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A New Uniformly Ultimate Boundedness Criterion for Temperature Dependent Average Bristle Deflections

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ABSTRACT

Temperature variation intensively affects parameters of the friction force, particularly the average bristle deflections. In our earlier research work, a temperature dependent friction compensation scheme was developed for serial rigid robot manipulators which was comprised of a temperature dependent viscous friction compensation scheme and a temperature dependent disturbance rejection scheme. In this paper, a new criterion for the uniformly ultimate boundedness of the temperature dependent average bristle deflections is proposed in such a way that the temperature dependent average bristle deflections preserve the property of uniformly ultimately boundedness in a larger region. This is an improvement to our earlier research work. As the result of this improvement, it is shown that the proposed method in our earlier work, is applicable to larger temperature dependent disturbance terms. These two improvements are the main contributions of this paper that augment our earlier research work. The idea is supported by a new theorem.

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1. INTRODUCTION

Temperature effects on the parameters of the friction force are very important. Particularly, the average bristle deflections are affected by temperature. The temperature effects must be compensated and if not, they might tend to poor system performances. In the literature, there has been low attention to these effects.

Bittencourt and Axelsson [1] studied the temperature effects on the friction and showed their importance. Mare [2] conducted an experimental study and showed the temperature dependency of the friction. The importance of the temperature effects has also been studied by Myklebust and Eriksson [3]. Carlson et al. [4] studied temperature effects on the joint's friction in industrial robot manipulators and modeled the temperature dependency. Du et al. [5] studied the temperature effects on the position control systems working in low temperatures.

Simoni et al. [6] proposed a new static friction model for industrial robot manipulators that takes the temperature effects into account and does not need the measurement of the temperature of the manipulator joint. Simoni et al. [7] then proposed a general framework for the inclusion of temperature in the friction model of industrial robots. They developed a new extended friction model considering temperature effects with simplifying assumptions [8].

Legnani et al. [9] proposed a new model that describes the behavior of friction in mechanical transmissions taking the temperature of the manipulator joint into account. Márton and van der Linden [10] proposed a linear temperature estimator using the temperature dependent coulomb and viscous friction models. Pagani et al. [11] proposed a fractional model that describes the relationship between power loss, friction and the temperature in the joints of industrial robots.

In our previous work [12], a temperature dependent friction compensation scheme was proposed for the serial rigid robot manipulators that contains a temperature dependent viscous friction compensation scheme and a temperature dependent disturbance rejection scheme.

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In this paper, a new uniformly ultimate boundedness criterion for the temperature dependent average bristle deflections is proposed; that improves our earlier work. The improvement is that by proposing this new uniformly ultimate boundedness criterion, a larger upper bound for the temperature dependent average bristle deflections is obtained. Using this larger upper bound, it is proved that the temperature dependent disturbance rejection scheme proposed in our earlier work, is applicable to larger temperature dependent disturbance terms. Therefore, the main contributions of this paper are summarized as follows:

- Firstly, a larger uniformly ultimate bound for the temperature dependent average bristle deflections is proposed.
- Secondly, it is proved that the temperature dependent disturbance rejection scheme proposed in our earlier work, is applicable to larger temperature dependent disturbance terms.

With these two improvements, the temperature dependent joint friction compensation scheme proposed in our earlier work [12], is augmented in terms of being applicable to larger temperature dependent disturbance terms.

This paper is organized as follows. Section 2 describes the problem and presents the preliminary arguments. In section 3, the larger uniformly ultimate bound for the temperature dependent average bristle deflections is obtained. Based on this larger bound, it is proved that the temperature dependent disturbance rejection scheme proposed in our earlier work, is applicable to larger temperature dependent terms. Concluding remarks are presented in section 5.

2. PROBLEM DESCRIPTION

The LuGre dynamic friction model is described by the following equations:

$$F_j = \sigma_{0j} Z_j(t) + \sigma_{1j} \dot{Z}_j(t) + f \quad (1)$$

$$\dot{Z}_j(t) = -\sigma_{0j} a_j(\dot{q}_j) Z_j(t) + \dot{q}_j \quad (2)$$

$$a_j(\dot{q}_j) = \frac{|\dot{q}_j|}{\alpha_{0j} + \alpha_{1j} e^{-(\dot{q}_j/\alpha_{2j})^2}} \quad (3)$$

where the parameters of these equations are defined as the following nomenclature.

$Z_j(t)$	Average bristles deflections
σ_0	Stiffness of the bristles
σ_1	Micro-damping
f	Macro-damping which normally stands for the viscous friction
F_j	Friction force
$\dot{q}_j$	Joint velocity
α_{ij}	Positive coefficients which are typically unknown
$\alpha_{0j} + \alpha_{1j} e^{-(\dot{q}_j/\alpha_{2j})^2}$	Approximation of Stribeck effect
$\alpha_{0j} + \alpha_{1j}$	Corresponding to stiction force
α_{0j}	Corresponding to Coulomb friction force
α_{2j}	Determines how the Stribeck friction varies within its bounds
$a_j(\dot{q}_j)$	Equivalent to the equation $\frac{|\dot{q}_j|}{\alpha_{0j} + \alpha_{1j} e^{-(\dot{q}_j/\alpha_{2j})^2}}$, by definition

In the LuGre friction model, the coefficients σ_0, σ_1 and f are indeed unknown and temperature dependent and their temperature dependency is adopted from literature [13] as stated in Equations (4), (5) and (6).

$$\sigma_0 = K_1 e^{-K_2 T} \quad (4)$$

$$\sigma_1 = -P_1 T + P_2 \quad (5)$$

$$f = h_1 e^{-h_2 T} \quad (6)$$

where K_i, P_i and h_i are the coefficients of the thermal profile of parameters σ_0, σ_1 and f which are generally unknown and T is the temperature.

Therefore, considering the Equations (1) to (6), the joint friction force is described by the equation below:

$$F_j = K_{1j} e^{-K_{2j}T} Z_j(t) + (P_{2j} - P_{1j}T)(\dot{q}_j - K_{1j} e^{-K_{2j}T} a_j(\dot{q}_j) Z_j(t)) + h_{1j} e^{-h_{2j}T} \quad (7)$$

where parameters K_{ij}, P_{ij} and h_{ij} are the elements of K_i, P_i and h_i.

This temperature dependent friction may be decoupled to a viscous term and a bounded disturbance term as presented in Equation (8).

$$F_j = \left[K_{1j} e^{-K_{2j}T} - \left(P_{2j} - P_{1j}T\right) K_{1j} e^{-K_{2j}T} a_j\left(\dot{q}_j\right)\right] Z_j(t) + h_{1j} e^{-h_{2j}T} + (P_{2j} - P_{1j}T)\dot{q}_j \quad (8)$$

$$F_{dj} = \left(K_{1j} e^{-K_{2j}T} - (P_{2j} - P_{1j}T) K_{1j} e^{-K_{2j}T} a_j(\dot{q}_j)\right) Z_j(t) + h_{1j} e^{-h_{2j}T} \quad (9)$$

The term F_{dj} is the temperature dependent disturbance friction term and it can be proved that it is bounded for a wide temperature range, using the fundamental property of uniformly boundedness of the temperature dependent average bristle deflections.

In our earlier work [12], the upper bound of the temperature dependent disturbance friction term F_{dj} is obtained as below.

$$F_{dj} < K_{1j\max} \Delta_j \gamma_1^{-1} + P_{1j\max} T_{\max} K_{1j\max} \frac{|\dot{q}_j|}{\alpha_{0j}} \Delta_j \gamma_1^{-1} - P_{2j\min} K_{1j\min} \frac{|\dot{q}_j|}{\alpha_{0j}} \frac{\Delta_j}{K_{1j\max}} + h_{1j\max} \quad (10)$$

where the following abbreviations are used.

$$\Delta_j = \alpha_{0j} + \alpha_{1j} \tag{11}$$

$$\gamma_1 = K - Kmax_{2jmax_{1jmin}} \tag{12}$$

One may refer to our previous work [12] in which the preliminary mathematics of this decomposition has been given and the boundedness of the temperature dependent disturbance term has been proved.

In the next section, a new Lyapunov function is proposed by which the uniformly ultimate boundedness of the temperature dependent average bristle deflections $Z_j(t)$ is proved with a larger bound than that of obtained in our earlier work. The new upper bound of the temperature dependent disturbance friction term F_{dj} is then obtained based on this new larger bound of the temperature dependent average bristle deflections $Z_j(t)$. This new upper bound of F_{dj} is larger than that of obtained in our earlier work which means that our recently proposed adaptive friction compensation scheme in our published work [12] is capable of compensating larger temperature dependent disturbance friction terms.

3. A NEW UNIFORLY ULTIMATE BOUNDEDNESS CRITERION

In this section, a new Lyapunov function is proposed by which the bound or radius of the invariant set which is used to prove the uniformly ultimate boundedness of the temperature dependent average bristle deflections, is increased compared with that of obtained in our earlier work [12]. In other words, by using the proposed Lyapunov function in this paper, a larger uniformly ultimate bound for the temperature dependent average bristle deflections is achieved via invariant set theory.

The new and larger uniformly ultimate bound of the temperature dependent average bristle deflections $Z_j(t)$ is obtained as introduced in the following theorem which is indeed an extension of theorem 1 in our earlier work [12].

Theorem 1:

Assume $|\dot{q}_j| > 1$, *if* $|Z_j(0)| < |\dot{q}_j| \frac{\alpha_{0j}+\alpha_{1j}}{K_{1j}e^{-K_{2j}T}}$ *then* $|Z_j(t)| < |\dot{q}_j| \frac{\alpha_{0j}+\alpha_{1j}}{K_{1j}e^{-K_{2j}T}}, \forall \quad t \geq 0.$

Proof: Let the Lyapunov function $V = \frac{Z_j(t)^2}{2} + Sin^2 Z_j(t)$. Its time derivative along the solution of Equation (2) may be calculated as follows.

Differentiating the proposed Lyapunov function yields

$$\dot{V} = Z_j(t)\dot{Z}_j(t) + 2\dot{Z}_j(t)\,Sin(Z_j(t))\,Cos(Z_j(t)) \tag{13}$$

The following trigonometric equilibrium holds.

$$2\,Sin(Z_j(t))\,Cos(Z_j(t)) = Sin(2Z_j(t)) \tag{14}$$

Taking Equations (2), (13) and (14) into account, the following equations are achieved.

$$\dot{V} = Z_j(t)(\dot{q}_j - \sigma_0 a(\dot{q}_j)Z_j(t)) + (\dot{q}_j - \sigma_0 a(\dot{q}_j)Z_j(t))\,Sin(2Z_j(t)) \tag{15}$$

$$\dot{V} = \dot{q}_j(Z_j(t) + Sin(2Z_j(t))) - \sigma_0 a(\dot{q}_j)Z_j(t)^2 - \sigma_0 a(\dot{q}_j)Z_j(t)\,Sin(2Z_j(t)) \tag{16}$$

By the use of Equation (3) we have

$$\dot{V} = \dot{q}_j(Z_j(t) + Sin(2Z_j(t))) - \frac{\sigma_0|\dot{q}_j|Z_j(t)^2}{\alpha_{0j}+\alpha_{1j}e^{-(\dot{q}_j/\alpha_{2j})^2}} - \frac{\sigma_0|\dot{q}_j|Z_j(t)\,Sin(2Z_j(t))}{\alpha_{0j}+\alpha_{1j}e^{-(\dot{q}_j/\alpha_{2j})^2}} \tag{17}$$

$$\dot{V} = |\dot{q}_j|\left(|\dot{q}_j|(Z_j(t) + Sin(2Z_j(t))) - \sigma_0 Z_j(t)\left(\frac{Z_j(t)+Sin(2Z_j(t))}{\alpha_{0j}+\alpha_{1j}e^{-(\dot{q}_j/\alpha_{2j})^2}}\right)\right) \tag{18}$$

$$\dot{V} = |\dot{q}_j|\left((Z_j(t) + Sin(2Z_j(t)))\left(|\dot{q}_j| - \frac{\sigma_0 Z_j(t)}{\alpha_{0j}+\alpha_{1j}e^{-(\dot{q}_j/\alpha_{2j})^2}}\right)\right) < 0 \tag{19}$$

In order to have a negative definite $\dot{V}$, Equation (19) should be smaller than zero, provided that $|\dot{q}_j| > 1$. Now, regarding the sign of $Z_j(t)$, there are two different modes that are investigated in the following.

Mode 1:

In the first mode the following inequalities must hold.

$$Z_j(t) + Sin(2Z_j(t)) > 0 \tag{20}$$

$$|\dot{q}_j| - \frac{\sigma_0 Z_j(t)}{\alpha_{0j}+\alpha_{1j}e^{-(\dot{q}_j/\alpha_{2j})^2}} < 0 \tag{21}$$

These inequalities may be solved as follows:

$$Z_j(t) + Sin(2Z_j(t)) > 0 \rightarrow Z_j(t) > 0 \tag{22}$$

which is achieved by graphical simulation for the span $(-\pi, +\pi)$ with steps $\frac{\pi}{180}$.

$$|\dot{q}_j| - \frac{\sigma_0 Z_j(t)}{\alpha_{0j}+\alpha_{1j}e^{-(\dot{q}_j/\alpha_{2j})^2}} < 0$$
$$|\dot{q}_j| < \frac{\sigma_0 Z_j(t)}{\alpha_{0j}+\alpha_{1j}e^{-(\dot{q}_j/\alpha_{2j})^2}} \tag{23}$$

$$\sigma_0 Z_j(t) > |\dot{q}_j|\left(\alpha_{0j} + \alpha_{1j}e^{-(\dot{q}_j/\alpha_{2j})^2}\right)$$
$$Z_j(t) > \frac{|\dot{q}_j|}{\sigma_0}\left(\alpha_{0j} + \alpha_{1j}e^{-(\dot{q}_j/\alpha_{2j})^2}\right) \tag{24}$$

Using Equation (4) we have

$$Z_j(t) > |\dot{q}_j| g(\dot{q}_j, T) \tag{25}$$

$$g(\dot{q}_j, T) = \frac{\alpha_{0j}+\alpha_{1j}e^{-(\dot{q}_j/\alpha_{2j})^2}}{K_{1j}e^{-K_{2j}T}} \tag{26}$$

Therefore, when Equations (20) and (25) hold, the time derivative of the proposed Lyapunov function is negative, provided that $|\dot{q}_j| > 1$. A known upper bound for $Z_j(t)$ may be obtained as below that is achieved if t goes to infinity.

$$g(\dot{q}_j, T) < \frac{\alpha_{0j}+\alpha_{1j}}{K_{1j}e^{-K_{2j}T}} \tag{27}$$

$$Z_j(t) < |\dot{q}_j| \frac{\alpha_{0j}+\alpha_{1j}}{K_{1j}e^{-K_{2j}T}} \tag{28}$$

Therefore, the first mode is held for the region $0 < Z_j(t) < |\dot{q}_j| \frac{\alpha_{0j}+\alpha_{1j}}{K_{1j}e^{-K_{2j}T}}$, provided that $|\dot{q}_j| > 1$.

Mode 2:

In this mode the following inequalities must hold.

$$Z_j(t) + Sin(2Z_j(t)) < 0 \tag{29}$$

$$|\dot{q}_j| - \frac{\sigma_0 Z_j(t)}{\alpha_{0j}+\alpha_{1j}e^{-(\dot{q}_j/\alpha_{2j})^2}} > 0 \tag{30}$$

These two inequalities may be solved as follows:

$$Z_j(t) + Sin(2Z_j(t)) < 0 \quad \rightarrow \quad Z_j(t) < 0 \tag{31}$$

which is also achieved by graphical simulation for the span $(-\pi, +\pi)$ with steps $\frac{\pi}{180}$.

$$\begin{aligned} &|\dot{q}_j| - \frac{\sigma_0 Z_j(t)}{\alpha_{0j}+\alpha_{1j}e^{-(\dot{q}_j/\alpha_{2j})^2}} > 0 \\ &Z_j(t) < \frac{|\dot{q}_j|}{\sigma_0}\left(\alpha_{0j} + \alpha_{1j}e^{-(\dot{q}_j/\alpha_{2j})^2}\right) \end{aligned} \tag{32}$$

Therefore, by taking Equation (4) into account and assuming $|\dot{q}_j| > 1$, the second mode is held for the region $Z_j(t) < 0$ which contains the span $-|\dot{q}_j| \frac{\alpha_{0j}+\alpha_{1j}}{K_{1j}e^{-K_{2j}T}} < Z_j(t) < 0$.

Considering these two different modes with the condition $|\dot{q}_j| > 1$, the region in which the derivative of the proposed Lyapunov function is always negative is obtained as follows:

$$\begin{aligned} &-|\dot{q}_j| \frac{\alpha_{0j}+\alpha_{1j}}{K_{1j}e^{-K_{2j}T}} < Z_j(t) < |\dot{q}_j| \frac{\alpha_{0j}+\alpha_{1j}}{K_{1j}e^{-K_{2j}T}} \\ &|Z_j(t)| < |\dot{q}_j| \frac{\alpha_{0j}+\alpha_{1j}}{K_{1j}e^{-K_{2j}T}} \end{aligned} \tag{33}$$

Thus, the time derivative of the Lyapunov function is negative where $|Z_j(t)| < |\dot{q}_j| \frac{\alpha_{0j}+\alpha_{1j}}{K_{1j}e^{-K_{2j}T}}, \forall \quad |\dot{q}_j| > 1$.

This way, it is concluded that the set $\Omega = \left\{Z_j(t): |Z_j(t)| \le |\dot{q}_j| \frac{\alpha_{0j}+\alpha_{1j}}{K_{1j}e^{-K_{2j}T}}\right\}$ is an invariant set for the solutions of Equation (2), provided that $|\dot{q}_j| > 1$, i.e. all the solutions of $Z_j(t)$ starting in Ω remain there. Therefore, the temperature dependent average bristle deflections $Z_j(t)$ are *uniformly ultimately bounded*, namely, $|Z_j(t)| < |\dot{q}_j| \frac{\alpha_{0j}+\alpha_{1j}}{K_{1j}e^{-K_{2j}T}}$ for all $t \ge 0$ and $|\dot{q}_j| > 1$. This finishes the proof of Theorem 1.

Therefore, considering the condition $|\dot{q}_j| > 1$, the uniformly ultimately boundedness of the temperature dependent average bristle deflections $Z_j(t)$ is obtained with a larger bound, compared with that of obtained in our earlier work [12].

Based on the new and larger upper bound of $Z_j(t)$, a new and larger upper bound for the temperature dependent disturbance term F_{dj} may be obtained.

In this paper, the upper bound of $Z_j(t)$ is obtained as $|Z_j(t)| < |\dot{q}_j| \frac{\alpha_{0j}+\alpha_{1j}}{K_{1j}e^{-K_{2j}T}}$ which may be optimized as follows:

$$|Z_j(t)| < |\dot{q}_j| \frac{\alpha_{0j}+\alpha_{1j}}{K - Kmax_{2jmax_{1jmin}}} \tag{34}$$

The following substitutes are defined.

$$\Delta_j = \alpha_{0j} + \alpha_{1j} \tag{35}$$

$$\gamma_1 = K - Kmax_{2jmax_{1jmin}} \tag{36}$$

In order to obtain the upper bound of F_{dj} (Equation (8)), the upper bound of its constitutive terms should be obtained. Based on Equation (3), the upper bound of $a_j(\dot{q}_j)$ is obtained as follows:

$$a_j(\dot{q}_j) \le \frac{|\dot{q}_j|}{\alpha_{0j}} \tag{37}$$

Using the inequality above, the term $(P_{1j} - P_{2j}T)K_{1j}e^{-K_{2j}T}a_j(\dot{q}_j)Z_j(t)$ in F_{dj} is represented as stated below:

$$\begin{aligned} &(P_{1j}T - P_{2j})K_{1j}e^{-K_{2j}T}a_j(\dot{q}_j)Z_j(t) < \\ &(P_{1j}T - P_{2j})K_{1j}\frac{|\dot{q}_j|}{\alpha_{0j}}Z_j(t) \end{aligned} \tag{38}$$

The right-hand side of this inequality is

$$P_{1j}T\frac{|\dot{q}_j|}{\alpha_{0j}}K_{1j}Z_j(t) - P_{2j}K_{1j}\frac{|\dot{q}_j|}{\alpha_{0j}}Z_j(t) \tag{39}$$

In order to obtain the upper bound of this expression, the upper bound of the first term and the lower bound of the second term should be determined.

Using Equations (34), (35) and (36), the upper bound of the first term of Equation (39) is obtained as follows:

$$K_{1j}Z_j(t) < K_{1j}|\dot{q}_j|\frac{\alpha_{0j}+\alpha_{1j}}{K_{1j}e^{-K_{2j}T}}_{1j} \, |\dot{q}_j|_{j_1}{}^{-1} \; max_{max} \tag{40}$$

$$P_{1j}T\frac{|\dot{q}_j|}{\alpha_{0j}}K_{1j}Z_j(t) < P_{1j}1j\frac{\dot{q}_j{}^2}{\alpha_{0j}{}_{j_1}}{}^{-1} \; {}_{max} \; max_{max} \tag{41}$$

The upper bound of $Z_j(t)$ is $Z_j(t) < \frac{|\dot{q}_j|\Delta_j}{K - Kmax_{2jmax_{1jmin}}}$

based on which the lower bound of $Z_j(t)$ is obtained as follows:

$$Z_j(t) > \frac{|\dot{q}_j|\Delta_j}{K_{1j_{max}}} \tag{42}$$

Therefore, the lower bound of the second term of Equation (39) is obtained as follows:

$$P_{2j}K_{1j}\frac{|\dot{q}_j|}{\alpha_{0j}}Z_j(t) > P_{2j}1j\frac{\dot{q}_j^{\ 2}}{\alpha_{0j}}\frac{\Delta_j}{K_{1j_{max}{min}_{min}}} \tag{43}$$

This way, the upper bound of the expression $(P_{1j} - P_{2j}T)K_{1j}e^{-K_{2j}T}a_j(\dot{q}_j)Z_j(t)$ in F_{dj} is obtained as follows:

$$(P_{1j} - P_{2j}T)K_{1j}e^{-K_{2j}T}a_j(\dot{q}_j)Z_j(t) < P_{1j}1j\frac{\dot{q}_j^{\ 2}}{\alpha_{0j_{j_1}}}^{-1} {}_{2j} 1j\frac{\dot{q}_j^{\ 2}}{\alpha_{0j}}\frac{\Delta_j}{K_{1j_{max}{min}}}{}_{{min}_{max}} \ max_{max} \tag{44}$$

Two other terms of F_{dj} may be obtained as follows:

$$K_{1j}e^{-K_{2j}T}Z_j(t) < K_{1j}Z_j(t) < K_{1j}|\dot{q}_j|\frac{\alpha_{0j}+\alpha_{1j}}{K-Kmax_{2jmax_{1j}}|\dot{q}_j|_{j_1}{}^{-1}}{}_{max_{1jmin_{max}}} \tag{45}$$

$$h_{1j}e^{-h_{2j}T} < h_{1j} < h_{1j_{max}} \tag{46}$$

Therefore, the upper bound of the temperature dependent disturbance friction term F_{dj} is obtained as follows:

$$F_{dj} < K_{1j\max}|\dot{q}_j|\Delta_j\gamma_1^{-1} + P_{1j\max}T_{\max}K_{1j\max}\frac{\dot{q}_j^{\ 2}}{\alpha_{0j}}\Delta_j\gamma_1^{-1} - P_{2j\min}K_{1j\min}\frac{\dot{q}_j^{\ 2}}{\alpha_{0j}}\frac{\Delta_j}{K_{1j\max}} + h_{1j\max} \tag{47}$$

It is notable that considering the condition $|\dot{q}_j| > 1$, this new upper bound of the temperature dependent disturbance term is larger than that of obtained in our earlier work [12]. It means that the adaptive temperature dependent friction compensation scheme that we have recently developed [12], is capable of handling larger temperature dependent disturbance friction terms as presented in Equation (47).

This way, the adaptive temperature dependent joint friction compensation scheme proposed in our recently published work [12], is augmented in terms of the ability to compensate the larger temperature dependent disturbance friction terms.

4. CONCLUSIONS

It is proved in the literature that the temperature has intense effects on the parameters of the friction force, particularly the average bristle deflections. In our previous work, the uniformly ultimate boundedness of the temperature dependent average bristle deflections has been proved based on which a temperature dependent disturbance rejection scheme was developed. In this paper, a new uniformly ultimate bound for the temperature dependent average bristle deflections is obtained that is larger than that of obtained in our earlier work. It is proved that using this larger uniformly ultimate bound of the temperature dependent average bristle deflections, the temperature dependent disturbance rejection scheme proposed in our earlier work, is applicable to larger temperature dependent disturbance terms.

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Persian Abstract

چکیده

تغییر دما تاثیر زیادی بر روی پارامترهای نیروی اصطکاک به ویژه میانگین انحرافات بریستل‌ها دارد. در کار قبلی ما، یک ساختار جبران ساز اصطکاک وابسته به دما برای بازوهای رباتیک سریال صلب توسعه داده شد که شامل یک ساختار جبران ساز اصطکاک ویسکوز وابسته به دما و یک ساختار دفع اغتشاش وابسته به دما بود. در این مقاله، یک معیار جدید برای ویژگی محدودیت یکنواخت نهایی میانگین انحرافات بریستل‌های وابسته به دما پیشنهاد می‌شود که بر اساس آن میانگین انحرافات بریستل‌های وابسته به دما می‌تواند ویژگی محدودیت یکنواخت نهایی را در یک ناحیه بزرگتر حفظ نماید. این یک بهبود نسبت به کار قبلی ما است. در نتیجه این بهبود، نشان داده می‌شود که ساختار دفع اغتشاش وابسته به دما که در کار قبلی‌مان توسعه داده‌ایم، به مولفه‌های اغتشاش وابسته به دما با دامنه بزرگتری قابل اعمال می‌باشد. این دو بهبود، نوآوری‌های اصلی این مقاله هستند که موجب تقویت کار تحقیقاتی قبلی ما می‌گردند. ایده جدید با اثبات یک قضیه جدید پشتیبانی می‌گردد.