BUILDING UP A REPETITIVE CONTROL LAW (RCL) WITH DESIRED TRAJECTORY PERIODIC SO REDUCED ONLINE COMPUTATION FOR ROBOT ALMEGA 16

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ABSTRACT

This paper presents a build of Repetitive Control Law with desired trajectory periodic in joint space so reduced on-line computation for the motion system of the Almega16 manipulator. In a Repetitive Control Law always has the desired cycle trajectory with time T and always provides state information update on the time-variant parameters. The true value is compared to the reference set-point and its evaluation result is input to the controller for adjustment. The results from Matlab - Simmechanic simulations and experiments show that the motion system of Robot Almega16 satisfies the requirement of a control system: the errors of rotating joints quickly converge to zero within a short transient time, so that closed-loop system is stable based on Lyapunov method.

Keywords: *Robot Almega 16, Repetitive Control Law, Lyapunov method.*

TÓM TẮT

Bài báo này trình bày xây dựng luật điều khiển lặp đi lặp lại với quỹ đạo chu kỳ mong muốn trong không gian khớp để giảm tính toán trực tiếp cho hệ chuyển động Robot Almega16. Thuật toán điều khiển RCL luôn có quỹ đạo chu kỳ đặt mong muốn với thời gian T, luôn cập nhật có các tham số hằng bất định để so sánh giá trị chỉnh định với giá trị thực rồi đưa vào bộ điều khiển để hiệu chỉnh. Kết quả được thể hiện qua mô phỏng trên phần mềm Matlab - Simulink và thực nghiệm cho thấy hệ chuyển động Robot Almega16 đã đáp ứng được yêu cầu điều khiển: đảm bảo sai số của các khớp quay nhanh chóng đạt tới không với thời gian quá độ nhỏ, làm cho hệ thống kín ổn định theo tiêu chuẩn Lyapunov.

Từ khóa: *Robot Almega 16, điều khiển RCL, tiêu chuẩn Lyapunov.*

1. INTRODUCTION

Industrial robots perform repetitive tasks in many manufacturing applications. Repetitive control is a promising control approach to achieve tracking of the periodic trajectories. This kind of control has gained a great deal of research interest in various forms, such as passivitybased repetitive control [7], nonlinear repetitive control [8], time-delay repetitive control [9], minimum-norm and timeoptimal repetitive control [11], optimal repetitive control [12] and adaptive repetitive control [10]. Industrial robots meet key structural features to perform repetitive trajectories in many manufacturing applications. Therefore, model-based control can be used for tracking repetitive trajectories if a precise model is available. This main content of the article presents a build of Repetitive Control Law (RCL) with desired trajectory periodic in joint space so reduced on-line computation for the motion system of the Almega16 manipulator. In a Repetitive Control Law always has the desired cycle trajectory with time T and always provides state information update on the time-variant parameters. The true value is compared to the reference set-point and its evaluation result is input to the controller for adjustment.

2. OBJECT CONTROL

The Almega 16 robot is shown in Figure 1, as follows [6]. This is a vertical welding robot with fast, rhythmic and precise movement characteristics, including six–link axes, each one link axes is equipped with a permanent magnet synchronous servo motor and closed loop control. In the article using only three-link axes as the research object, specifically the main specifications of the three joints as follows.

Figure 1. Six-link Almega 16 arm

First joint: Rotation angle: $\pm135^0$. Center tops from top to bottom: 28cm. Center line of axis I to the center of the cylinder: 35cm. Second joint: Rotation angle: $\pm135^0$. The length between the center of the axis I and II is 65cm. Third joint: Angle of rotation: 90^0 and -45^0. The length between the two centers of axis I and II is 47cm. The total volume of the Almega16 Robot: V = 0,12035 m^3. Total weight of the robot: 250kg. The mass of joints is as follows: $m_0 = 100$kg, $m_1 = 67$kg, $m_2 = 52$kg, $m_3 = 16$kg, $m_4 = 10$ kg, $m_5 = 4$kg, $m_6 = 1$kg.

The motion system Almega16 Robot is a nonlinear system that has constant model parameters and is interfering with the channel between the component motion axes. According to the literature as follows [3], the first three joints have fully integrated the dynamics of the freedom arm. The motor connected to the joint is usually a planetary gear and Small air gap. It is influenced by friction such as static friction, friction, viscous friction and so on. Therefore, the first three joints are the basic chain that ensures movement in 3D (X, Y, Z) space. The basis for the study of the next steps in robot manipulator motion systems. The problem with the controller is that: should design the quality control ensures precise orbit grip that does not depend on the parameters of the model uncertainty and the impact on channel mix between match-axis error between joint angles and the angle joints actually put a small (<0.1%).

3. REPETITIVE CONTROL LAW

3.1. Dynamic Model of Robot Manipulators

The dynamic of an n-link rigid manipular [1, 2, 3, 4, 6] can be written as

$$\tau = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{V_m}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) + \mathbf{F_d}\dot{\mathbf{q}} \qquad (1)$$

Where $\mathbf{q}$ is the n x 1 joint variable vector, τ is a n x 1 generalized torque vector $\mathbf{M}(\mathbf{q})$ is the nxn inertia matrix, $\mathbf{H}(\mathbf{q},\dot{\mathbf{q}})$ is the n x 1 Coriolis/centripetal vector, $\mathbf{G}(\mathbf{q})$ is the n x1 gravity vector and $\mathbf{F_d}$ is the n x n positive-definite, diagonal matrix that is used to represent the dynamic coefficients of friction, and all other quantities are as defined in Chapter 3, [3].

3.2. Controller Design

To motivate the design of the repetitive control law (RCL) [Sadegh et al. 1990], [3], we note that the dynamics given by

$$\mathbf{u_d}(t) = \mathbf{M}(\mathbf{q_d})\ddot{\mathbf{q}}_d + \mathbf{V_m}(\mathbf{q_d},\dot{\mathbf{q}}_d)\dot{\mathbf{q}}_d + \mathbf{G}(\mathbf{q_d}) + \mathbf{F_d}\dot{\mathbf{q}}_d \qquad (2)$$

are repeatable if the desired trajectory is periodic. That is, even though there may be unknown constant parametric quantities in (2), the signal represented by the n×1 vector ud(t) will be periodic or repeatable. Therefore, in the subsequent discussion, we assume that the desired trajectory is periodic with period T. This periodic assumption on the desired trajectory allows us to write

$$\mathbf{u_d}(t) = \mathbf{u_d}(t - T) \qquad (3)$$

since the dynamics represented by ud(t) depend only on periodic quantities. Utilizing the repeatability of the dynamics given by (2), the RCL is formulated as:

$$\tau = \hat{\mathbf{u}}_d(t) + \mathbf{k_v}\mathbf{r} + \mathbf{k_p}\mathbf{e} + \mathbf{k_a}\|\mathbf{e}\|^2\mathbf{r} \qquad (4)$$

Where the n×1 vector ûd(t) is a learning term that is used to compensate for the repeatable dynamics ud(t) and all other quantities are the same as those defined for the DCAL. The learning term ûd(t) is updated from trial to trial by the learning update rule:

$$\hat{\mathbf{u}}_d(t) = \hat{\mathbf{u}}_d(t - T) + \mathbf{k_L}\mathbf{r} \qquad (5)$$

Where kL is a positive scalar control gain.

The filtered tracking error is defined as: $\mathbf{r} = \mathbf{e} + \dot{\mathbf{e}}$

We will write the learning update rule given in (5) in terms of the learning error, which is defined as:

$$\tilde{\mathbf{u}}_d(t) = \hat{\mathbf{u}}_d(t) - \hat{\mathbf{u}}_d(t) \qquad (6)$$

Specifically, multiplying (5) by -1 and then adding ud(t) to both sides of (5) yields

$$\mathbf{u}_d(t) - \hat{\mathbf{u}}_d(t) = \mathbf{u}_d(t) - \hat{\mathbf{u}}_d(t - T) - \mathbf{k_L}\mathbf{r} \qquad (7)$$

By utilizing the periodic assumption given by (3), we can write (7)

$$\mathbf{u}_d(t) - \hat{\mathbf{u}}_d(t) = \mathbf{u}_d(t - T) - \hat{\mathbf{u}}_d(t - T) - \mathbf{k_L}\mathbf{r} \qquad (8)$$

From (6) instead of (8), which gives the learning error update rule:

$$\tilde{\mathbf{u}}_d(t) = \tilde{\mathbf{u}}_d(t - T) - \mathbf{k_L}\mathbf{r} \qquad (9)$$

where $\tilde{\mathbf{u}}_d(t)$ is defined in terms of (6).

we rewrite (1) in terms of r defined in $\mathbf{r} = \mathbf{e} + \dot{\mathbf{e}}$. That is, we have

$$\mathbf{M}(\mathbf{q})\dot{\mathbf{r}} = -\mathbf{V_m}(\mathbf{q},\dot{\mathbf{q}})\mathbf{r} + \mathbf{u_a}(t) - \tau \qquad (10)$$

where the n×1 vector $\mathbf{u_a}(t)$ is used to represent the "actual manipulator dynamics" given by

$$\mathbf{u_a}(t) = \mathbf{M}(\mathbf{q})(\ddot{\mathbf{q}}_d + \mathbf{e}) + \mathbf{V_m}(\mathbf{q},\dot{\mathbf{q}})(\dot{\mathbf{q}}_d + \mathbf{e}) + \mathbf{G}(\mathbf{q}) + \mathbf{F_d}\dot{\mathbf{q}} \qquad (11)$$

Adding and subtracting the term $\mathbf{u}_d(t)$ on the right-hand side of (10 yields)

$$\mathbf{M}(\mathbf{q})\dot{\mathbf{r}} = -\mathbf{V_m}(\mathbf{q},\dot{\mathbf{q}})\mathbf{r} + \mathbf{u}_d(t) + \tilde{\mathbf{U}} - \tau \qquad (12)$$

where $\tilde{\mathbf{U}}$ is defined as

$$\tilde{\mathbf{U}} = \mathbf{u_a}(t) - \mathbf{u}_d(t) \qquad (13)$$

As shown similarly in [Sadegh and Horowitz 1990], this difference between the actual manipulator dynamics (i.e., ua(t)) and the repeatable manipulator dynamics (i.e., ud(t)) can be quantified as

$$\|\tilde{\mathbf{U}}\| \leq \varsigma_1\|\mathbf{e}\| + \varsigma_2\|\mathbf{e}\|^2 + \varsigma_3\|\mathbf{r}\| + \varsigma_4\|\mathbf{r}\|\|\mathbf{e}\| \qquad (14)$$

where $\varsigma_1, \varsigma_2, \varsigma_3, \varsigma_4$ are positive bounding constants that depend on the desired trajectory and the physical properties of the specific robot configuration (i.e., link mass, link length, friction coefficients, etc.). The last step in

forming the error system is to substitute the control given by (4) into (12) to yield

$$\mathbf{M}(q)\dot{r} = -\mathbf{V_m}(q,\dot{q})\mathbf{r} - \mathbf{k_v}\mathbf{r} - \mathbf{k_p}e - \mathbf{k_a}\|e\|^2\mathbf{r} + \tilde{u}_d(t) + \tilde{U} \qquad (15)$$

3.3. A Globally Stable Repetitive Control Law

We now analyze the stability of the error system given by (15) with the Lyapunov-like function

$$\mathbf{V} = \frac{1}{2}\mathbf{r}^\mathsf{T}\mathbf{M}(q)\mathbf{r} + \frac{1}{2}\mathbf{k_p}e^\mathsf{T}e + \frac{1}{2\mathbf{k_L}}\int_{t-T}^{t}\tilde{u}_d^\mathsf{T}(\sigma)\tilde{u}_d(\sigma)d\sigma \qquad (16)$$

Differentiating (16) with respect to time yields

$$\dot{\mathbf{V}} = \frac{1}{2}\mathbf{r}^\mathsf{T}\dot{\mathbf{M}}(q)\mathbf{r} + \mathbf{r}^\mathsf{T}\mathbf{M}(q)\dot{r} + \mathbf{k_p}e^\mathsf{T}e$$
$$+ \frac{1}{2\mathbf{k_L}}(\tilde{u}_d^\mathsf{T}(t)\tilde{u}_d(t) - \tilde{u}_d^\mathsf{T}(t-T)\tilde{u}_d(t-T)) \qquad (17)$$

Substituting the error system given by (15) into (17) yields

$$\dot{\mathbf{V}} = \mathbf{k_p}e^\mathsf{T}e - \mathbf{k_v}\mathbf{r}^\mathsf{T}\mathbf{r} - \mathbf{k_p}\mathbf{r}^\mathsf{T}e - \mathbf{k_a}\|e\|^2\mathbf{r}^\mathsf{T}\mathbf{r} + \mathbf{r}^\mathsf{T}\tilde{U}$$
$$+ \frac{1}{2k_L}(\dot{\mathbf{M}}(q) - 2\mathbf{V_m}(q,\dot{q}))\mathbf{r} + \mathbf{r}^\mathsf{T}\tilde{u}_d^\mathsf{T}(t) \qquad (18)$$
$$+ \frac{1}{2\mathbf{k_L}}(\tilde{u}_d^\mathsf{T}(t)\tilde{u}_d(t) - \tilde{u}_d^\mathsf{T}(t-T)\tilde{u}_d(t-T))$$

Since **M + 2Vm** is an inclined matrix, it is easy to see that the second line of (18) is zero and based on (9), determine the following:

$$\dot{\mathbf{V}} = \mathbf{k_p}e^\mathsf{T}\mathbf{e} - \mathbf{k_v}\mathbf{r}^\mathsf{T}\mathbf{r} - \mathbf{k_p}\mathbf{r}^\mathsf{T}\mathbf{e} - \mathbf{k_a}\|e\|^2\mathbf{r}^\mathsf{T}\mathbf{r} + \mathbf{r}^\mathsf{T}\tilde{U} - \frac{1}{2}\mathbf{k_L}\mathbf{r}^\mathsf{T}\mathbf{r} \quad (19)$$

From (19) we can place an upper bound on in the following manner:

$$\Rightarrow \dot{\mathbf{V}} \leq -\mathbf{k_p}\|e\|^2 - (\mathbf{k_v} + \frac{1}{2}\mathbf{k_L})\|\mathbf{r}\|^2 - \mathbf{k_a}\|e\|^2\|\mathbf{r}\|^2 + \|\mathbf{r}\|\|\tilde{U}\| \quad (20)$$

Which $\mathbf{k_a}, \mathbf{k_v} + \frac{1}{2}\mathbf{k_L}$ satisfies the following conditions:

$$\mathbf{k}_a > \varsigma_2 + \varsigma_4$$

$$\mathbf{k}_p > \frac{\varsigma_1}{2} + \frac{\varsigma_4}{4} \qquad (21)$$

$$\mathbf{k}_v + \frac{1}{2}\mathbf{k_L} > \frac{\varsigma_1}{2} + \varsigma_3 + \frac{\varsigma_4}{4}$$

where $\varsigma_1, \varsigma_2, \varsigma_3, \varsigma_4$ are defined (14).

We can place the new upper bound on :

$$\dot{\mathbf{V}} \leq -\boldsymbol{\lambda}_3\|\mathbf{x}\|^2 \qquad (22)$$

Where λ_3 is a positive scalar constant given by $\boldsymbol{\lambda}_{min}\{Q_0\}$:

$$\mathbf{Q} = \begin{bmatrix} \mathbf{k_p} - \varsigma_2/4 & -\varsigma_1/2 \\ -\varsigma_1/2 & \mathbf{k_v} + \frac{1}{2}\mathbf{k_L} - \varsigma_3 - \frac{\varsigma_4}{4} \end{bmatrix} \text{ và } \mathbf{x} = \begin{bmatrix} \|\mathbf{e}\| \\ \|\mathbf{r}\| \end{bmatrix}, \qquad (23)$$

We now detail the type of stability for the tracking error. First note that from (22), we can place the new upper bound on:

$$\dot{\mathbf{V}} \leq -\boldsymbol{\lambda}_3\|\mathbf{r}\|^2 \qquad (24)$$

which implies that

$$\int_0^\infty \dot{\mathbf{V}}(\sigma)d\sigma \leq -\boldsymbol{\lambda}_3\int_0^\infty\|\mathbf{r}(\sigma)\|^2 d\sigma \qquad (25)$$

Multiplying (25) by -1 and integratis the left-hand side of (25) yields

$$\mathbf{V(0)} - \mathbf{V}(\infty) \geq \boldsymbol{\lambda}_3\int_0^\infty\|\mathbf{r}(\sigma)\|^2 d\sigma \qquad (26)$$

Since is negative semidefinite as delineated by (22), we can state that **V** is a nonincreasing function and therefore is upper bounded by **V**(0). By recalling that **M**(q) is lower bounded as delineated by the positive-definite property of the inertia matrix, we can state that **V** given in (16) is lower bounded by zero. Since **V** is nonincreasing, upper bounded by **V**(0), and lower bounded by zero, we can write (26) as

$$\boldsymbol{\lambda}_3\int_0^\infty\|\mathbf{r}(\sigma)\|^2 d\sigma < \infty \qquad (27)$$

or

$$\sqrt{\boldsymbol{\lambda}_3\int_0^\infty\|\mathbf{r}(\sigma)\|^2 d\sigma} < \infty \qquad (28)$$

The bound delineated by (28) informs us that (see Chapter 2), [3], which means that the filtered tracking error r is bounded in the "special" way given by (28).

To establish a stability result for the position tracking error e, we establish the transfer function relationship between the position tracking error and the filtered tracking error r. From $\mathbf{r} = \mathbf{e} + \dot{\mathbf{e}}$, we can state that

$$\mathbf{e(s) = G(s)r(s)} \qquad (29)$$

where s is the Laplace transform variable,

$$\mathbf{G(s) = (sI + I)^{-1}} \qquad (30)$$

and **I** is the n×n identity matrix. Since **G(s)** is a strictly proper, asymptotically stable transfer function and $\mathbf{r} \in \mathbf{L_2^n}$, we can use Theorem 2.4.7 in Chapter 2, [3] to state that

$$\lim_{t\to\infty} e = 0 \qquad (31)$$

Therefore, if the controller gains are selected according to (21), the position tracking error e is asymptotically stable. In accordance with the theoretical development presented in this section, all we can say about the velocity tracking error e is that it is bounded. It should be noted that if the learning estimate $\hat{\mathbf{u}}_d(\mathbf{t})$ in (3) is "artificially" kept from growing, we can conclude that the velocity tracking error is asymptotically stable [Sadegh et al. 1990],[3]. The stability proof for this modification is a straightforward application of the adaptive control proofs presented in Chapter 6,[3].

The repetitive controller examined in this section is summarized in Table 1 and depicted in Figure 2.
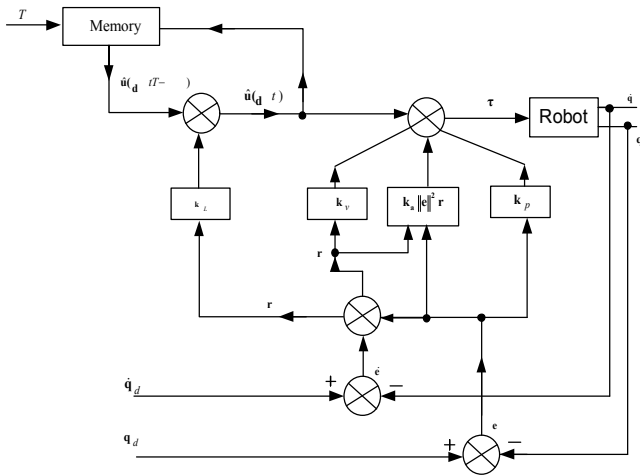
Figure 2. Block diagram of RCL

Table 1. RCL Controller

Torque Controller	$\tau = \hat{u}_d(t) + k_v r + k_p e + k_a \|e\|^2 r$ where: $r = e + \dot{e}$
Learning Update rule	$\tilde{u}_d(t) = \tilde{u}_d(t - T) - k_L r$
Stability	Tracking error e is an asymptotical state. Tracking error $\dot{e}$ is bounded
Comments	Desired trajectory must be periodic with period T, and the controller gain k_a, k_p, k_L and k_v must be sufficiently large.

After glancing through Table 1, we can see that the RCL requires very little information about the robot being controlled as opposed to adaptive controllers that required the formulation of regression-type matrices. Another obvious advantage of the RCL is that it requires very little on-line computation.

4. REPETITIVE CONTROL LAW FOR THE THREE –LINK ARM

4.1. The problem

We wish to design and simulate the Repetitive controll law given in Table 1 for a three-link arm in Figure 1. The dynamics for this Robot arm are given in [6]. From Table 3.1 the RCL can be written as

$$\tau_1 = \hat{u}_{d1}(t) + k_v r_1 + k_p e_1 + k_a \|e\|^2 r_1$$
$$\tau_2 = \hat{u}_{d2}(t) + k_v r_2 + k_p e_2 + k_a \|e\|^2 r_2 \qquad (32)$$
$$\tau_3 = \hat{u}_{d3}(t) + k_v r_3 + k_p e_3 + k_a \|e\|^2 r_3$$

where $r_1 = e_1 + \dot{e}_1, r_2 = e_2 + \dot{e}_2, r_3 = e_3 + \dot{e}_3$

and $\|e\|^2 = e_1^2 + e_2^2 + e_3^2$

Formulating the learning update rule as given in Table 1 yields

$$\tilde{u}_{d1}(t) = \tilde{u}_{d1}(t - T) - k_L r_1$$
$$\tilde{u}_{d2}(t) = \tilde{u}_{d2}(t - T) - k_L r_2 \qquad (33)$$
$$\tilde{u}_{d3}(t) = \tilde{u}_{d3}(t - T) - k_L r_3$$

4.2. Simulation

Afer building up the algorithms and control programs, we will proceed to run the simulation program to test computer program. the Desired Compensation Adaptation law was Simulink with Table 2.

Table 2. The Parameter of Repetitive Control Law

Symbol	The parameter	The Parameter value of the joint axis
q_d	Desired joint position	$q_{d1} = q_{d2} = q_{d3} = 1(t)$ $q_{d1} = q_{d2} = q_{d3} = \sin t$
k_v	Scalar	$k_v = 250$
k_p	Constant	$k_p = 250$
k_a	Control gain	$k_a = 250$
T		$T = 2p$

After simulation we have results position and position tracking error is depicted Figure 3, 4, 5, 6.

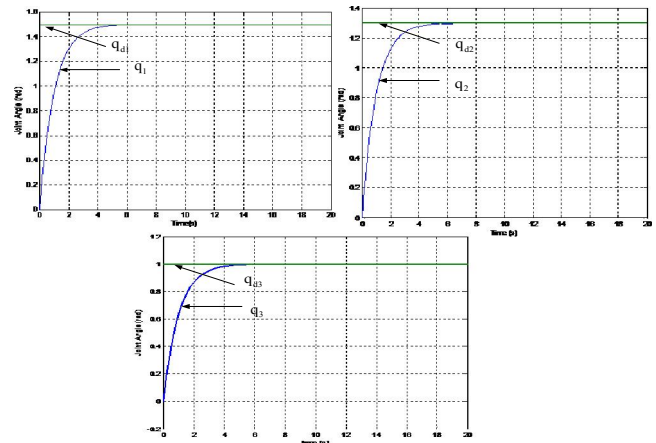#### 4.2.1. Desired joint position is 1(t)

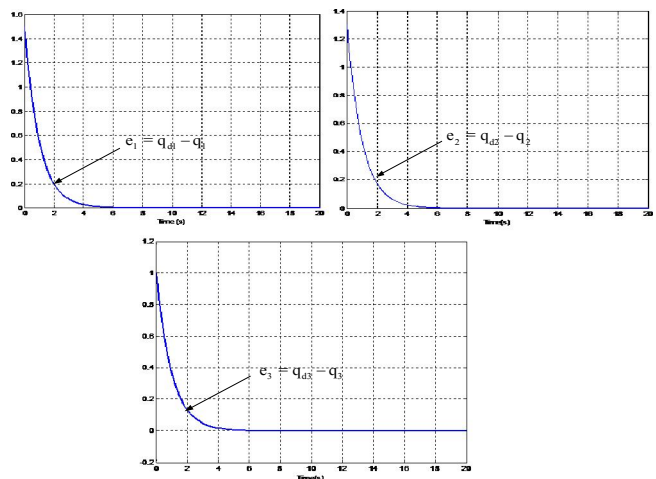Figure 3. RCL with steady-state position error eliminated

Figure 4. RCL with the errors between joints angles

Comment: the robot Almega 16 motion has meet controlled requirements: Steady - state error of joint angle conveges to zero very fast with transient time is small.
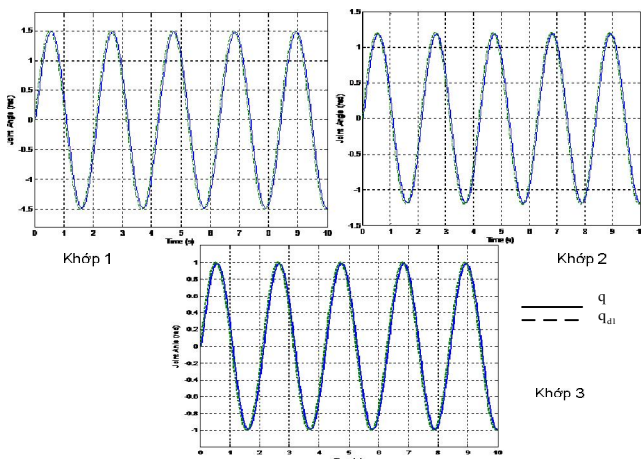
4.2.2. Desired joint position is sin(t)

Figure 5. Desired Compensation Adaptation controller with steady-state position error eliminated
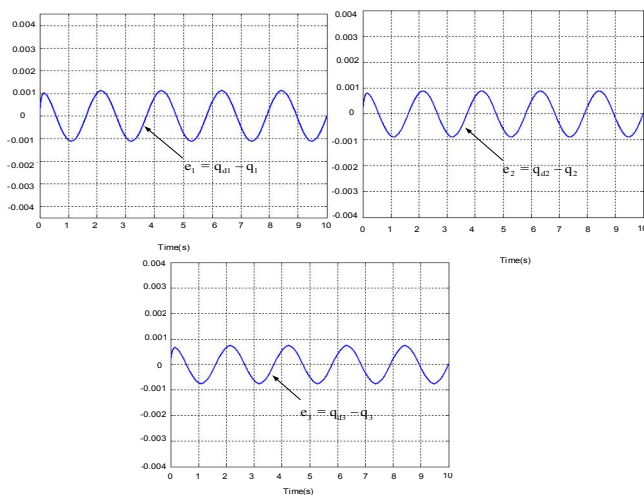

Figure 6. RCL with the errors between joints angles

Comment: The desired trajectory and the real trajectory of the Almega 16 robot have a small error and the transition period of the system is very fast, the mean position error of the total three joints was very low (~ 0.002%). As illustrated in the figure, the position tracking error is both asymptotically stable. Tracking error $\dot{e}$ is bounded. Controller gain k_a, k_p, k_L and k_v must be sufficiently large.

5. CONCLUSION

As research in robot control has progressed over the last couple of year, many robot controls began to focus on implementation issues. That is, implementation concerns, such as the reduction of on-line computation is causing the researcher to rethink the previous theoretical development of robot controllers so that these concerns are addressed. This paper addresses the problem of re-proofing the repetitive control law for Robot Almega 16 Robot. In a Repetitive Control Law always has the desired cycle trajectory with time T and always provides state

information update on the time-variant parameters. The true value is compared to the reference set-point and its evaluation result is input to the controller for adjustment. Thus the volume of mathematics in the control algorithm to reduce more than controls algorithm to research. The simulation results in software Matlab - Simulink shows that the Robot motion has meet controlled requirements: Steady - state error of joint angle converges to zero very fast and transient time is small.

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