fig. 2. MRAC for biped mimicking human gait

3. MRAC formulation

3.1 Biped servo model

The biped servo motor model is considered as a 2nd order system with 2 poles, no zero, 1 input, and 2 states described by

$$\dot{\mathbf{x}}_a = \mathbf{A}_a \mathbf{x}_a + \mathbf{B}_a \mathbf{u}_a \tag{1}$$

3.2 Reference model

The adaptive controller scheme for MRAC is shown in Fig. 3, where the reference model for the servo motor is specified by

$$\dot{\mathbf{x}}_m = \mathbf{A}_m \mathbf{x}_m + \mathbf{B}_m \mathbf{u}_m \tag{2}$$

The controller $\mathbf{u}_a$ comprises of a state feedback and a command feedforward terms, given as

$$\mathbf{u}_a = -\mathbf{L}\mathbf{x}_a + \mathbf{N}\mathbf{u}_m \tag{3}$$

The adaptation algorithm in the MRAC will adjust the gains **L** and **N** based on Lyapunov stability criteria as follows.

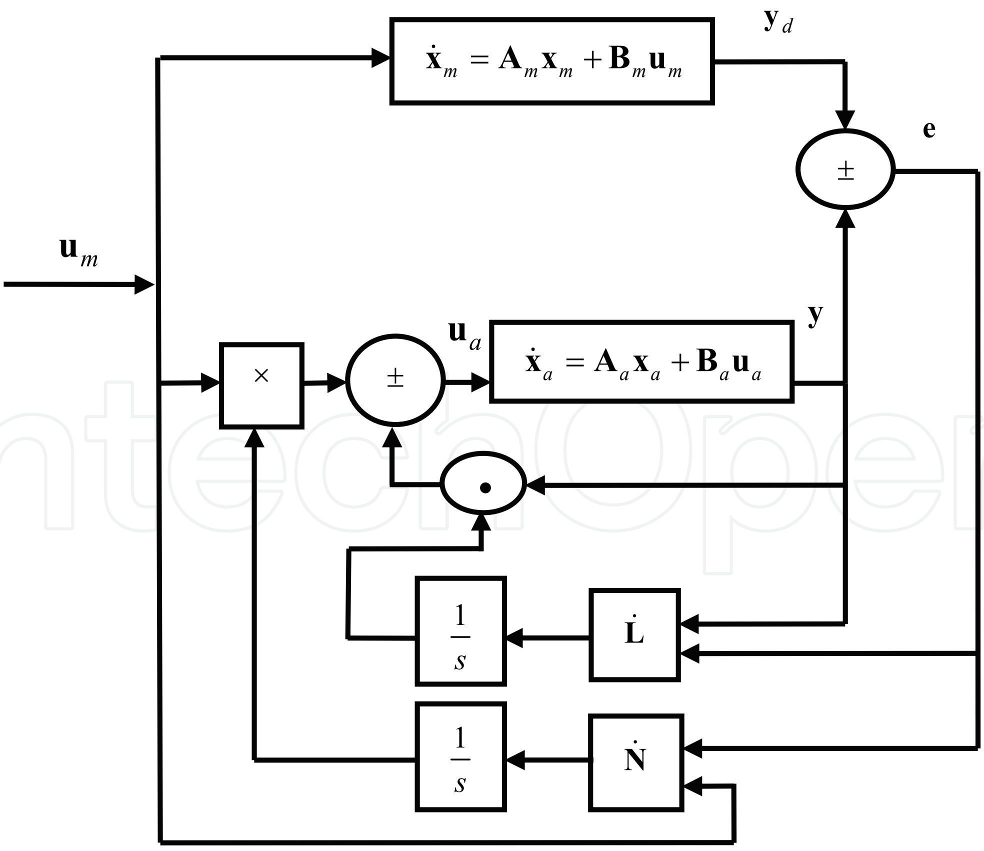

Fig. 3. Lyapunov Stability based MRAC Scheme

3.3 Error equation

Define the errors $\mathbf{e}$ between the biped servo motor states and the desired reference human motion output states as

$$\mathbf{e} = \mathbf{x}_m - \mathbf{x}_a \tag{4}$$

$$\dot{\mathbf{e}} = \mathbf{A}_m\mathbf{e} + \left[\mathbf{A}_a - \mathbf{B}_a\mathbf{L} - \mathbf{A}_m\right]\mathbf{x}_a + \left[\mathbf{B}_a\mathbf{N} - \mathbf{B}_m\right]\mathbf{u}_m \tag{5}$$

3.4 Lyapunov stability analysis

We define the Lyapunov candidate function as

$$\begin{aligned} v = {} & \mathbf{e}^T\mathbf{P}\mathbf{e} + trace\left(\mathbf{A}_m - \mathbf{A}_a - \mathbf{B}_a\mathbf{L}\right)^T \mathbf{Q}\left(\mathbf{A}_m - \mathbf{A}_a - \mathbf{B}_a\mathbf{L}\right) + \\ & trace\left(\mathbf{B}_m - \mathbf{B}_a\mathbf{N}\right)^T \mathbf{R}\left(\mathbf{B}_m - \mathbf{B}_a\mathbf{N}\right) \end{aligned} \tag{6}$$

where $\mathbf{P} = \mathbf{P}^T > 0$, $\mathbf{Q} = \mathbf{Q}^T > 0$ and $\mathbf{R} = \mathbf{R}^T > 0$ are positive definite matrices.

$$\begin{aligned} \dot{v} &= \dot{\mathbf{e}}^T\mathbf{P}\mathbf{e} + \mathbf{e}^T\mathbf{P}\dot{\mathbf{e}} \\ &\quad +2\left(trace\left(\mathbf{A}_m - \mathbf{A}_a - \mathbf{B}_a\mathbf{L}\right)^T \mathbf{Q}\left(\mathbf{B}_a\dot{\mathbf{L}}\right)\right) + 2\left(trace\left(\mathbf{B}_m - \mathbf{B}_a\mathbf{N}\right)^T \mathbf{R}\left(-\mathbf{B}_a\dot{\mathbf{N}}\right)\right) \\ &= \mathbf{e}^T\left[\mathbf{P}\mathbf{A}_m + \mathbf{A}_m^T\mathbf{P}\right]\mathbf{e} + \\ &\quad 2\left(trace\left(\mathbf{A}_m - \mathbf{A}_a - \mathbf{B}_a\mathbf{L}\right)^T\left(\mathbf{P}\mathbf{e}\mathbf{x}_a^T + \mathbf{Q}\left(\mathbf{B}_a\dot{\mathbf{L}}\right)\right)\right) \\ &\quad +2\left(trace\left(\mathbf{B}_m - \mathbf{B}_a\mathbf{N}\right)^T\left(\mathbf{P}\mathbf{e}\mathbf{u}_m^T + \mathbf{R}\left(-\mathbf{B}_a\dot{\mathbf{N}}\right)\right)\right) \end{aligned} \tag{7}$$

From inspection, we choose

$$\begin{aligned} \mathbf{B}_a\dot{\mathbf{L}} &= \mathbf{Q}^{-1}\mathbf{P}\mathbf{e}\mathbf{x}_a^T \\ \mathbf{B}_a\dot{\mathbf{N}} &= -\mathbf{R}^{-1}\mathbf{P}\mathbf{e}\mathbf{u}_m^T \end{aligned} \tag{8}$$

So that,

$$\dot{v} = \mathbf{e}^T\left[\mathbf{P}\mathbf{A}_m + \mathbf{A}_m^T\mathbf{P}\right]\mathbf{e} \tag{9}$$

Next, choose $\mathbf{S} = \mathbf{S}^T > 0$ and solve $\mathbf{P}$ from

$$\mathbf{P}\mathbf{A}_m + \mathbf{A}_m^T\mathbf{P} = -\mathbf{S} < 0 \tag{10}$$

We now arrive at

$$\dot{v} = -\mathbf{e}^T\mathbf{S}\mathbf{e} \tag{11}$$

It is desirable to then ensure that $\mathbf{P}\mathbf{A}_m + \mathbf{A}_m^T\mathbf{P} = -\mathbf{S} < 0$ (negative definite) where $\mathbf{S} > 0$ (positive definite). $\mathbf{P}$ is solved from the Lyapunov equation (10).
Lyapunov stability theory ensures that the solution $\mathbf{P} > 0$ because $\mathbf{A}_m$ is stable.

4. Human motion sensing

4.1 Human gait acquisition setup

A low cost human motion capturing system is developed using Nintendo Wii remotes (Wiimote). A Wiimote is a Bluetooth based wireless joystick with an ADXL330 tri-axis accelerometer embedded in it. An ADXL330 tri-axis accelerometer can measure acceleration with a full scale range of $\pm 3g$, and can be used to measure the tilt angles when appended to a human body. Fig. 4, shows basic human motion capturing system with Wiimotes attached to the human body. For controlling and instructing the robot on bipedalism, a minimum of five accelerometers are required, two on each leg (attached to thigh and the calf muscles), and one on the torso.

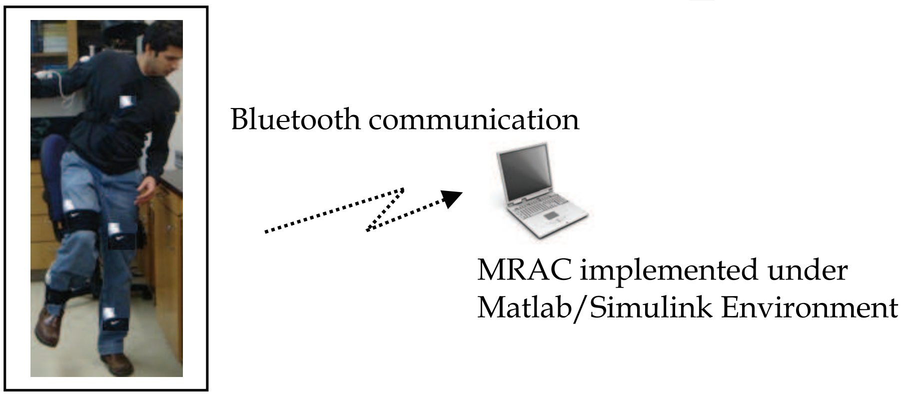

Fig. 4. Nintendo Wiimotes based human motion capturing system

4.2 Human motion data filter

Human motion data is sampled for every 300ms. The raw data captured has noise, redundancy and sensitivity. Due to this the biped may respond for every redundant movement of the human. Therefore in order to reduce this effect, a filter is designed to remove the unwanted human motion data. Fig. 5, shows the human gait data filter algorithm.

The filter basically takes the human motion data and calculates the difference of the first value $\mathbf{u}_m(i)$, with its subsequent value $\mathbf{u}_m(j)$.

The difference $Diff_{\mathbf{u}_m}$ is compared with the threshold values set as 8 degrees and 6 degrees for $PosThresUpper$ and $PosThresLower$. If the difference is satisfied by the condition, then that position data value is sent as the input command $\mathbf{u}_m$, else process is repeated. Fig. 6 shows the filtered data from the raw human gait data acquisition from all the 5 Wii sensors.

It is clearly seen from the plots that the data that is redundant and noisy are ignored. Data is collected and processed only when there is a significant amount of change. This method also helps in sending only the useful information to the biped as well as in saving computer memory storage.

5. Real-Time Implementation

5.1 Robonova biped robot

Robonova is controlled by an Atmel ATMEGA128 8bit RISC processor, and has the capability of simultaneously controlling up to 24 servo motors. In this work, commands for the servo motors are sent from the computer under a Matlab/Simulink environment.

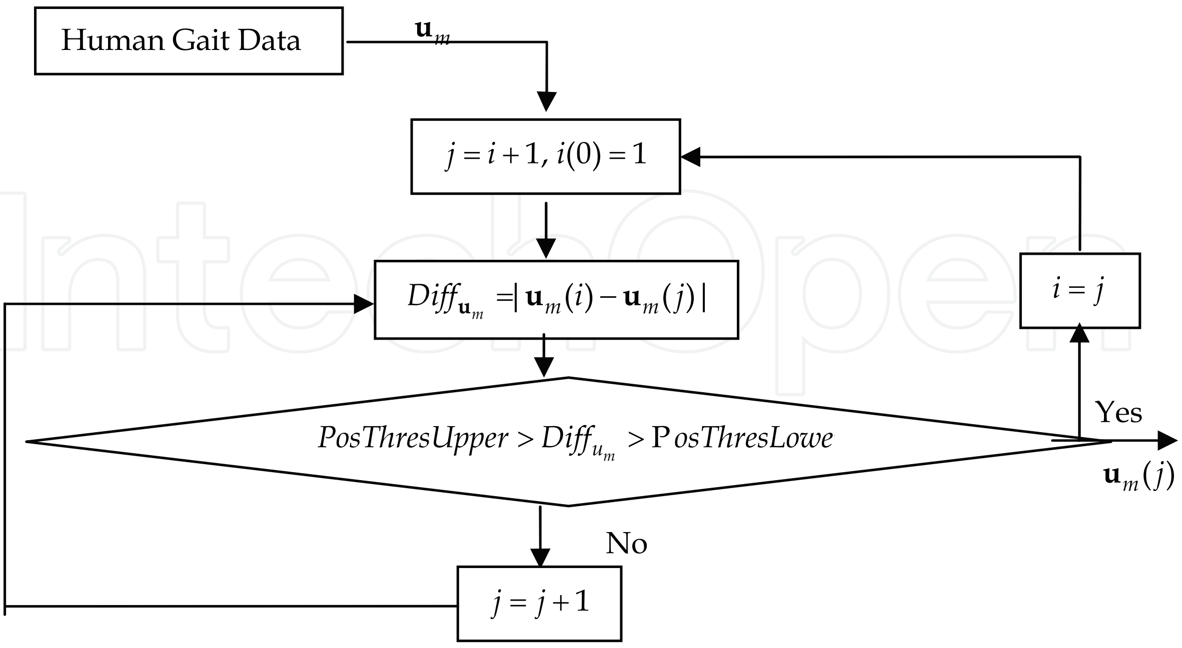

Fig. 5. Filter algorithm for human motion data

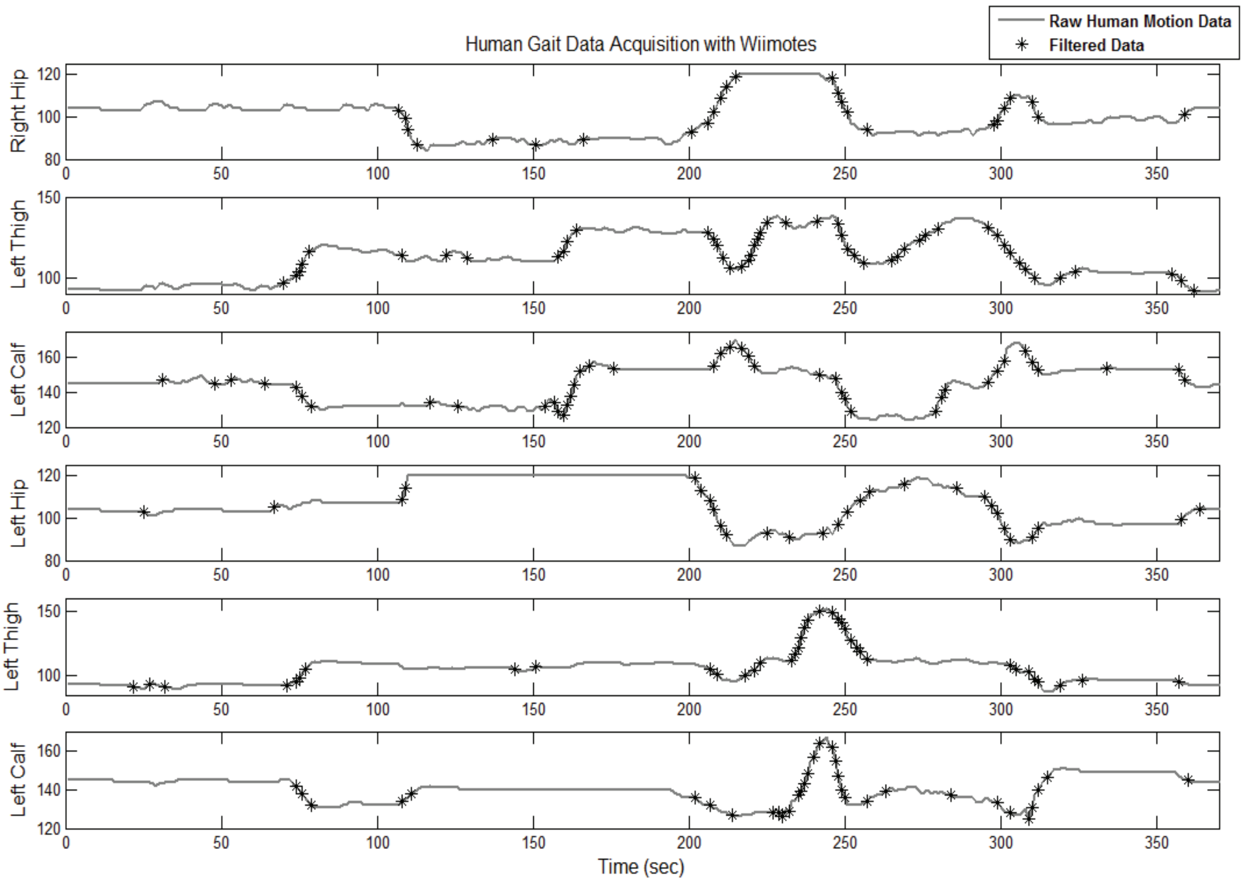

Fig. 6. Ouput of the human motion data filter

Commands for 16 servo motors are issued to the ATMEGA processor via RS232 interface. Five tri-axis ADXL335 ($\pm 3g$ acceleration) accelerometers appended on to its legs (thigh and calf muscles) and onto its torso for position feedback. Fig. 7, shows the basic control and communication setup for Robonova-Computer interaction (Zannatha &Limon, 2009).

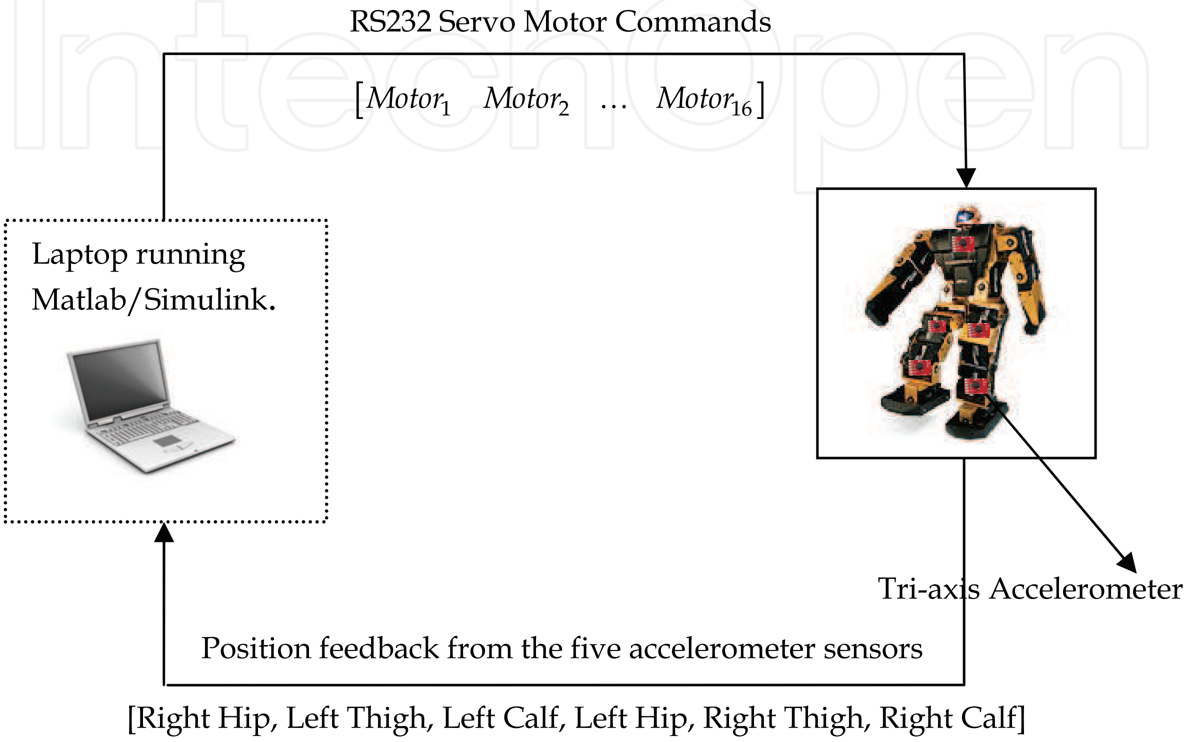

Fig. 7. Biped-Computer Interaction and Interface setup

5.2 Computation of the human movements

Desired human motion data from the Wii device is represented as

$$\mathbf{y}_d = \left[\theta_{Thigh\,Right} \quad \theta_{Calf\,Right} \quad \theta_{Thigh\,Left} \quad \theta_{Calf\,Left} \quad \theta_{Torso}\right]^T_{Human} \tag{12}$$

Output $\mathbf{y}$ is constructed from the biped's accelerometer sensors as,

$$\mathbf{y} = \left[\theta_{Thigh\,Right} \quad \theta_{Calf\,Right} \quad \theta_{Thigh\,Left} \quad \theta_{Calf\,Left} \quad \theta_{Torso}\right]^T_{biped} = C_y\theta \tag{13}$$

The desired output will be to have $\mathbf{y} \to \mathbf{y}_d$.

5.2.1 Dynamics of the servo motors

The biped output states $\mathbf{x}_a = \boldsymbol{\theta}$ are the biped servomotor angular displacements. The objective is to derive $\mathbf{u}_a$ which will drive $\boldsymbol{\theta} \to \boldsymbol{\theta}_d$.

It follows that (1) can be decoupled into individual motors represented by the second order dynamics given as

$$\begin{aligned}
\mathbf{x}_a &= \begin{bmatrix} x_{a1} & x_{a2} & x_{a3} & x_{a4} & x_{a5} & x_{a6} & x_{a7} & x_{a8} \end{bmatrix}^T \\
\mathbf{u}_a &= \begin{bmatrix} u_{a1} & u_{a2} & u_{a3} & u_{a4} & u_{a5} & u_{a6} & u_{a7} & u_{a8} \end{bmatrix}^T \\
\mathbf{A}_a &= diag\{ a_{a1} \quad a_{a2} \quad a_{a3} \quad a_{a4} \quad a_{a5} \quad a_{a6} \quad a_{a7} \quad a_{a8} \} \\
\mathbf{B}_a &= diag\{ b_{a1} \quad b_{a2} \quad b_{a3} \quad b_{a4} \quad b_{a5} \quad b_{a6} \quad b_{a7} \quad b_{a8} \}
\end{aligned}$$

$\mathbf{A}_a$ and $\mathbf{B}_a$ are the uncertain parameter vectors and the states $\mathbf{x}_a$ and the control $\mathbf{u}_a$ are accessible.

5.2.2 Configuration of MRAC for biped servo motors

From (3), the controller $\mathbf{u}_a$ comprises a state feedback and a command feedforward terms
Where,

$$\begin{aligned}
\mathbf{L} &= diag\{ l_1 \quad l_2 \quad l_3 \quad l_4 \quad l_5 \quad l_6 \quad l_7 \quad l_8 \} \\
\mathbf{N} &= diag\{ n_1 \quad n_2 \quad n_3 \quad n_4 \}
\end{aligned} \tag{14}$$

Where $\mathbf{u}_m$ is the command input to the MRAC system. The controller gains $\mathbf{L}$ and $\mathbf{N}$ are to be tuned, so that the closed-loop system

$$\dot{\mathbf{x}}_a = \left(\mathbf{A}_a - \mathbf{B}_a \mathbf{L} \right) \mathbf{x}_a + \mathbf{B}_a \mathbf{N} \mathbf{u}_m \tag{15}$$

behaves with the characteristics of the reference model defined by (2).
From the Lyapunov design 3.1.3, the gains (14) are adjusted according to

$$\begin{aligned}
\dot{l}_i &= \frac{1}{b_{ai} q_i} p_i (\theta_{di} - x_{ai}) x_{ai} \\
\dot{n}_i &= -\frac{1}{b_{ai} r_i} p_i (\theta_{di} - x_{ai}) u_{mi}
\end{aligned} \tag{16}$$

The convergence analysis for tuning p, q and r is discussed by (Vempaty et al., 2010).

5.3 Simulation of biped servo motor model

Consider one of the biped servo motor models, derived based on the system identification analysis. The corresponding model is given from (1)

$$\mathbf{A}_a = \begin{bmatrix} 0 & 1 \\ -a_{a2} & -a_{a1} \end{bmatrix}, \mathbf{B}_a = \begin{bmatrix} 0 \\ b_{a1} \end{bmatrix}, \mathbf{x}_a = \begin{bmatrix} x_{a1} \\ x_{a2} \end{bmatrix}, \mathbf{C}_a = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{17}$$

Where, $a_{a1} = -4, a_{a2} = -2,$ and $\mathrm{b}_{a1} = 2.28$.
We would like (17) to behave with characteristics of the reference model (2) defined as

$$\mathbf{A}_m = \begin{bmatrix} 0 & 1 \\ -a_{m2} & -a_{m1} \end{bmatrix}, \mathbf{B}_m = \begin{bmatrix} 0 \\ b_{m1} \end{bmatrix}, \mathbf{x}_m = \begin{bmatrix} x_{m1} \\ x_{m2} \end{bmatrix}, \mathbf{C}_m = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{18}$$

Where, $a_{m1} = -4, a_{a2} = -8,$ and $\mathrm{b}_{a1} = 8$.

The adaptation of the biped servo model to the reference model is shown in Fig. 8.

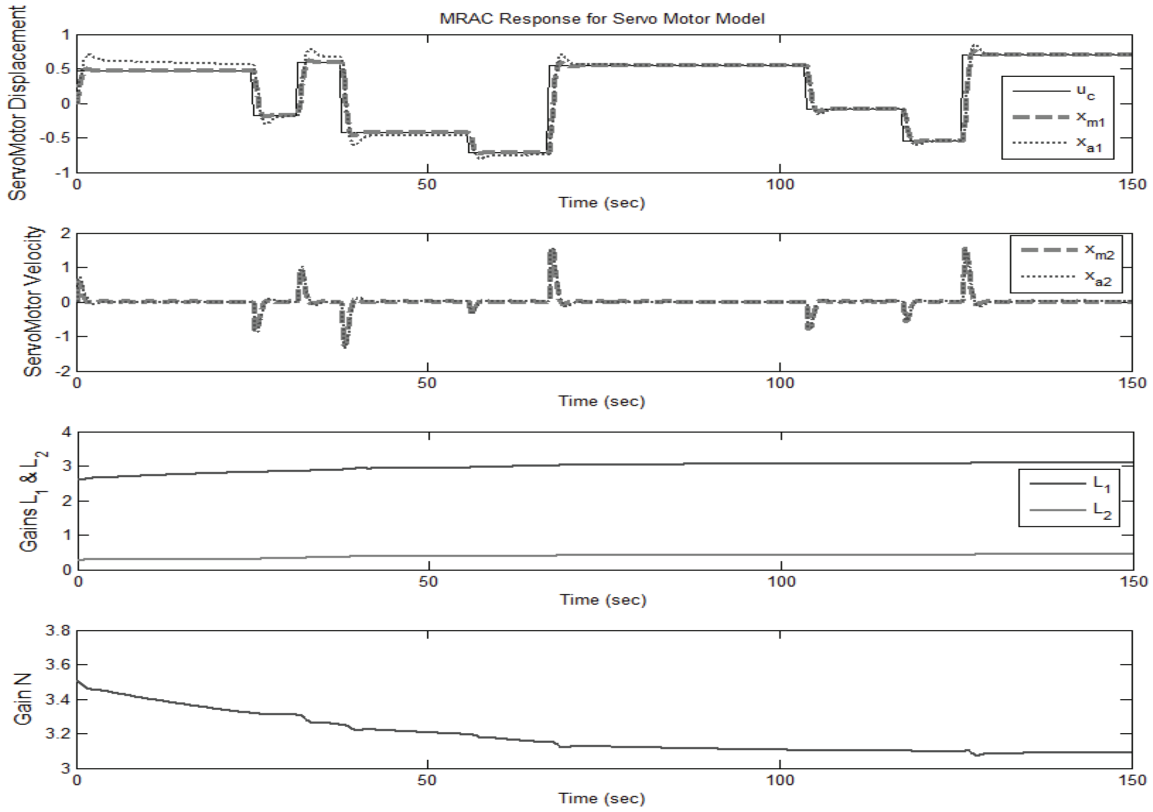

Fig. 8. MRAC response of the biped servo motor model

The coefficients a_{m1}, a_{m2}, and b_m represent the desirable characteristics for the model. It is clear from Fig. 8 that l_1, l_2, and n_1 are tuned so that, from (2), (15) and (4) we infer,

$$\mathbf{A}_a - \mathbf{B}_a\mathbf{L} \to \mathbf{A}_m,\ \mathbf{B}_a\mathbf{N} \to \mathbf{B}_m, \text{and } \mathbf{e} \to 0$$

6. Experiment and results

6.1 Closed-loop setup

The process of a robot learning to walk by mimicking human gait is discussed in this section. Fig. 9, shows the human-robot interaction setup with MRAC scheme. Human movements from the Wiimotes are transferred to Matlab/Simulink; these angles are transformed and calibrated with the accelerometer feedback angles coming from the Robonova.

The angles coming from the human motion change from 10 to 190; these signals are scaled between -1 and 1 to avoid singularities in the computation of MRAC.

The five angles derived from the human movements are sent to the MRAC as the command input signals. In this experiment $\theta_{Torso_{Human}}$ and $\theta_{Torso_{Biped}}$ are set to be constant.

The output of the MRAC with the five control signals is transformed to the corresponding individual servo signals to the Robonova via serial port, and the position of the biped feedback to the controller is transformed via a Kalman filter to reduce the sensor noise.

MRAC is implemented individually to the servo motors defined by (12). The tracking responses of each servo motor are monitored with ±5 % tolerance limit. After the tracking

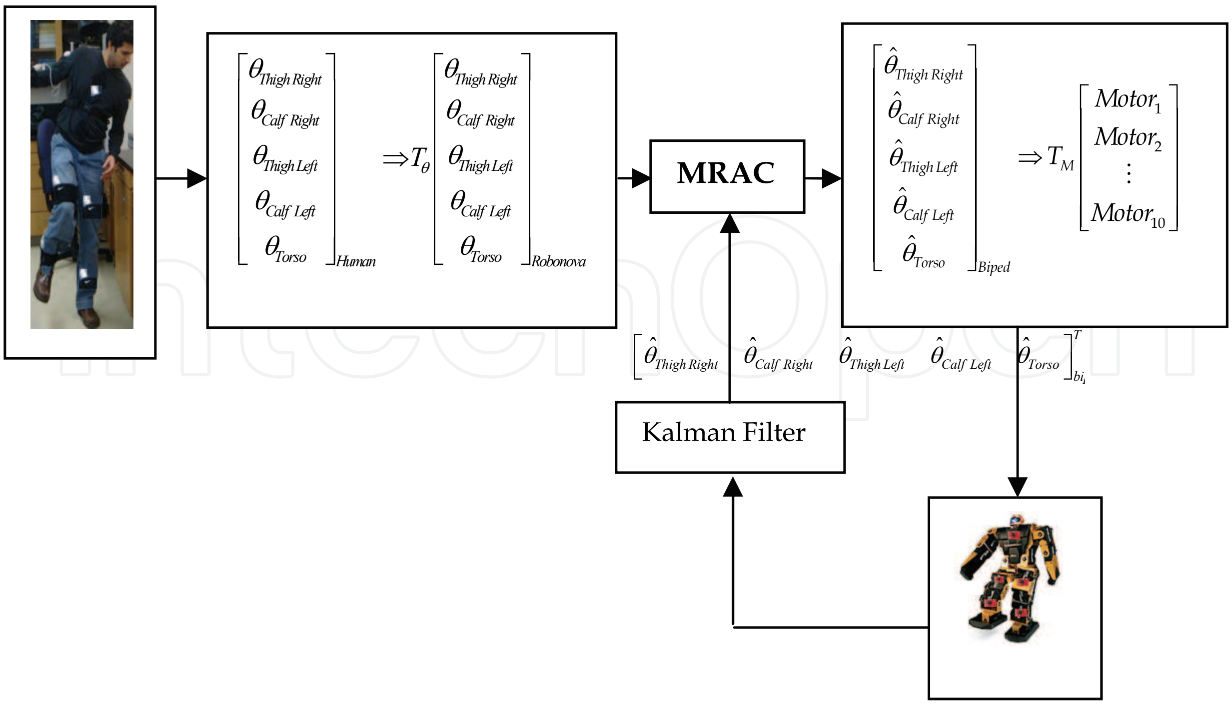

Fig. 9. Closed-loop setup for biped walker imitating human gait with MRAC

requirement is reached, the next input command is issued to the controller and the process repeats.

Although Lyapunov guarantees stability of the system under control, it never guarantees a precise tracking performance. For this, Lyapunov based MRAC schemes should be incorporated with other control schemes.

In this experiment, in order for the biped to meet the real-time response, an integrator is implemented at the command input $\mathbf{u}_a$.

This approach is used in instructing the robot in walking. Here, the robot derives its dynamic and kinematic movements from the human dynamic and kinematic movements.

6.2 Output results of the MRAC based biped walker imitating human gait

Following are the results of the MRAC for a 2-step walking cycle of the biped imitating human gait. Fig. 10-13 show the MRAC outputs when the biped responds to the human gait data.

7. Conclusion

The experimental results verify the MRAC approach for the biped walker imitating the human gait under a real-time environment. The model reference adaptive control system for the servo motor control is derived and successfully implemented with Matlab/Simulink.

It has been shown that the application of MRAC for biped walking indeed makes the humanoid robot adapt to whatever reference that is provided.

Therefore, it can be concluded that the use of MRAC for biped walking makes it easy to develop and control a biped system. Tracking performance and learning based on neural networks shall be included in future research.

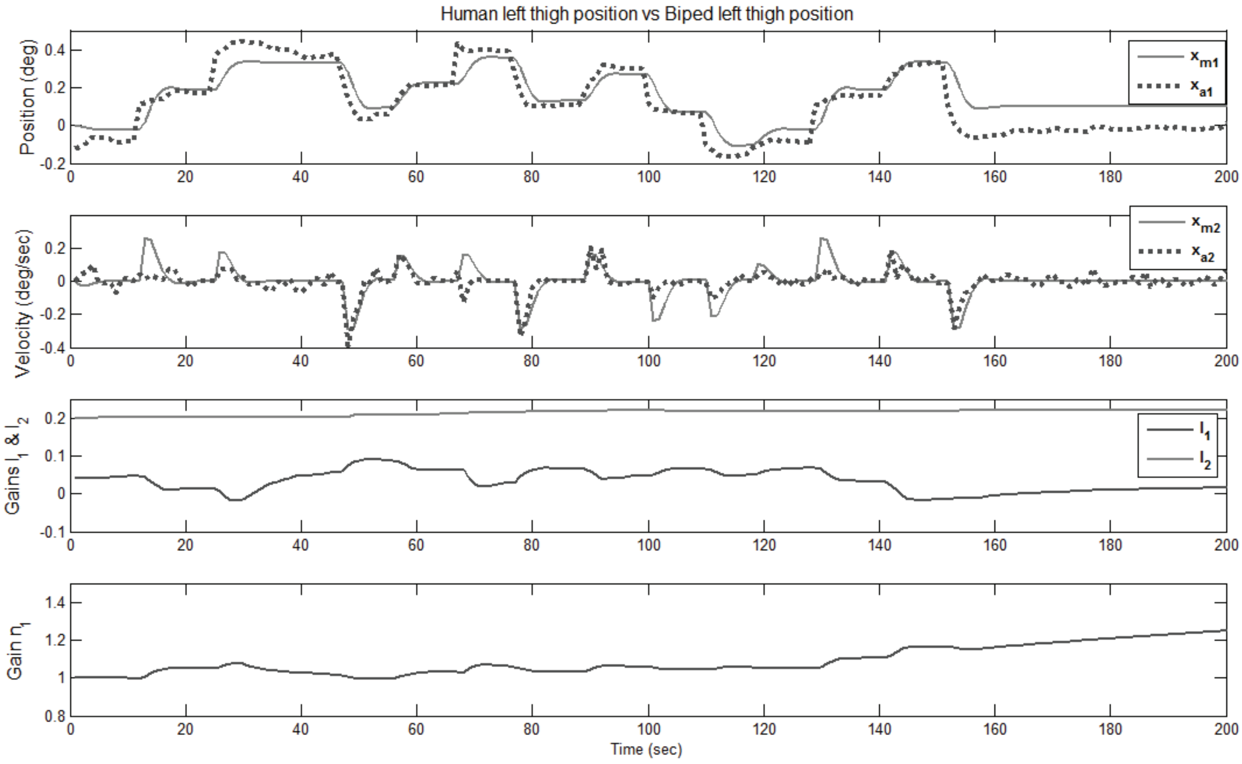

Fig. 10. Closed-loop MRAC biped response to human left thigh motion

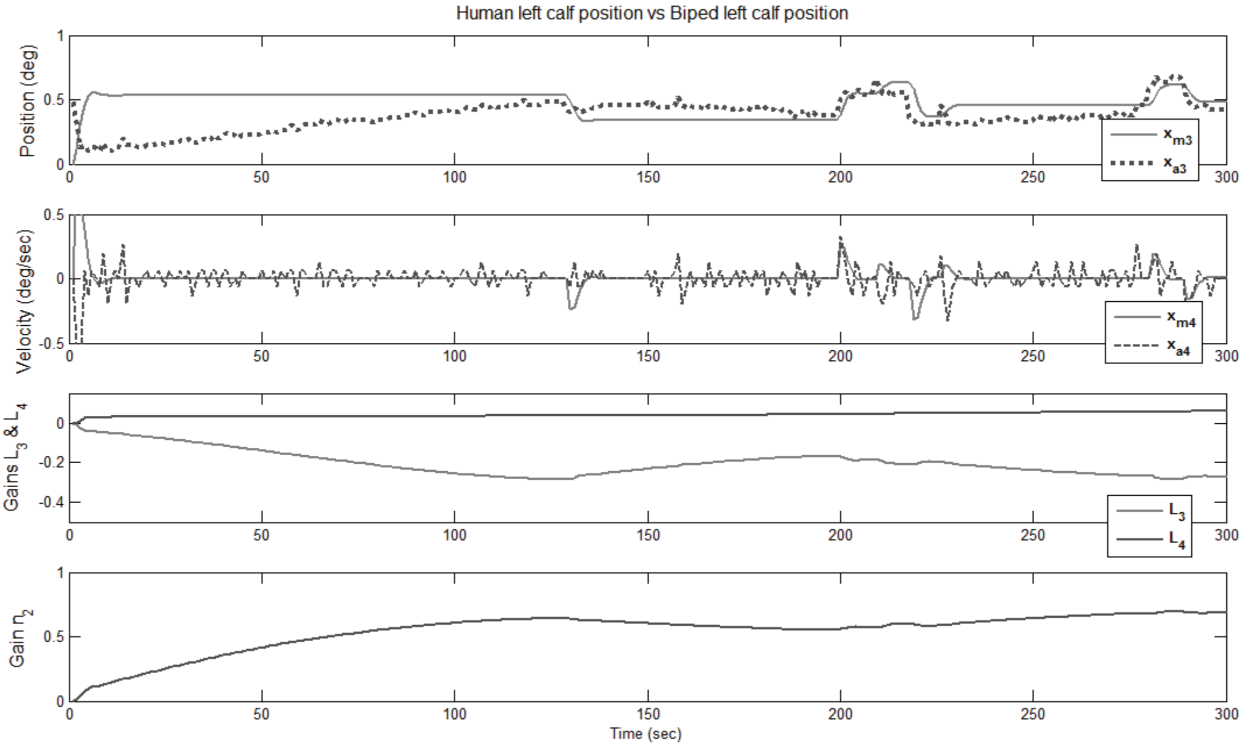

Fig. 11. Closed-loop MRAC biped response to human left calf motion

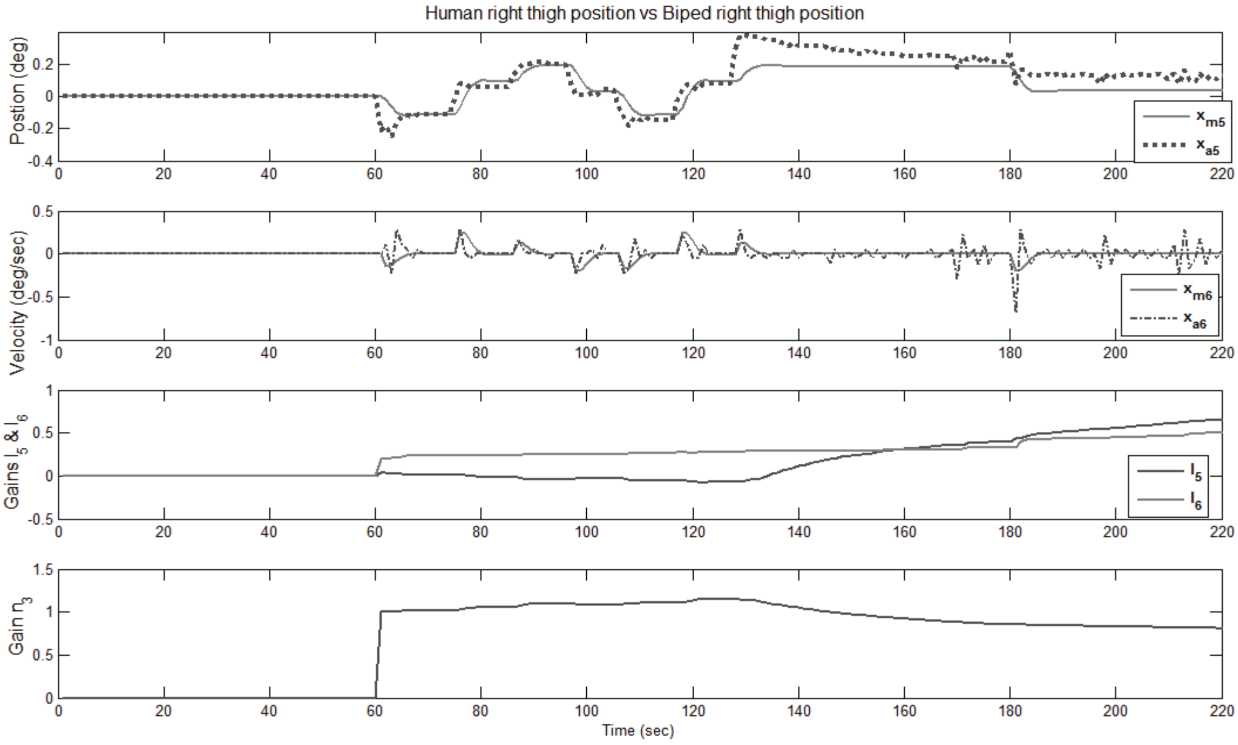

Fig. 12. Closed-loop MRAC biped response to human right thigh motion

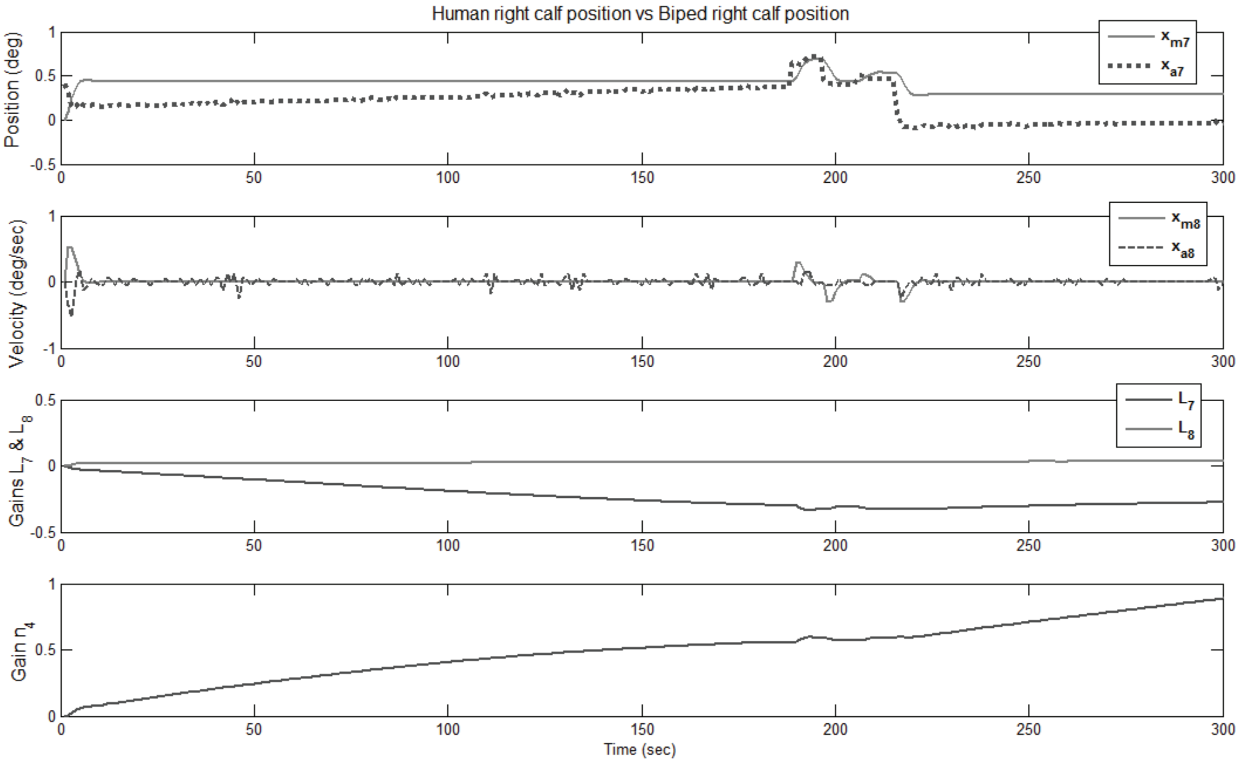

Fig. 13. Closed-loop MRAC biped response to human right calf motion

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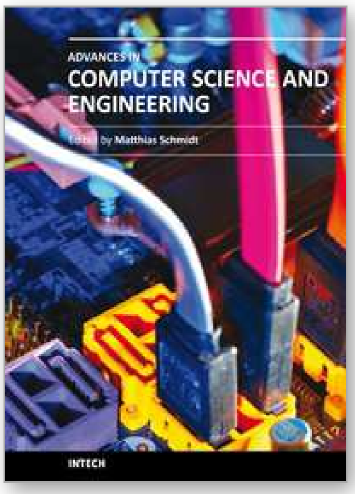

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