

Adaptive Dynamic Programming based Integral Sliding Mode Control Law for Continuous-Time Systems: A Design for Inverted Pendulum Systems

Dao Phuong Nam, Nguyen Van Huong, and Do Trong Tan

School of Electrical Engineering, Hanoi University of Science and Technology, Hanoi, Vietnam

Email: nam.daophuong@hust.edu.vn, huong.nguyenvan2102@gmail.com

Abstract—This work presents an adaptive optimal control algorithm-based integral sliding mode control law for a class of continuous-time systems with input disturbance or uncertain and unknown parameters. The primary objective is to find a general form of integral sliding mode control law can assure that the system states are forced to reach a sliding surface in a finite time. Then, an adaptive optimal control based on the adaptive dynamic programming method is responsible for the robust stability of the closed-loop system. Finally, the theoretical analysis and simulation results demonstrate the performance of the proposed algorithm for an inverted pendulum system.

Index Terms—adaptive dynamic programming, Integral sliding mode control, Robust control, Unknown system dynamics, Inverted pendulum

I. INTRODUCTION

Your Sliding mode control was first proposed in the early 1950s (Utkin, 1977, 1992; Pisano and Usai, 2011), and many studies about the sliding mode control method have been published in recent years (Man and Yu, 1997; Drakunov, 1992; Ting et al., 2012). The most positive feature of sliding mode control consists of the complete compensation of the so-called matched disturbances (i.e. disturbances acting on the control input channel) when the system is in the sliding phase, and a sliding mode is enforced. The latter takes place when the state is on a suitable subspace of the state space, called sliding manifold.

The integral sliding mode (ISM) technique was first proposed in [1], [2] as a solution to the reaching phase problem for systems with matched disturbances only. The ISM has found many applications in industrial processes like robots and electromechanical systems, [6], [7]. To avoid the phase and let robustness from the initial time, the concept of ISM has been introduced [3], [4], [5].

In this paper, we propose the combined idea of adaptive dynamic programming and ISM control for introducing controllers for unknown systems. At that

time, besides our concern for system stability, we also pay attention to the bound of the cost function that other articles have been not mentioned.

II. PROBLEM STATEMENTS

We study a class of continuous-time systems described by:

$$\dot{x} = Ax + B(u + f(x, u, t)) \quad (1)$$

Where $x \in \mathbb{R}^n$ is the measured component of the state available for feedback control and $u \in \mathbb{R}^m$ ($m \leq n$) is the input. Suppose that $A \in \mathbb{R}^{n \times n}$ is an unknown constant matrix and $f(x, u, t) \in \mathbb{R}^m$ is the disturbance or/and uncertain of system.

The control objective is to find an adaptive optimal control based ISM control law ensures that that the closed-loop system (1) is robustly stable and the cost function $J = \int_0^{\infty} (x^T Q x + u^T R u) d\tau$ is bounded with Q, R are the symmetric definite matrices $Q \geq 0, R > 0$.

Assumption 1: The matrix B has linearly independent columns, i.e. $rank(B) = m$.

Assumption 2: There exists a constant value $\rho > 0$, a continuous function $\mu(\cdot)$ and a continuous function $\lambda(t)$ such that $0 < \lambda(t) < 1; \forall t$, and the disturbance and uncertain of system satisfied:

$$\|f(x; u; t)\| < \rho + \mu(\|x(t)\|) + \lambda(t)\|u\|$$

We define B^+ as the Moore–Penrose pseudoinverse of matrix B . By **assumption 1**, B^+ can be computed as: $B^+ = (B^T B)^{-1} B^T$.

Assumption 3: There exists a number $\sigma > 0$ such that: $\|MA\| < \sigma$, where $M = B^+ = (B^T B)^{-1} B^T$.

III. CONTROL DESIGN

Define the sliding mode $S(t)$ as follows:

$$S(t) = \{x \in \mathbb{R}^n : s(t) = 0\} \quad (2)$$

Where $s(t)$ is defined as:

$$s(t) = Mx - \int_0^t v(\tau) d\tau \quad (3)$$

with v is later designed.

Theorem 1: The control signal $u = v - k(t) \frac{s}{\|s\|}$, with:

$$k(t) = \frac{1}{1 - \lambda(t)} (\rho + \mu(\|x\|) + \sigma\|x\| + \lambda(t)\|v(t)\| + c) \quad (4)$$

and c is a positive constant, can be guaranteed that the system states are forced to reach the sliding surface at time $t_s < \infty$.

Proof:

The time derivative of (3) given by:

$$\begin{aligned} \dot{s} &= B^T B^T (Ax + B(u + f)) - v(t) \\ \dot{s} &= MAX + (u + f) - v \end{aligned} \quad (5)$$

It follows from **assumption 2**, we have:

$$\begin{aligned} (1 - \lambda)k(t) &= (\rho + \mu(\|x(t)\|) + \sigma\|x(t)\| + \lambda\|v(t)\| + c) \\ \Rightarrow k(t) &= \rho + \mu(\|x(t)\|) + \lambda(\|v(t)\| + k(t)) + \sigma\|x(t)\| + c \\ \Rightarrow k(t) &> \rho + \mu(\|x(t)\|) + \lambda(\|u(t)\|) + \|MA\|\|x(t)\| + c \\ \Rightarrow k(t) &> \|f(x, u, t)\| + \|MA\|\|x(t)\| + c \end{aligned} \quad (6)$$

We consider a Lyapunov function candidate:

$$V = \frac{1}{2} s^T s \quad (7)$$

The derivative of V is computed as:

$$\begin{aligned} \dot{V} &= s^T \dot{s} = s^T [MAX + (u + f) - v] \\ \dot{V} &= s^T \cdot \left[MAX + \left(v - k(t) \frac{s}{\|s\|} + f \right) - v \right] \\ \dot{V} &= s^T (MAX + f) - k(t)\|s\| \\ \dot{V} &\leq \|s\|(\|MA\|\|x\| + \|f\|) - k(t)\|s\| \\ \dot{V} &< -c\|s\| = -cV^{1/2} \end{aligned} \quad (8)$$

Integrating (8) over the time interval $0 \leq \tau \leq t$ we obtain:

$$V^{1/2}(t) - V^{1/2}(0) \leq -\frac{1}{2} ct$$

Consequently, $V(t)$ can reach zero in a finite time t_s , that is bounded by:

$$t_s \leq \frac{2V^{1/2}(0)}{c}$$

When $s = \dot{s} = 0$, from (5) we have:

$$u_{eq} + f(x, u_{eq}, t) = -MAX + v$$

The system can be rewritten:

$$\begin{aligned} \dot{x} &= Ax + B(-MAX + v) = (A - BMA)x + Bv \\ \dot{x} &= \bar{A}x + \bar{B}v \end{aligned} \quad (9)$$

where $\bar{A} = A - BMA; \bar{B} = B$.

Remark 1: It is necessary to ensure that the time of convergence of sliding surface is finite. The fact is described based on the following example:

We consider the system as follows:

$$\begin{cases} \frac{dx}{dt} = Ax + Bs \\ \frac{ds}{dt} = Cx + Ds \end{cases}$$

where: $A \in \mathbb{R}^{n \times n}, B \in \mathbb{R}^{n \times r}, C \in \mathbb{R}^{r \times n}, D \in \mathbb{R}^{r \times r}$, s is the sliding surface. Selecting A is Hurwitz matrix and $\begin{bmatrix} A & B \\ C & D \end{bmatrix}$ is not Hurwitz matrix. We obtain that although s converges to zero in infinite time, x does not converge to zero.

Theorem 2: Let K_0 be any matrix such that $\bar{A} - \bar{B}K_0$ is Hurwitz, and repeat the following steps for $k = 0, 1, \dots$

Step 1: Solve for the real symmetric positive definite solution P_k of the Lyapunov equation:

$$\bar{A}_k^T P_k + P_k \bar{A}_k + Q + K_k^T R K_k = 0 \quad (10)$$

where $\bar{A}_k = \bar{A} - \bar{B}K_k$.

Step 2: Update the matrix by:

$$K_{k+1} = R^{-1} \bar{B}^T P_k \quad (11)$$

Then, the following properties hold:

- (1) $\bar{A} - \bar{B}K_k$ is Hurwitz
- (2) $P^* \leq P_{k+1} \leq P_k$
- (3) $\lim_{k \rightarrow \infty} K_k = K^*; \lim_{k \rightarrow \infty} P_k = P^*$

with $K^* = R^{-1} \bar{B}^T P^*$ and P^* is a unique symmetric, positive, definite matrix such that:

$$\bar{A}^T P^* + P^* \bar{A} + Q - P^* \bar{B} R^{-1} \bar{B}^T P^* = 0 \quad (12)$$

Now, we find an approximate optimal control policy by using the online measurements of the closed-loop system (9).

$$\text{We consider that: } V(x) = x^T P_k x \quad (13)$$

So, we have:

$$\begin{aligned} x(t+T)^T P_k x(t+T) - x(t)^T P_k x(t) &= \int_t^{t+T} \dot{V}(x(\tau)) d\tau \\ &= \int_t^{t+T} x^T (\bar{A}_k^T P_k + P_k \bar{A}_k) x + 2(\bar{B}^T (v_0 + K_k x))^T P_k x d\tau \end{aligned}$$

$$= \int_t^{t+T} \left[-x^T (Q + K_k^T R K_k) x + 2(v_0 + K_k x)^T \bar{B}^T P_k x \right] d\tau \quad (14)$$

Applying

Kronecker product representation gives:

$$\left(x(t_{j+1,k})^T \otimes x(t_{j+1,k})^T - x(t_{j,k})^T \otimes x(t_{j,k})^T \right) \text{vec}(P_k) = \int_{t_{j,k}}^{t_{j+1,k}} \begin{bmatrix} -(x^T \otimes x^T) \text{vec}(Q + K_k^T R K_k) \\ +2(x^T \otimes v_0^T)(\bar{B} \otimes I) \text{vec}(P_k) \\ +2(x^T \otimes x^T)(\bar{B} K_k \otimes I) \text{vec}(P_k) \end{bmatrix} d\tau$$

Define:

$$I_1(t_{j,k}) = x(t_{j+1,k})^T \otimes x(t_{j+1,k})^T - x(t_{j,k})^T \otimes x(t_{j,k})^T$$

$$I_2(t_{j,k}) = 2 \int_{t_{j,k}}^{t_{j+1,k}} (x^T \otimes v_0^T)(\bar{B} \otimes I) d\tau$$

$$I_3(t_{j,k}) = 2 \int_{t_{j,k}}^{t_{j+1,k}} (x^T \otimes x^T)(\bar{B} K_k \otimes I) d\tau$$

$$I(t_{j,k}) = I_1(t_{j,k}) - I_2(t_{j,k}) - I_3(t_{j,k})$$

$$J(t_{j,k}) = - \int_{t_{j,k}}^{t_{j+1,k}} (x^T \otimes x^T) \text{vec}(Q + K_k^T R K_k) d\tau$$

Consequently, we have:

$$\begin{bmatrix} I(t_{1,k}) \\ I(t_{2,k}) \\ \vdots \\ I(t_{s,k}) \end{bmatrix} \text{vec}(P_k) = \begin{bmatrix} J(t_{1,k}) \\ J(t_{2,k}) \\ \vdots \\ J(t_{s,k}) \end{bmatrix}$$

$$\text{So } \Phi_k \text{vec}(P_k) = \Psi_k \quad (15)$$

with:

$$\Phi_k = \begin{bmatrix} I(t_{1,k}) \\ I(t_{2,k}) \\ \vdots \\ I(t_{s,k}) \end{bmatrix}; \Psi_k = \begin{bmatrix} J(t_{1,k}) \\ J(t_{2,k}) \\ \vdots \\ J(t_{s,k}) \end{bmatrix}$$

Assumption 4: There exists a number $s > 0$ such that Φ_k has full column rank for all $k \in \mathbb{Z}^+$.

By using **assumption 4**, P_k can be uniquely determined by:

$$\text{vec}(P_k) = (\Phi_k^T \Phi_k)^{-1} \Phi_k^T \Psi_k \quad (16)$$

Algorithm 1:

(1) Select K_0 such that $\bar{A} - \bar{B}K_0$ is Hurwitz and a threshold $\nu > 0$. Let $k \rightarrow 0$.

repeat

(2) Solve P_k from (16)

(3) Update K_{k+1} by using (11).

$k \leftarrow k + 1$

until $\|P_k - P_{k+1}\| < \nu$

$k^* \leftarrow k$

We obtain the approximated optimal control policy:

$$v = -K_{k^*} x$$

Lemma 1: Under **assumption 4**, by using **algorithm 1**, we have $\lim_{k \rightarrow \infty} K_k = K^*$; $\lim_{k \rightarrow \infty} P_k = P^*$.

Proof:

From (13),(14) one can see that the $(P_k; K_{k+1})$ obtained from (10),(11) must satisfy the condition(14),(15). In addition, by **assumption 4**, it is unique determined by (16). Therefore, from **theorem 2**, we obtain that $\lim_{k \rightarrow \infty} K_k = K^*$; $\lim_{k \rightarrow \infty} P_k = P^*$.

Lemma 2: There exists a sufficiently small constant $\varepsilon > 0$ such that for all symmetric matrix $P > 0$ satisfying $\|P - P^*\| < \varepsilon$ the system (9) can be stable by $u = -R^{-1} \bar{B}^T P x$.

Proof:

Because $Q + P^* \bar{B} R^{-1} \bar{B}^T P^* > 0$, there exists $\alpha > 0$ such that $Q + P^* \bar{B} R^{-1} \bar{B}^T P^* > \alpha I$. For any symmetric matrix $P > 0$ we have:

$$\bar{A}^T P + P \bar{A} + \bar{Q} - P \bar{B} R^{-1} \bar{B}^T P = 0$$

where:

$$(\bar{Q} + P \bar{B} R^{-1} \bar{B}^T P) = (Q + P^* \bar{B} R^{-1} \bar{B}^T P^*) + (P^* - P) \bar{A} + \bar{A}^T (P^* - P) + 2(P \bar{B} R^{-1} \bar{B}^T P - P^* \bar{B} R^{-1} \bar{B}^T P^*)$$

Because of continuity, there exists a sufficiently small constant $\varepsilon > 0$ such that for all symmetric matrix $P > 0$ satisfying $\|P - P^*\| < \varepsilon$ we have:

$$\bar{Q} + P \bar{B} R^{-1} \bar{B}^T P > Q + P^* \bar{B} R^{-1} \bar{B}^T P^* - \alpha I > 0$$

We consider the Lyapunov function $V = \frac{1}{2} x^T P x$, we have:

$$\begin{aligned} \dot{V} &= x^T \left((\bar{A} - \bar{B} R^{-1} \bar{B}^T P)^T P + P (\bar{A} - \bar{B} R^{-1} \bar{B}^T P) \right) x \\ \dot{V} &= -x^T (\bar{Q} + P \bar{B} R^{-1} \bar{B}^T P) x \end{aligned}$$

From $\bar{Q} + P \bar{B} R^{-1} \bar{B}^T P > 0$ so the system(9) is globally asymptotically stabilises.

Theorem 3: The feedback control designed from **theorem 1** and **algorithm 1** can make sure that the closed-loop system (1) is robustly stable and the cost

function $J = \int_0^\infty (x^T Q x + u^T R u) d\tau$ is bounded.

Proof:

From **theorem 1**, the system states are forced to reach a sliding surface in a finite time. When on the sliding surface, the control designed by **algorithm 1** can make the system is globally stable. Therefore, the closed-loop system (1) is robustly stable.

Moreover, by continuity we infer that:

$$J = \int_0^\infty (x^T Q x + u^T R u) d\tau$$

$$J = \int_0^{t_s} (x^T Qx + u^T Ru) d\tau + \int_{t_s}^{\infty} (x^T Qx + v^T Rv) d\tau$$

$$J < \Omega + \int_0^{\infty} (x^T Qx + v^T Rv) d\tau$$

where:

$$\Omega = t_s \left(\lambda_{\max}(Q) \max_{0 \leq t \leq t_s} \|x\|^2 + \lambda_{\max}(R) \max_{0 \leq t \leq t_s} \|u\|^2 \right)$$

Due to the relation $v = -K_k^* x \approx K^* x$, there exists a positive number β such that $J < \beta$.

IV. SIMULATION

TABLE I. PARAMETERS AND VARIABLES OF AN INVERTED PENDULUM SYSTEM

M	Weight of car	0.5	kg
m	Weight of link	0.2	kg
B	Friction coefficient	0.1	Ns / m
L	½ length of link	0.3	m
I	Inertial moment of link	0.006	kg.m ²
G	Gravity	9.8	m / s ²

In this section, we apply the proposed an adaptive optimal control based ISM control law to an inverted pendulum on a cart described as (17) and Table 1. Fig. 1 and Fig. 2 show the control and states of system using theorem 1 and algorithm 1. On the other hand, Fig. 3 and Fig. 4 show the control and states of system when algorithm 1 has not been used. Fig. 5 and Fig. 6 show the convergence of matrix P and K of proposed algorithm 1, and the tracking errors converge to zero.

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dot{\phi} \\ \ddot{\phi} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & \frac{-(I+ml^2)b}{I(M+m)+Mml^2} & \frac{m^2gl^2}{I(M+m)+Mml^2} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{-mlb}{I(M+m)+Mml^2} & \frac{mgl(M+m)}{I(M+m)+Mml^2} & 0 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ \phi \\ \dot{\phi} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{I+ml^2}{I(M+m)+Mml^2} \\ 0 \\ \frac{ml}{I(M+m)+Mml^2} \end{bmatrix} u$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \end{bmatrix} u$$

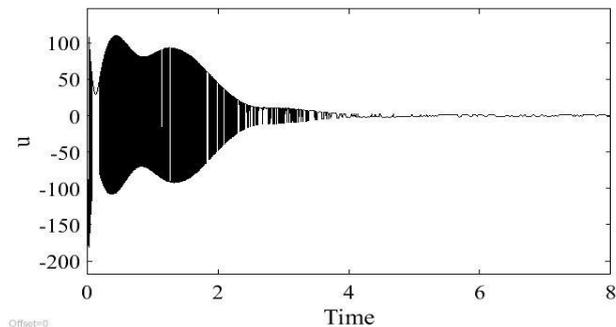


Figure 1. The control input

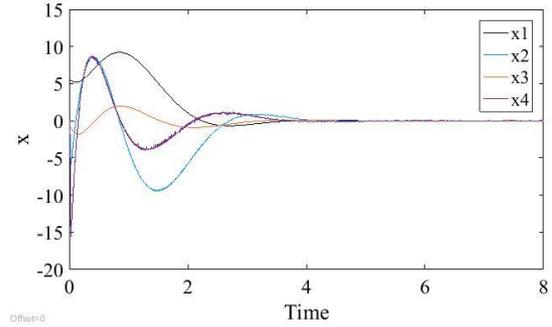


Figure 2. The states of system

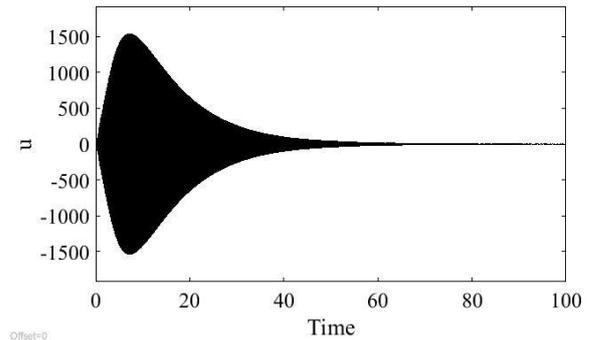


Figure 3. The control input

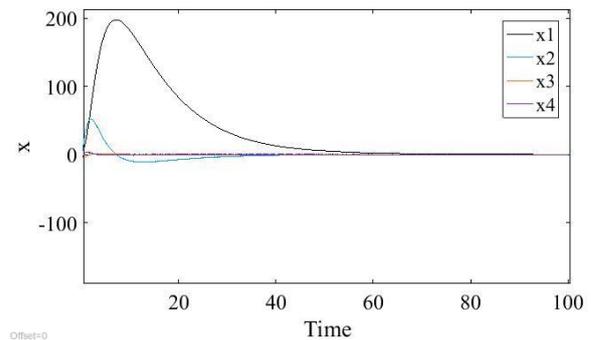


Figure 4. The states of system

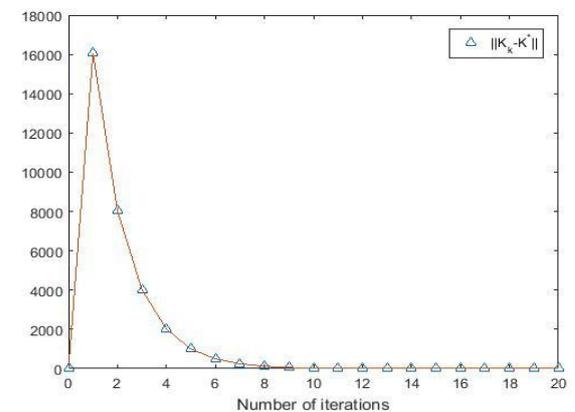


Figure 5. The convergence of proposed algorithm

V. CONCLUSION

This paper presents an adaptive optimal control algorithm-based ISM control law for continuous-time

systems with unknown system dynamics and external disturbance. The proposed algorithm pointed out the robust stability of system and the bound of cost function. The theory analysis and simulation results illustrate the effectiveness of proposed algorithm.

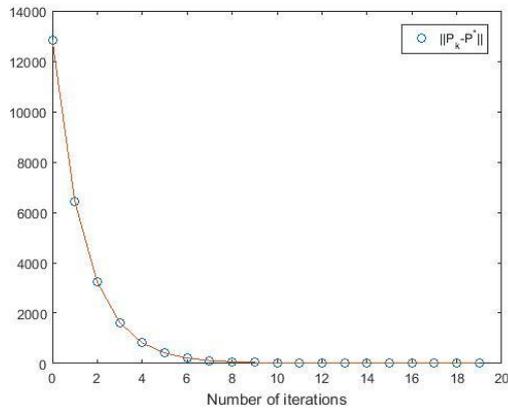


Figure 6. The convergence of proposed algorithm

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the constructive and insightful comments of reviewers to further improve the quality of this paper. This work is supported in part by the Hanoi University of Science and Technology (T2017-PC-105).

REFERENCES

[1] G. P. Matthews and R. A. DeCarlo, "Decentralized tracking for a class of interconnected nonlinear systems using variable structure control," *Automatica*, vol. 24, pp. 187–193, 1988.

[2] V. Utkin and J. Shi, "Integral sliding mode in systems operating under uncertainty conditions," in *Proc. 35th IEEE Conf. Decision Control*, Kobe, Japan, pp. 4591–4596, Dec. 1996

[3] In-Cheol Baik, Kyeong-Hwa Kim and Myung-Joong Youn "Robust nonlinear speed control of PM synchronous motor using boundary layer integral sliding mode control technique" *IEEE Transactions on Control Systems Technology*, vol 8, no.1, Jan 2000.

[4] M. Taleb et al., "High order integral sliding mode control with gain adaptation," *European Control Conference*, Zürich, Switzerland, 2013.

[5] C. C. Feng, "Integral sliding-based robust control, recent advances in robust control—novel approaches and design methods," Dr. Andreas Mueller (Ed.), ISBN: 978-953-307-339-2, InTech.

[6] J. K. Lin et al, "Integral sliding mode control and its application on Active suspension System," in *Proc. 4th International Conference on Power Electronics Systems and Applications*, Hong Kong, 2011.

[7] V. I Utkin. et al., "Sliding mode control in electro mechanical systems (second edition)," *CRC Press*, Boca Raton, 2009.



Ph.D. Phuong Nam Dao obtained Doctor degree in January 2013 at Hanoi University of Science and Technology (Vietnam).

Currently, he holds the position as lecturer at Hanoi University of Science and Technology, Vietnam. His research interests include control of robotic systems and robust/adaptive, optimal control.

He is the author/co-author of more than 70 papers (Journals, Conferences,...)



Nguyen Van Huong:

Place of birth: Hai Duong, Viet Nam.

Date of birth: 02/21/1995.

Nguyen Van Huong received a B.S. degree in Electronic Engineering in 2018 from the Hanoi University of Science and Technology, Vietnam. Presently, he works in research lines such as robotics, electric power systems and control systems.