Adaptive Decentralized Control of a Class of Nonlinear interconnected systems

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Summary
In this paper, a completely decentralized adaptive fuzzy control is proposed for a class of interconnected nonlinear systems. The proposed controller does not need to know subsystem dynamics and interconnection's bounds. By combining the fuzzy logic, orthogonal basis functions and sliding mod control technique we propose a new adaptive fuzzy decentralized controller able to approximate unknown subsystems and predict the interconnection terms. Based on Lyapunov stability theorem, the stability of the closed-loop systems is verified and the resultant controller guarantees that all the signals involved are bounded and achieve the H** tracking performance. The simulation results confirm the effectiveness of the proposed control methodology.
Key words:
Decentralized Control System, Interconnected Nonlinear System, Fuzzy basis functions, Orthogonal basis

1. Introduction

Decentralized adaptive control of large–scale interconnected systems has been studied for nearly two decades [8,9] due to its wide applicability in many practical situations, such as large-scale space structures. One essential problem in controlling a large-scale system is how to handle the interactions among different subsystems. An effective approach is to apply the so called decentralized strategy where each subsystem is controlled, independently and separately, by one controller based on local information and with local actions. Usually, parameter uncertainties in a large-scale system require adaptive decentralized techniques[Spooner 96] for which many decentralized adaptive control schemes have been developed, including the model reference adaptive control based on decentralized systems [1] [5] [7], and nonlinear control with a special class of interconnections [3]. Most of the literature on decentralized control is focalized on systems with first order bounded interconnections [4] [5]. The dynamics of subsystems are assumed to be: known nonlinear functions [10], linear with a set of unknown parameters or consider the uncertainties to be contained within the dynamics describing the subsystem interconnections which are bounded.

However, in practice, large-scale systems may contain significant uncertainties, with unknown nonlinear parameters, unknown structures and unknown interconnections. Therefore, traditional adaptive control schemes cannot deal with such complex or ill-defined nonlinear systems. Fuzzy control has found promising applications for a wide variety of industrial systems. Based on the universal approximation capability [2][11], many effective adaptive fuzzy control schemes have been developed to incorporate with human experts knowledge and information in a systematic way. The main advantages of this fuzzy logic based control schemes lie in the fact that the developed controllers can deal with increasingly complex systems and implement controllers without precise knowledge of the model structure of the underlying dynamic system.
In this paper, we design a decentralized fuzzy logic controller for a class of large-scale nonlinear systems with unknown interconnection terms. We exploit the fuzzy systems, orthogonal basis functions and sliding mode control technique to approximate the unknown subsystem and predict on line the unknown interconnections for each subsystem for a class of large-scale systems.
The paper is organized as follow: section 2 describes the problem under investigation; in section 3, we introduce the direct adaptive fuzzy decentralized control. Simulation results are given to demonstrate the effectiveness of the proposed approach in section 4.

2. Problem Formulation

We consider a large-scale nonlinear system composed of N interconnected subsystems:

$$S_i: \quad \begin{cases} \dot{x}_{i,1} = x_{i,2} \\ \vdots \\ \dot{x}_{i,n_i} = f_i(\underline{x}_i) + g_i(\underline{x}_i)u_i + \Delta_i(\underline{x}_1, \underline{x}_2, \ldots, \underline{x}_N) \\ y_i = x_{i,1} \end{cases} \tag{1}$$

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where $\underline{x}_i = [x_{i,1}, x_{i,2}, ..., x_{i,n_i}]^T$, is the n_i-dimensional state vector, $u_i(t) \in \Re$ is the control signal input, $f_i(\underline{x}_i)$ and $g_i(\underline{x}_i)$ are unknown smooth functions and $\Delta_i(\underline{x}) \in \Re$, $i = 1,2,...,N$ are the interconnections among subsystems $i = 1,2,...,N$. The input gain $g_i(\underline{x}_i)$ is assumed to be bounded $0 < g_{0i} \le g_i(\underline{x}_i)$.

The desired output trajectory and its derivative $y_{ri}, \dot{y}_{ri} \ldots, y_{ri}^{(n_i-1)}$ for the i^{th} subsystem S_i are measurable and bounded.

The reference vector is denoted as $\underline{y}_{r,i} = (y_{r,i},\ \dot{y}_{r,i},\ ..., y_{r,i}^{(n_i-1)})^T$

Define the tracking error of the i^{th} subsystem as $e_i = y_{r,i} - y_i$. Then the error vector of the i^{th} subsystem is given by $\underline{e}_i = (e_i,\ \dot{e}_i,\ ..., e_i^{(n_i-1)})^T$ and the one of the large-scale system is given by $\underline{e} = (\underline{e}_1,\ \underline{e}_2,\ ..., \underline{e}_N)^T$.

Define the following filtred error $s_i(t)$ for the i^{th} subsystem:

$$s_i(t) = k_{i,1}e_i(t) + k_{i,2}\dot{e}_i(t) + \ldots k_{i,n_i-1}e_i^{(n_i-2)}(t) + e_i^{(n_i-1)}(t) \tag{2}$$

Where the coefficients $(k_{i,1}, k_{i,2}, \ldots, k_{i,n_i-1})$ are chosen such that all roots of the polynomial $k_{i,1} + k_{i,2}p + \ldots k_{i,n_i-1}p^{(n_i-2)} + p^{(n_i-1)}$ are located inside the left-plane.

Let

$$\upsilon_i = -y_{r,i}^{(n_i)} + k_{i,1}\dot{e}_i(t) + k_{i,2}\ddot{e}_i(t) + \ldots k_{i,n_i-1}e_i^{(n_i-1)}(t) \tag{3}$$

The time derivative of the equation (2) my be written as:

$$\dot{s}_i(t) = f_i(\underline{x}_i) + g_i(\underline{x}_i)u_i + \upsilon_i + \Delta_i(\underline{x}) \tag{4}$$

In the case, that $f_i(\underline{x}_i)$ and $g_i(\underline{x}_i)$ are known and there exist a first derivative of $g_i(\underline{x}_i)$ and $\Delta_i(\underline{x}) = 0$ (each subsystem is isolated), the primary control system should be designed to have the following idealized control law [2003]:

$$\begin{aligned} u_i^* &= -\eta_i s_i - \frac{f_i(\underline{x}_i) + \upsilon_i}{g_i(\underline{x}_i)} + \frac{\dot{g}_i(\underline{x}_i)}{2g_i^2(\underline{x}_i)} s_i \\ &= -\eta_i s_i + u_{d,i}^* \end{aligned} \tag{5}$$

Where $\eta_i > 0$, and assuming that the subsystem tracking error $s_i(t)$ converges to zero asymptotically ($u_{d,i}^*$ is the desired controller). Since $f_i(\underline{x}_i)$ and $g_i(\underline{x}_i)$ in (4) are, in the general case, nonlinear and unknown, $\Delta_i(\underline{x}) \neq 0$ and assumption about the existence of the first derivative of $g_i(\underline{x}_i)$ is more restrictive and can not be verified. It is clear that the ideal controller (5) cannot be used to control interconnected system (1). Then we use fuzzy logic system to approximate the ideal controller.

3. Fuzzy decentralized control

In this study, the nonlinearities of the functions $f_i(\underline{x}_i)$ and $g_i(\underline{x}_i)$ are unknown and $g_i(\underline{x}_i) \neq 0$. The desired controller $u_{d,i}^*$ is not available. In the following, fuzzy systems will be used for approximating the unknown function $u_{d,i}^*$.

$$\begin{aligned} u_{d,i}^* &= -\frac{f_i(\underline{x}_i) + \upsilon_i}{g_i(\underline{x}_i)} + \frac{\dot{g}_i(\underline{x}_i)}{2g_i^2(\underline{x}_i)} s_i \\ &= \psi_i^{*T} \varphi_i(\underline{x}_i) + \varepsilon_i \end{aligned} \tag{6}$$

Where $\psi_i^* = [\psi_{i,1}^*, \psi_{i,2}^{*\ T}, \ldots, \psi_{i,m_i}^{*\ T}]^T$ is the optimal parameter vector, $\varphi_i(\underline{x}_i) = [\varphi_{i,1}(\underline{x}_i), \varphi_{i,2}(\underline{x}_i), \ldots, \varphi_{i,m_i}(\underline{x}_i)]^T$ is a regressive vector with regressor $\varphi_{i,1}(\underline{x}_i)$ ($1 \le l \le m_i$, m_i is the number of rules) which is defined as a fuzzy basis function [11] and ε_i is the approximation error for the i^{th} subsystem.

Assumption 1: on the compact set Ω_{s_i} there exists an ideal constant weight vector ψ_i^* such that the approximation error ε_i is bounded $|\varepsilon_i| \le \varepsilon_{M_i}$ with $\varepsilon_{M_i} > 0$.

Then, the direct adaptive control is designed as:

$$u_i = -\eta_i s_i - \hat{u}_i(\psi_i / \underline{x}_i) + u_{\Delta_i} + u_{c_i} \tag{7}$$

Where $\hat{u}_i(\psi_i / \underline{x}_i) = \psi_i^T \varphi_i(\underline{x}_i)$ is the primary control, u_{Δ_i} and u_{c_i} are auxiliary control compensation terms introduced to compensate the interconnections and approximation error

Substituting (7) into (4) and adding $u_{d,i}^*$ and then subtracting $u_{d,i}^*$ on the right-hand side of (4), one obtains:

$$\dot{s}_i = g_i(\underline{x}_i)[-\eta_i s_i - \tilde{\psi}_i^T \varphi_i(\underline{x}_i) + u_{\Delta_i} + u_{c_i} + \varepsilon_i + \frac{\dot{g}_i(\underline{x}_i)}{2g_i^2(\underline{x}_i)} s_i] + \Delta_i(\underline{x}) \quad (8)$$

Where $\tilde{\psi}_i = \psi_i^* - \psi_i$ is the vector's error parameter.

The optimal vector parameter ψ_i^* is defined as

$$\underline{\psi}_i^* = \arg\min_{\underline{\psi}_i \in \Omega_i} \left\{ \sup_{\underline{x}_i \in \Re^{m_i}} \left| u_{d,i}^* - \psi_i^T \varphi_i(\underline{x}_i) \right| \right\} \quad (11)$$

Where $\Omega_i = \left\{ \underline{\psi}_i / \underline{\psi}_i^T \underline{\psi}_i \leq M_i \right\}$ is the compact set which contains feasible parameter sets for $\underline{\psi}_i^*$. M_i is the designed parameter.

The equation (8) can be written as:

$$\frac{\dot{s}_i}{g_i(\underline{x}_i)} - \frac{\dot{g}_i(\underline{x}_i)}{2g_i^2(\underline{x}_i)} s_i = -\eta_i s_i - \tilde{\psi}_i^T \varphi_i(\underline{x}_i) + u_{\Delta_i} + u_{c_i} + \varepsilon_i + \frac{\Delta_i(\underline{x})}{g_i(\underline{x}_i)} \quad (9)$$

Assumption 2: The problem of interconnection is relaxed by introducing the orthogonal basis functions [6] and we suppose, in the beginning, that the interconnections $\Delta_i(\underline{x})$ can be written as:

$$\left|\Delta_i(\underline{x})\right| = d_{0i} + \sum_{j=1}^{N} q_{ij}(s_j) s_i \quad (10)$$

Where $d_{0i} > 0$ is an unknown constant and the smooth functions $q_{ij}(s_j)$ are also unknown.

The following update laws, for the i^{th} subsystem, are defined as:

The primary adaptive fuzzy controller:

$$\hat{u}_i(\psi_i / \underline{x}_i) = \psi_i^T \varphi_i(\underline{x}_i) \quad (11)$$

$$\dot{\psi}_i = \mu_{\psi_i} \varphi_i(\underline{x}_i) s_i$$

The auxiliary compensators:

$$u_{\Delta_i} = -\Gamma_i^T G_i s_i \quad (12)$$

$$\dot{\Gamma}_i = \mu_{\Gamma_i} G_i s_i^2 \quad (13)$$

$$u_{c_i} = -\pi_i \, sign(s_i) \quad (14)$$

$$\dot{\pi}_i = \mu_{\pi_i} \left| s_i \right| \quad (15)$$

Where $\mu_{\psi_i}, \mu_{\Gamma_i}$ and μ_{π_i} are positive constants.

Theorem:

For the large-scale nonlinear system (1), the direct adaptive fuzzy decentralized control is chosen as (7) with parameter adaptation laws (11)-(15), if assumptions hold, then all the signals in the closed-loop system are bounded and the tracking error s_i converges asymptotically to zero.

Proof:

Consider the following Lyapunov-type function for the i^{th} subsystem:

$$V = \sum_{i=1}^{N} \left(\frac{1}{2} \frac{s_i^2}{g_i(\underline{x}_i)} + \frac{1}{2\mu_{\psi_i}} \tilde{\psi}_i^T \tilde{\psi}_i + \frac{1}{2\mu_{\Gamma_i}} \tilde{\Gamma}_i^T \tilde{\Gamma}_i + \frac{1}{2\mu_{\pi_i}} \tilde{\pi}_i^T \tilde{\pi}_i \right) \quad (16)$$

The derivative of V is:

$$\dot{V} = \sum_{i=1}^{N} \left(\left(\frac{\dot{s}_i}{g_i(\underline{x}_i)} - \frac{\dot{g}_i(\underline{x}_i)}{2g_i^2(\underline{x}_i)} s_i \right) s_i + \frac{1}{\mu_{\psi_i}} \tilde{\psi}_i^T \dot{\tilde{\psi}}_i + \frac{1}{\mu_{\Gamma_i}} \tilde{\Gamma}_i^T \dot{\tilde{\Gamma}}_i + \frac{1}{\mu_{\pi_i}} \tilde{\pi}_i^T \dot{\tilde{\pi}}_i \right) \quad (17)$$

Substituting (9) into (17) and applying (11), (12), yields

$$\dot{V} \leq \sum_{i=1}^{N} \left(-\eta_i s_i^2 - \Gamma_i^T G_i s_i^2 + u_{c_i} s_i + \varepsilon_i s_i + \frac{\left|\Delta_i(\underline{x})\right|}{g_i(\underline{x}_i)} \left| s_i \right| + \frac{1}{\mu_{\Gamma_i}} \tilde{\Gamma}_i^T \dot{\tilde{\Gamma}}_i + \frac{1}{\mu_{\pi_i}} \tilde{\pi}_i^T \dot{\tilde{\pi}}_i \right) \quad (18)$$

By using the assumption 2 and the fact that $2ab \leq a^2 + b^2$ the equation (18) can be written as:

$$\dot{V} \leq \sum_{i=1}^{N} \left(-\eta_i s_i^2 - \Gamma_i^T G_i s_i^2 + u_{c_i} s_i + \left(\left|\varepsilon_i\right| + \frac{d_{0i}}{g_{i0}(\underline{x}_i)} \right) \left| s_i \right| + \left[\frac{1}{2g_i^2(\underline{x}_i)} + \frac{1}{2} \sum_{j=1}^{N} q_{ij}^2(s_j) \right] s_i^2 + \frac{1}{\mu_{\Gamma_i}} \tilde{\Gamma}_i^T \dot{\tilde{\Gamma}}_i + \frac{1}{\mu_{\pi_i}} \tilde{\pi}_i^T \dot{\tilde{\pi}}_i \right) \quad (19)$$

Let $\Lambda_i = \frac{1}{2g_i^2(\underline{x}_i)} + \frac{1}{2} \sum_{j=1}^{N} q_{ij}^2(s_j)$ which is approximated by

$$\Lambda_i = \Gamma_i^{*T} G_i + \xi_{\Lambda_i} \quad (20)$$

G_i is the orthogonal basis vector and ξ_{Λ_i} is the bounded function approximation error , i.e., $\left|\xi_{\Lambda_i}\right| \leq \xi_{M_i}$ (ξ_{M_i} is known positive constant).

The weights Γ_i^* are unknown and need to be estimated using the above approximation

Substituting u_{c_i} in (14) into (19), yields.

$$\dot{V} \leq \sum_{i=1}^{N} (-\eta_i s_i^2 + (\varepsilon_{M_i} + \frac{d_{0i}}{g_{i0}(\underline{x}_i)} - \pi_i)|s_i| + \tilde{\Gamma}_i^T G_i s_i^2 + \xi_{M_i} s_i^2 + \frac{1}{\mu_{\Gamma_i}} \tilde{\Gamma}_i^T \dot{\tilde{\Gamma}}_i + \frac{1}{\mu_{\pi_i}} \tilde{\pi}_i^T \dot{\tilde{\pi}}_i) \qquad (21)$$

With $\tilde{\Gamma}_i = \Gamma_i^* - \Gamma_i$ and $\tilde{\pi}_i = \pi_i^* - \pi_i$ with adaptation laws (13) and (15), $\dot{V}$ is given by

$$\dot{V} \leq \sum_{i=1}^{N} (\xi_{M_i} - \eta_i) s_i^2 \qquad (22)$$

To assure the stability of all subsystems we choose $\eta_i > \xi_{M_i} > 0$

Thus, the solutions, s_i, ψ_i, Γ_i and π_i are bounded.

Since V is a positive function definite and

$$\int_0^\infty \dot{V} dt < -\int_0^\infty (\xi_{M_i} - \eta_i) s_i^2 dt \qquad (23)$$

$$\int_0^\infty (\xi_{M_i} - \eta_i) s_i^2 dt < -\int_0^\infty \dot{V} dt = V(0) - V(\infty) < \infty$$

This implies that $s_i \in L_2$, then by Barbalat's Lemma $\lim_{t \to \infty} s_i = 0$.

4. Simulation

Within this section, we will present an illustrative example. Consider two inverted pendulums connected by a spring [14]. Each pendulum may be positioned by a torque input u_i applied by a servomotor at its base. It is assumed that both ϕ_i and $\dot{\phi}_i$ (angular position and rate) are available to the i^{th} controller for $i = 1,2$ .Fig.1.

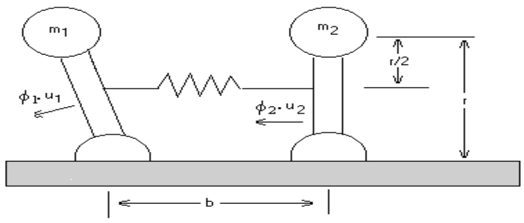

Fig. 1 Two inverted pendulums connected by a spring.

Fig1. Two inverted pendulums connected by a spring.

The equations which describe the motion of the pendulums are defined by:

$$\dot{x}_{11} = x_{12}, \dot{x}_{12} = (\frac{m_1 gr}{j_1} - \frac{kr^2}{4j_1})\sin(x_{11}) + \frac{kr}{2j_1}(l-b) + \frac{u_1}{j_1} + \frac{kr^2}{4j_1}\sin(x_{21}) \qquad (24)$$

$$\dot{x}_{21} = x_{22}, \dot{x}_{22} = (\frac{m_2 gr}{j_2} - \frac{kr^2}{4j_2})\sin(x_{21}) + \frac{kr}{2j_2}(l-b) + \frac{u_2}{j_2} + \frac{kr^2}{4j_2}\sin(x_{12}) \qquad (25)$$

where $x_{11} = \phi_1$ and $x_{21} = \phi_2$ are the angular displacements of the pendulums from vertical. The parameters $m_1 = 2kg$ and $m_2 = 2.5kg$ are the pendulum end masses, $j_1 = 0.5kg$ and $j_2 = 0.625kg$ are the moments of inertia, the constant of the connecting spring is $k = 100N/m$, the pendulum height is r=0.5m, the natural length of the spring is $l = 0.5m$ and the gravitational acceleration is $g = 9.81m/s^2$. The distance between the pendulum hinges is defined as $b = 0.4m$ (with $b < l$ in this example, so that the pendulum links repel each other when both are in the upright position.

The subsystems described with the equations (24) and (25) can be rewritten as (1).

In (24),

$$f_2(\underline{x}_2) = (\frac{m_1 gr}{j_1} - \frac{kr^2}{4j_1})\sin(x_{11}) + \frac{kr}{2j_1}(l-b)$$

$$g_2(\underline{x}_2) = \frac{1}{j_1} \text{ and } \Delta_2(\underline{x}) = \frac{kr^2}{4j_1}\sin(x_{21})$$

In (25)

$$f_2(\underline{x}_2) = (\frac{m_2 gr}{j_2} - \frac{kr^2}{4j_2})\sin(x_{21}) + \frac{kr}{2j_2}(l-b)$$

$$g_2(\underline{x}_2) = \frac{1}{j_2} \text{ and } \Delta_2(\underline{x}) = \frac{kr^2}{4j_2}\sin(x_{12})$$

The proposed fuzzy decentralized controller given by (7) is used:

$$u_i = -\eta_i s_i - \psi_i^T \varphi_i(\underline{x}_i) + -\Gamma_i^T G_i s_i + -\pi_i sign(s_i) \qquad (26)$$

Where ψ_i, Γ_i and π_i are updated by (11),(13) and (15) respectively.

Here we will attempt to drive the angular positions to zero, so that $e_i = -\phi_i$ (i.e., $y_{1r} = y_{2r} = 0$) for $i = 1,2$

To construct the fuzzy approximators $W_i(\underline{x}_i, \underline{\theta}_i)$, we define three fuzzy sets for the component of each $\underline{x}_1 = (x_{11}, x_{12})$ and $\underline{x}_2 = (x_{21}, x_{22})$ with labels $A^1_{x_{ij}}$, …, $A^5_{x_{ij}}$ ($j = 1,2$ and $i = 1,2$) characterized by:

$$\mu_{A^1_{x_{ij}}}(x_{ij}) = \exp(-(x_{ij} + 0.8)^2)$$

$$\mu_{A^2_{x_{ij}}}(x_{ij}) = \exp(-(x_{ij} + 0.4)^2)$$

$$\mu_{A^3_{x_{ij}}}(x_{ij}) = \exp(-(x_{ij})^2)$$

$$\mu_{A^4_{x_{ij}}}(x_{ij}) = \exp(-(x_{ij} - 0.4)^2)$$

$$\mu_{A^5_{x_{ij}}}(x_{ij}) = \exp(-(x_{ij} - 0.8)^2)$$

Defining 25 fuzzy rules in the following linguistic description:

$R_i^{(l)}$: *if* x_{i1} *is* $A^{j_1}_{x_{i1}}$ *and* x_{i2} *is* $A^{j_2}_{x_{i2}}$ *then* y_i^l *is* C_i^l T he initial conditions are chosen as: $(x_{11}, x_{12}, x_{21}, x_{22})^T = (0,0,0,0)^T$,

$\psi_1(0) = \psi_2(0) = zeros(9,1)$ $\pi_1 = \pi_2 = 0$ and $\Gamma_i = [0\ 0\ 0]$. The controller parameters are taken as $k_{i,1} = k_{i,2} = 1$, $\mu_{\psi_i} = \mu_{\Gamma_i} = \mu_{\pi_i} = 0.1$ *and*

$K_1 = K_2 = 5.$

Fig. 2 shows the simulation results for the designed controller. The proposed approach achieves good control.

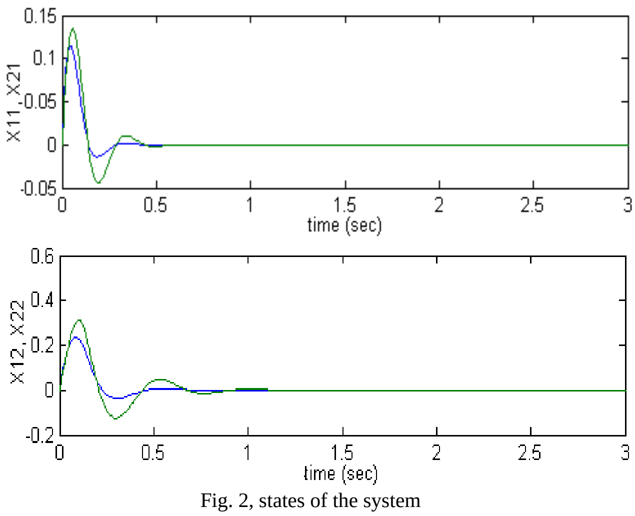

Fig. 2, states of the system

5. Conclusion

In this work, we have presented an adaptive fuzzy decentralized control for a class of large-scale nonlinear systems with unknown interconnection terms. In the proposed method, fuzzy logic is used to approximate the unknown part of the subsystem and the interconnection terms are predicted by projecting them onto orthogonal basis. The adaptive control laws are derived from the Lyapunov analysis which ensures that the semi-global stability results are obtained and tracking error converges to zero.

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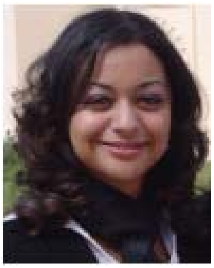

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