

Model Reference Adaptive Control for Actuators of a Biped Robot Locomotion

Pavan K. Vempaty, Ka C. Cheok, and Robert N. K. Loh

Abstract — Many robotics problems do not take dynamics of actuators into account in the formulation of the control solution. The fallacy is in assuming that desired forces/torques can be instantaneously and accurately generated. In practice actuator dynamics may be unknown and can have significant transient effect on the overall results. This paper presents a Model Reference Adaptive Controller for the actuators of a robotic biped walker. The actuators learn and produce the torque required for a walking cycle presented in the form of a torque reference model. The actuators of the biped adapt themselves to match with the desired torque reference model with the aid of Lyapunov stability criterion. This control scheme for the biped robot is simulated on a sagittal plane. The results verify the MRAC scheme for the actuators.

Keywords- Model Reference Adaptive Control, Biped walker, Actuator Dynamics.

I. INTRODUCTION

Biped walking dynamics is highly non-linear, has many degrees of freedom and requires developing highly complicated model to describe its walking behavior. There are number of novel approaches emerging in the field of biped walking to address this complicated control mechanism. Existing biped walking methods [3]-[5], give precise stability control for walking bipeds. However these methods require highly precise biped walking dynamics. In the recent years, biped walking through imitation has been a promising approach, since it avoids developing complex kinematics of the human walking trajectory and gives the biped a human like walking behavior. These methods combine the conventional control schemes to develop the walking mechanism for the bipeds. Examples include, imitation based on intelligent control methods like genetic algorithm [6], [4], fuzzy logic [7], neural network approach [8], and other methods such as adaptation of biped locomotion [5], learning to walk through imitation [8] and reinforcement learning [4], [7]. But these methods cannot readily adapt their behavior to the changes in the dynamics of the process and the character of the disturbances [2]. Therefore there are adaptive control approaches [10]-[12].

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To address the problem of poorly known actuator dynamic characteristics and unpredictable variations of a biped system, we propose a Lyapunov based model reference adaptive control system (MRAC) method for the biped walking control. In MRAC the presence of the reference

model specifies the plants desired performance. The plant (biped actuators) adapts itself with the reference system (desired signals to the actuators). In this paper, reference system signals are represented by torques derived from a simulated biped walking control parameters [1]. Alternatively, we can also capture the walking control parameters from human walking movements using motion capturing devices. Once we have the walking control parameters either derived or captured, the reference model will be implemented based on this control data. The plant will then adapt itself to provided control data (reference model). Lyapunov's stability criterion is applied in feedback for tuning the parameters to make the error between the reference and the plant tends to zero. Through this scheme, a robot can learn its behavior through its reference models.

II. PROBLEM DESCRIPTION

A. Objective

Consider the objective of controlling a biped robot so that it imitates the movements of a person. Due to uncertainty associated with nonlinear actuator dynamics and unknown parameters, an adaptive control scheme will be used to achieve the objective. Fig.1. shows the concept where a model references adaptive control (MRAC) scheme is proposed for a biped robot to imitate human movement.

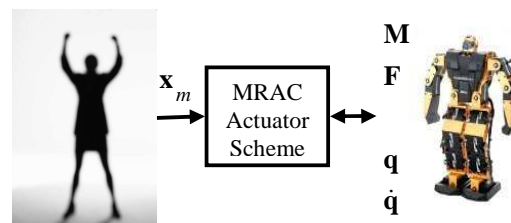


Fig. 1 Biped Robot, Its Actuators and Human Movements

The study presented in this paper deals with the formulation, simulation and experimental aspects of the MRAC actuator scheme.

Equations for describing the dynamics of a biped robot have been introduced in [1], and can be summarized as follows.

$$\mathbf{A}_q(\mathbf{q})\ddot{\mathbf{q}} = \mathbf{b}(\mathbf{q}, \dot{\mathbf{q}}, \mathbf{M}, \mathbf{F}) \quad (1)$$

where \mathbf{q} is the generalized coordinates of the robot, \mathbf{M} the moments/torques applied to the joints in the robot and \mathbf{F} the reaction forces at the contact of the robot's feet and ground. Many literatures assume that \mathbf{M} can be readily generated without considering dynamics of actuators. As an example, if a set of desired torques are calculated as \mathbf{M}_d , then it would assume that $\mathbf{M} = \mathbf{M}_d$ and applied directly as inputs to the robot. However, this is not a valid assumption since in practice the moments \mathbf{M} will be generated by actuators. We model the moment as states $\mathbf{x}_a = \mathbf{M}$ as follows:

$$\dot{\mathbf{x}}_a = \mathbf{A}_a \mathbf{x}_a + \mathbf{B}_a \mathbf{u}_a + \mathbf{d}_a(\mathbf{q}, \dot{\mathbf{q}}, \boldsymbol{\tau}_{ext}) \quad (2)$$

where \mathbf{u}_a are inputs of actuators and $\mathbf{d}_a(\mathbf{q}, \dot{\mathbf{q}}, \boldsymbol{\tau}_{ext})$ represents disturbance torques to the actuators due to robot movements. $\boldsymbol{\tau}_{ext}$ is an external disturbance torque. It is assumed that we can monitor torques \mathbf{x}_a by measuring the currents in the actuators.

The movements of a person is represented by the states \mathbf{r} . The control objective can therefore be expressed as the desire to drive a part of \mathbf{q} to \mathbf{r} .

B. Adaptive Control Approach

The problem here is that we have to deal with unknowns and uncertainties in the dynamics and parameters of the systems described by (1) & (2). An MRAC scheme based on Lyapunov stability synthesis is proposed for dealing with the issue. Fig. 2. shows the adaptation scheme:

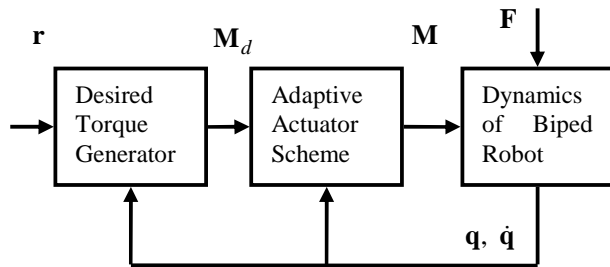


Fig. 2 MRAC scheme for the biped walker.

III. PRELIMINARIES

A. Dynamics of Walking Biped

The bipedal model in this project has five links connected by pin joints as shown in the figure 3.a. One link represents the upper body and two links are for each lower

limb. The biped has two hip joints, two knee joints and two ankles at the tips of the lower limbs. There is an actuator located at each joint and all of the joints are considered rotating only in the sagittal plane. As the system can move freely in the x-y-plane and contains five links, it has seven degrees of freedom. The corresponding seven coordinates are selected according to fig. 3a.

$$\mathbf{q} = [x_o, y_o, \alpha, \beta_L, \beta_R, \gamma_L, \gamma_R]^T \quad (3)$$

The coordinates (x_o, y_o) fix the position of the center of mass of the torso, and the rest of the coordinates describe the joint angles. The link lengths are denoted as (l_0, l_1, l_2) and masses as (m_0, m_1, m_2) . The centers of mass of the links are located at the distances (r_0, r_1, r_2) from the corresponding joints.

The model is actuated with four moments two of them acting between the torso and both thighs and two at the knee joints, which is shown in fig. 3.b.

$$\mathbf{M} = [M_{L1}, M_{R1}, M_{L2}, M_{R2}]^T \quad (4)$$

The walking surface is modeled using external forces that affect both leg tips shown in fig. 3b.

$$\mathbf{F} = [F_{Lx}, F_{Ly}, F_{Rx}, F_{RY}] \quad (5)$$

When the leg should touch the ground, the corresponding forces are switched on to support the leg. As the leg rises, the forces are zeroed.

Using Lagrangian mechanics, the dynamic equations for the biped system can be derived as shown in (1) where

$\mathbf{A}(q) \in \mathcal{R}^{7 \times 7}$ is the inertia matrix and $\mathbf{b}(q, \dot{q}, \mathbf{M}, \mathbf{F}) \in \mathcal{R}^{7 \times 1}$ is a vector containing the right hand sides of the seven partial differential equations. The closed form formulas for both A and b are presented in [1].

B. Computation of Desired Moments

The desired human movement is represented by

$$\mathbf{r} = [\alpha_m \quad \beta_{lm} - \beta_{rm} \quad \gamma_{lm} \quad \gamma_{rm}]^T \quad (6)$$

An output \mathbf{y} is constructed from the biped feedback info \mathbf{q} as

$$\mathbf{y} = [\alpha \quad \beta_l - \beta_r \quad \gamma_l \quad \gamma_r]^T = \mathbf{C}_y \mathbf{q} \quad (7)$$

The desired torque is derived as the output of a controller that operates on the error between \mathbf{r} and \mathbf{y} . That is

$$\mathbf{M}_d(s) = \mathbf{G}_c(s)(\mathbf{r}(s) - \mathbf{y}(s)) \quad (8)$$

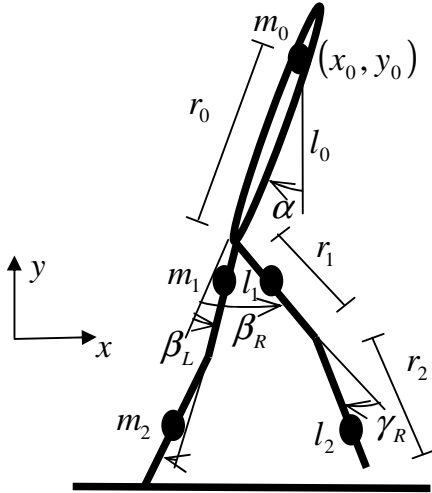


Fig. 3a Biped robot with the corresponding 7 co-ordinates $\mathbf{q} = [x_o, y_o, \alpha, \beta_L, \beta_R, \gamma_L, \gamma_R]^T$.

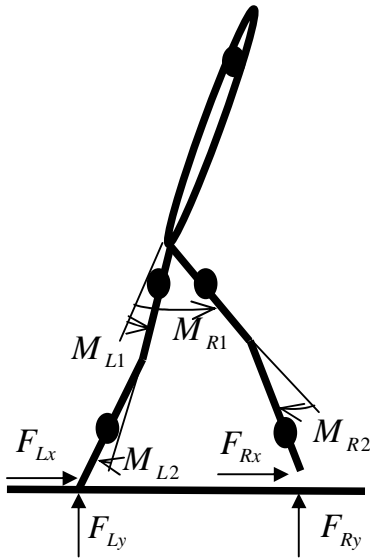


Fig. 3b Biped robot with the moments $M = [M_{L1}, M_{R1}, M_{L2}, M_{R2}]^T$ and the walking surface external forces $F = [F_{Lx}, F_{Ly}, F_{Rx}, F_{Ry}]$.

C. Dynamics of Actuators

We note that the actuator states $\mathbf{x}_a = \mathbf{M}$ are the torques that will drive the biped robot. The goal is to find \mathbf{u}_a such that $\mathbf{M} \rightarrow \mathbf{M}_d$. We assume that dc motors are used as actuators. It follows that (2) can be decoupled into individual motors representing the first-order stator-rotor dynamics (a_{ai}, b_{ai}) that generates output torque (x_{ai}) while subjected to disturbance (d_{ai}) . That is

$$\begin{aligned} \mathbf{x}_a &= [x_{a1} \ x_{a2} \ x_{a3} \ x_{a4}]^T \\ \mathbf{u}_a &= [u_{a1} \ u_{a2} \ u_{a3} \ u_{a4}]^T \\ \mathbf{A}_a &= \text{diag}\{a_{a1}, a_{a2}, a_{a3}, a_{a4}\} \\ \mathbf{B}_a &= \text{diag}\{b_{a1} \ b_{a2} \ b_{a3} \ b_{a4}\}^T \\ \mathbf{d}_a(\mathbf{q}, \dot{\mathbf{q}}, \boldsymbol{\tau}_{ext}) &= [d_{a1} \ d_{a2} \ d_{a3} \ d_{a4}]^T \end{aligned}$$

IV. MODEL REFERENCE ADAPTIVE CONTROL

A. Configuration of MRAC Actuator

The adaptive actuator scheme is shown in Fig 4 below, where the reference model is specified by

$$\dot{\mathbf{x}}_m = \mathbf{A}_m \mathbf{x}_m + \mathbf{B}_m \mathbf{u}_m \quad (9)$$

and the control to the actuator by.

$$\mathbf{u}_a = \mathbf{L} \mathbf{x}_a + \mathbf{N} \hat{\mathbf{u}}_m \quad (10)$$

where , $\mathbf{L} = \text{diag}\{l_1, l_2, l_3, l_4\}$
 $\mathbf{N} = \text{diag}\{n_1, n_2, n_3, n_4\}$

B. Input Estimator

In the MRAC approach, the movements of a person will represent the states \mathbf{r} of the reference model $\dot{\mathbf{x}}_m = \mathbf{A}_m \mathbf{x}_m + \mathbf{B}_m \mathbf{u}_m$. E.g., \mathbf{x}_m might be represented by $[\alpha_m \ \beta_{lm} - \beta_{rm} \ \gamma_{lm} \ \gamma_{rm}]^T$. However, we would not know the input \mathbf{u}_m , which is required for the MRAC. Hence a problem in the approach is to estimate the unknown \mathbf{u}_m knowing \mathbf{x}_m . The unknown \mathbf{u}_m can be represented as the output of an waveform shaping model, i.e.,

$$\begin{aligned} \dot{\mathbf{x}}_u &= \mathbf{A}_u \mathbf{x}_u + \mathbf{w}_u \\ \mathbf{u}_m &= \mathbf{C}_u \mathbf{x}_u \end{aligned} \quad (11)$$

where \mathbf{A}_u & \mathbf{C}_u represents approximate waveform characteristics and \mathbf{w}_u is a sparse & small shaping input.

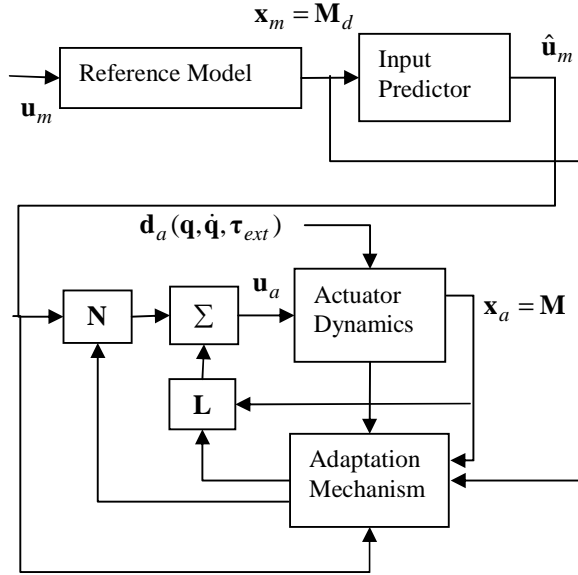


Fig. 4 The MRAC with the input predictor.

E.g., (1) is a so-called $\alpha\beta$ model if $\mathbf{A}_u = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$ &

$\mathbf{C}_u = [1 \ 0]$. The reference model and shaping model can be augmented as

$$\begin{aligned} \dot{\mathbf{x}}_{mu} &= \mathbf{A}_{mu}\mathbf{x}_{mu} + \mathbf{B}_{mu}\mathbf{w}_u \\ \mathbf{x}_m &= \mathbf{C}_{mu}\mathbf{x}_{mu} \end{aligned} \quad (12)$$

where $\mathbf{x}_{mu} = \begin{bmatrix} \mathbf{x}_m \\ \mathbf{x}_u \end{bmatrix}$, $\mathbf{A}_{mu} = \begin{bmatrix} \mathbf{A}_m & \mathbf{B}_m\mathbf{C}_u \\ 0 & \mathbf{A}_u \end{bmatrix}$, $\mathbf{B}_{mu} = \begin{bmatrix} \mathbf{0} \\ \mathbf{I} \end{bmatrix}$

& $\mathbf{C}_{mu} = [\mathbf{I} \ \mathbf{0}]$; $\mathbf{0}$ & \mathbf{I} are null and identity matrix, respectively, of appropriate dimensions. An estimate of the of \mathbf{u}_m can be found using an observer of the form

$$\begin{aligned} \dot{\hat{\mathbf{x}}}_{mu} &= \mathbf{A}_{mu}\hat{\mathbf{x}}_{mu} + \mathbf{K}_{mu}[\mathbf{x}_m - \mathbf{C}_{mu}\hat{\mathbf{x}}_{mu}] \\ \hat{\mathbf{u}}_m &= [\mathbf{0} \ \mathbf{C}_m]\hat{\mathbf{x}}_{mu} \end{aligned} \quad (13)$$

$\hat{\mathbf{u}}_m$ is used as the input to the MRAC as shown in (10)

C. MRAC

The adaptation algorithm in the MRAC adjusts the gains \mathbf{L} and \mathbf{N} based on Lyapunov stability design. In design, we assume that the disturbances are negligible. It follows from the Lyapunov design that the gains $\mathbf{L} = \text{diag}\{l_1, l_2, l_3, l_4\}$ & $\mathbf{N} = \text{diag}\{n_1, n_2, n_3, n_4\}$ are adjusted according to

$$\begin{aligned} l_i &= \frac{1}{b_{ai}q_i} p_i(M_{di} - x_{ai})x_{ai} \\ n_i &= -\frac{1}{b_{ai}r_i} p_i(M_{di} - x_{ai})\hat{u}_{mi} \end{aligned} \quad (14)$$

where we have used the notation

$$\begin{aligned} \mathbf{M}_d &= [m_{d1} \ m_{d2} \ m_{d3} \ m_{d4}]^T \\ \hat{\mathbf{u}}_m &= [\hat{u}_{m1} \ \hat{u}_{m2} \ \hat{u}_{m3} \ \hat{u}_{m4}]^T \end{aligned} \quad (15)$$

D. Analysis of Error Dynamics

In the ensuing analysis we will assume that the $\hat{\mathbf{u}}_m$ generated by the input observer converges to the unknown \mathbf{u}_m . Define the errors \mathbf{e} between the actuator torque $\mathbf{x}_a = \mathbf{M}$ and the desired torque $\mathbf{x}_m = \mathbf{M}_d$ as

$$\mathbf{e} = \mathbf{x}_a - \mathbf{x}_m \quad (16)$$

It can be shown that

$$\begin{aligned} \dot{\mathbf{e}} &= \mathbf{A}_m\mathbf{e} + [\mathbf{A}_a - \mathbf{B}_a\mathbf{L} - \mathbf{A}_m]\mathbf{x}_a \\ &\quad + [\mathbf{B}_aN - \mathbf{B}_m]\hat{\mathbf{u}}_m + \mathbf{d}_a(\mathbf{q}, \dot{\mathbf{q}}, \boldsymbol{\tau}_{ext}) \end{aligned} \quad (17)$$

E. Lyapunov Stability Analysis

Define a candidate for a Lyapunov function as

$$\begin{aligned} v &= \mathbf{e}^T \mathbf{P} \mathbf{e} \\ &\quad + \text{trace}(\mathbf{A}_a - \mathbf{B}_a\mathbf{L} - \mathbf{A}_m)^T \mathbf{Q}(\mathbf{A}_a - \mathbf{B}_a\mathbf{L} - \mathbf{A}_m) \\ &\quad + \text{trace}(\mathbf{B}_aN - \mathbf{B}_m)^T \mathbf{R}(\mathbf{B}_aN - \mathbf{B}_m) \end{aligned} \quad (18)$$

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

$$\begin{aligned} \dot{v} &= \dot{\mathbf{e}}^T \mathbf{P} \mathbf{e} + \mathbf{e}^T \mathbf{P} \dot{\mathbf{e}} \\ &\quad + 2\left(\text{trace}(\mathbf{A}_a - \mathbf{B}_a\mathbf{L} - \mathbf{A}_m)^T \mathbf{Q}(-\mathbf{B}_a\dot{\mathbf{L}})\right) \\ &\quad + 2\left(\text{trace}(\mathbf{B}_aN - \mathbf{B}_m)^T \mathbf{R}(\mathbf{B}_a\dot{\mathbf{N}})\right) \\ &= \mathbf{e}^T \left[\mathbf{P}\mathbf{A}_m + \mathbf{A}_m^T \mathbf{P} \right] \mathbf{e} + 2\mathbf{e}^T \mathbf{A}_m^T \mathbf{d}_a(\mathbf{q}, \dot{\mathbf{q}}, \boldsymbol{\tau}_{ext}) \\ &\quad + 2\left(\text{trace}(\mathbf{A}_a - \mathbf{B}_a\mathbf{L} - \mathbf{A}_m)^T (\mathbf{P}\mathbf{e}\mathbf{x}_a^T + \mathbf{Q}(-\mathbf{B}_a\dot{\mathbf{L}}))\right) \\ &\quad + 2\left(\text{trace}(\mathbf{B}_aN - \mathbf{B}_m)^T (\mathbf{P}\mathbf{e}\hat{\mathbf{u}}_m^T + \mathbf{R}(\mathbf{B}_a\dot{\mathbf{N}}))\right) \end{aligned} \quad (19)$$

From inspection, we choose

$$\begin{aligned} \mathbf{B}_a \dot{\mathbf{L}} &= \mathbf{Q}^{-1} \mathbf{P} \mathbf{e} \mathbf{x}_a^T \\ \mathbf{B}_a \dot{\mathbf{N}} &= -\mathbf{R}^{-1} \mathbf{P} \mathbf{e} \hat{\mathbf{u}}_m^T \end{aligned} \quad (20)$$

so that

$$\dot{\mathbf{v}} = \mathbf{e}^T \left[\mathbf{P} \mathbf{A}_m + \mathbf{A}_m^T \mathbf{P} \right] \mathbf{e} + 2\mathbf{e}^T \mathbf{A}_m^T \mathbf{d}_a(\mathbf{q}, \dot{\mathbf{q}}, \boldsymbol{\tau}_{ext}) \quad (21)$$

We note that expansion of (20) leads to the (14). We next choose an $\mathbf{S} = \mathbf{S}^T > 0$ and solve \mathbf{P} from

$$\mathbf{P} \mathbf{A}_m + \mathbf{A}_m^T \mathbf{P} = -\mathbf{S} \quad (22)$$

We arrive at

$$\dot{\mathbf{v}} = -\mathbf{e}^T \mathbf{S} \mathbf{e} + 2\mathbf{e}^T \mathbf{A}_m^T \mathbf{d}_a(\mathbf{q}, \dot{\mathbf{q}}, \boldsymbol{\tau}_{ext}) \quad (23)$$

where $\dot{\mathbf{v}}$ is negative under the assumption that

$$\mathbf{e}^T \mathbf{S} \mathbf{e} > 2\mathbf{e}^T \mathbf{A}_m^T \mathbf{d}_a(\mathbf{q}, \dot{\mathbf{q}}, \boldsymbol{\tau}_{ext}) \quad (24)$$

or when error is more significant than the effect of disturbance. Hence we claim the overall dynamic system comprising of (17) and (20) has a candidate function that satisfies the Lyapunov stability criterion under condition (24).

V. SIMULATION RESULTS

A. Description of Simulation Test

The proposed control scheme for the 5 link biped model consisting of (1)-(10) and (13)-(14) is simulated. The biped is excited with a walking cycle that is manually developed and provided as the desire human movement \mathbf{r} . This walking cycle is repeated for the subsequent steps for every 1.5 seconds. Biped walking is tested for 3seconds. The desired torques $M_d = [M_{dL1} \ M_{dL2} \ M_{dL3} \ M_{dL4}]^T$ are generated using Eq. (8). Fig.5. shows the output $M = [M_{L1} \ M_{L2} \ M_{L3} \ M_{L4}]^T$ of the adaptive actuator scheme adapting itself with the reference input M_d . The first interval, 0 to 1.5 (s), of Fig. 5.1 to Fig 5.4 shows the adapted torques M oscillates and adjusts to converge to the desired torques M_d . The second interval, 1.5 to 3.0 (s), shows convergence settling smoothly to desired reference. Fig.5.5 illustrates the result of the biped walking behavior from the adapted torques M . Fig. 5.6 plots the height of the biped torso.

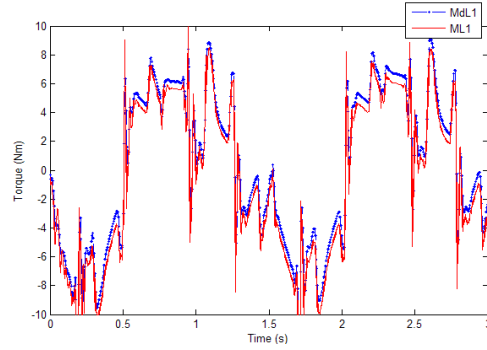


Fig. 5.1 Adaptation of M_{L1} to M_{dL1} .

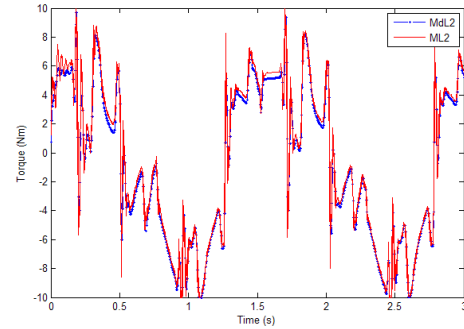


Fig. 5.2 Adaptation of M_{L2} to M_{dL2} .

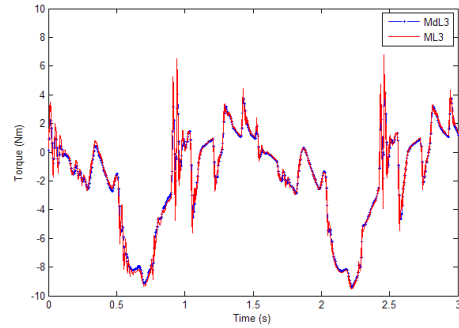


Fig. 5.3 Adaptation of M_{L3} to M_{dL3} .

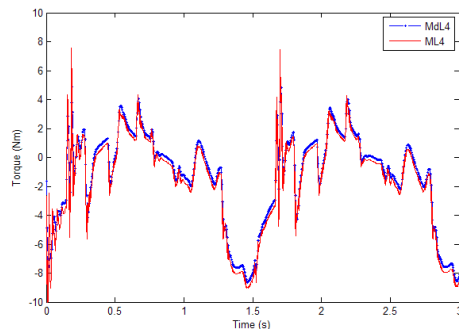


Fig. 5.4 Adaptation of M_{L4} to M_{dL4} .

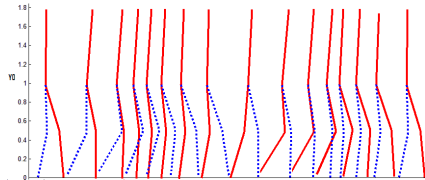


Fig. 5.5 A 2-step simulation of biped walking on the sagittal plane with the Y-axis representing the height of the biped torso y_o .

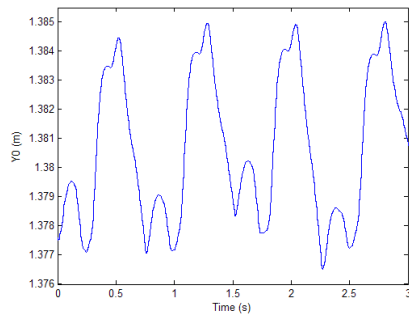


Fig. 5.6 Height of the biped torso y_o .

Equation (2) includes disturbance torques $\mathbf{d}_a(\mathbf{q}, \dot{\mathbf{q}}, \boldsymbol{\tau}_{ext})$ which represents torque feedback and other external moments. This causes the dynamics of the actuator to vary. In the simulation, we disturbed the biped walker by introducing two sharp impulses as shown in Fig. 5.7. Fig. 5.8 shows that the biped recovers from the impact due to the external disturbance.

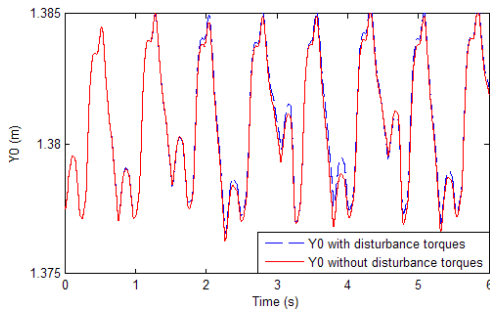


Fig. 5.7 Height of the biped torso with and without disturbance torques $\mathbf{d}_a(\mathbf{q}, \dot{\mathbf{q}}, \boldsymbol{\tau}_{ext})$, simulated over 6 (s).

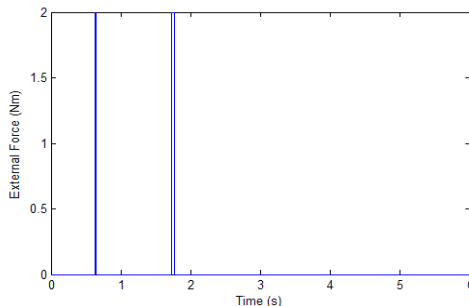


Fig. 5.8 Simulated external disturbance to (2), at $t=0.65(s)$ and $t=1.77(s)$.

VI. CONCLUSIONS

In this paper, we presented an MRAC technique to ensure that the actuators faithfully produce desired torques necessary for a walking robot. An observer was used to predict an anticipated state of the desired torque, thus cause the adaptive actuators to anticipate motion torques. We provided a proof to show that the MRAC scheme results in a stable system in the sense of Lyapunov when errors between the desired and actuator torques are significant. Simulation results verify that the system is robust when tested with various parameters and unknown coefficients. We plan to implement the MRAC scheme for an actual humanoid biped robot to follow the gait of a person in future work.

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