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A New Robust Control Framework for Robot Manipulators without Velocity Measurements: A Modified Dual-loop Control Scheme

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Abstract— **This paper proposes a new framework for the computed torque method (CTM) of robot manipulators without velocity measurements. We first introduce the Luenberger-observer-based CTM with only position measurements. We then clarify that the external disturbance affects not only the tracking performances with respect to the plant but also the estimation accuracies relevant to the state observer. To address this problem, we establish a new architecture for the so-called dual-loop control scheme, by which both the tracking performances and estimation accuracies can be simultaneously improved, in contrast to its existing structure. A guideline for taking control parameters corresponding to the proposed control structure is also provided with respect to the stabilization of the overall closed-loop systems. Finally, simulation and experimental results are provided to demonstrate the validity and practical feasibility of the developed structure.**

I. INTRODUCTION

The controller synthesis leading to high performance for the trajectory tracking problem of robot manipulators has been regarded as one of the most significant issues with respect to the potential applicability of the robot manipulators. In particular, one of the most effective and verified strategies is the computed torque method (CTM) [1]–[4], in which a feedback linearization scheme corresponding to the *nonlinear* dynamics of Lagrange equations is concerned with. More precisely, the nonlinear dynamic equation of motion of an n-linked robot manipulator is transformed into n number of decoupled and linear-time invariant (LTI) dynamic equations through an inverse dynamics control approach.

When the CTM generates a torque input, it is generally assumed that the joint positions and velocities can be obtained without measurement errors [1]–[4]. However, it is not always feasible to use accurate velocity information in industrial applications because the signals from tachometers usually contain a certain amount of noise. Furthermore, commercial robot systems are not always equipped with velocity sensors because adding such components increases the cost, weight, and volume. In this sense, observer-based CTM schemes with only position measurements have been deeply studied in the last few decades [5]–[9].

These existing observer-based CTM schemes estimate the joint velocity based on the measured joint positions, and this value together with the dynamic model of robot manipulators leads to the torque input. However, they consist of nonlinear controllers and observers with excessive computing costs and many tuning parameters, and thus it is still required to develop a relatively simple control structure for commercial robot systems equipped with low-cost computing units. Motivated by this, we construct a readily applicable control architecture with LTI controller and LTI observer on the top of the computed torque treatment of robot manipulators, and a guideline for taking control parameters with respect to the stabilization of the closed-loop systems is also provided.

To put it another way, the aforementioned objectives can be achieved through sophisticated treatment of the so-called dual-loop robust control scheme [10], [11], in which two control loops with a nominal controller and a robust controller are considered. In these existing methods of dual-loop robust control, the former is described by a static feedback controller whose input is obtained by the LTI state observer, while the main role of the latter is to reduce the effects of the external disturbance on the tracking performance. To do this, both the signals resulting in the nominal and robust controllers are embedded to the state estimator in the existing structure, although the status of the estimator does not depend on the external disturbance. More importantly, even though the estimation errors in the computed torque framework for robot manipulators immediately lead to a tracking performance degradation, no argument on improving the estimation accuracies is discussed in this conventional control structure. The new structure for the dual-loop control scheme proposed in this paper aims at dealing with both the tracking performance and estimation accuracy simultaneously. To summarize, the proposed scheme is more effective in reducing the effects of the disturbance on both the tracking performance and estimation accuracies than the conventional scheme because of their structural differences.

The organization of this paper is as follows. We introduce the CTM for robot manipulators and its observer-based treatment without velocity measurements in Sections II and III, respectively. In Section IV, the proposed dual-loop robust control and a guideline for taking the relevant control parameters with respect to the stability issues are provided. Some simulation and experimental results are given in Section V to verify the effectiveness of the proposed method.

II. COMPUTED TORQUE METHOD

The dynamic equation of motion of an n-linked robot manipulator is given by

$$M(q)\ddot{q} + V(q,\dot{q}) + G(q) = \tau + \tau_d \tag{1}$$

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where $q \in \mathbb{R}^n$ denotes the generalized coordinates, $M(q) \in \mathbb{R}^{n\times n}$ is the inertia matrix, and $V(q,\dot{q}), G(q), \tau, \tau_d \in \mathbb{R}^n$ mean the coriolis and centrifugal torque vector, gravitational torque vector, applied torque input vector, external disturbance torque vector, respectively, while $\mathbb{R}^\mu$ denotes the set of μ-dimensional real numbers.

To facilitate a linear controller synthesis for the nonlinear dynamic equation of (1), we apply the linearization scheme so-called computed torque method (CTM) [1]–[4] to robot manipulators. For a simplicity of the arguments to derive an ideal feedback linearization procedure, we first assume that the external disturbance torque is zero, i.e., $\tau_d = 0$, while we will return to the general case with $\tau_d \neq 0$ at the end of this section. The torque input τ is taken based on the model information as

$$\tau = M(q)q^* + V(q,\dot{q}) + G(q) \tag{2}$$

where $q^* \in \mathbb{R}^n$ is an auxiliary input vector. Substituting (2) into (1) directly leads to

$$\ddot{q} = q^* \tag{3}$$

and thus the nonlinear differential equation (1) is equivalently converted to the linear differential equation (3). For this manipulator system, we consider a trajectory tracking problem described by

$$q \to q_d \quad (t \to \infty) \tag{4}$$

with the reference trajectory $q_d \in \mathbb{R}^n$. If we define the trajectory tracking error as $e := q_d - q$, the objective is to keep the tracking error as small as possible. With respect to this, we define the auxiliary input vector as

$$q^* := \ddot{q}_d - u \tag{5}$$

where $u \in \mathbb{R}^n$ is a control input vector. By combining (3) and (5) together with considering the general case of $\tau_d \neq 0$, we can describe the error dynamics as

$$\ddot{e} = u + w \tag{6}$$

with the disturbance vector $w := -M^{-1}(q)\tau_d$. We take with diagonal positive matrices K_p and K_d the control input as

$$u = -K_p e - K_v \dot{e}, \tag{7}$$

then (6) is further represented by

$$\frac{d}{dt}\begin{bmatrix} e \\ \dot{e} \end{bmatrix} = \begin{bmatrix} 0 & I \\ -K_p & -K_v \end{bmatrix}\begin{bmatrix} e \\ \dot{e} \end{bmatrix} + \begin{bmatrix} 0 \\ I \end{bmatrix} w. \tag{8}$$

The control parameters (K_p, K_v) are selected depending on the desired control objectives.

III. OBSERVER-BASED CONTROL WITH ONLY POSITION MEASUREMENTS

Even for robot manipulators equipped with velocity sensors, their measurement values generally contain a certain amount of noise, and this often leads to limiting the (velocity) control parameter K_v as well as performance deterioration. Moreover, many commercial robotic systems are not always equipped with velocity sensors. In this sense, we establish a new framework for the observer-based CTM [5]–[9] relevant to robot manipulators without velocity sensors.

It should be noted that operating the CTM without direct velocity measurements is disadvantageous for a calculation of the torque input; $V(q,\dot{q})$ in (2) and $\dot{e}$ in (7) are unavailable since these input values require velocity data. To address this problem, we use the estimate of $\dot{q}$ for the torque input, i.e.,

$$\tau = M(q)(\ddot{q}_d - u) + V(q,\hat{\dot{q}}) + G(q) \tag{9}$$

$$u = -K_p e - K_v \hat{\dot{e}} \tag{10}$$

where $\hat{\dot{q}}$ denotes the estimate of $\dot{q}$ and $\hat{\dot{e}} := \dot{q}_d - \hat{\dot{q}}$ means the estimated velocity tracking error. Substituting (9) and (10) into (1) allows us to arrive at

$$\begin{aligned}\ddot{e} &= -K_p e - K_v\hat{\dot{e}} + M^{-1}(q)(V(q,\dot{q}) - V(q,\hat{\dot{q}}) - \tau_d) \\ &=: -K_p e - K_v(\dot{q}_d - \dot{q}) - K_v(\dot{q} - \hat{\dot{q}}) + w_o \\ &= -K_p e - K_v\dot{e} - K_v\tilde{\dot{q}} + w_o \end{aligned} \tag{11}$$

where $w_o := M^{-1}(q)(V(q,\dot{q}) - V(q,\hat{\dot{q}}) - \tau_d)$ and $\tilde{\dot{q}} := \dot{q} - \hat{\dot{q}}$.

Now, we denote the integral value of $\hat{\dot{q}}$ by $\hat{q}$ for a notational simplicity, and introduce the state observer to compute $(\hat{q},\ \hat{\dot{q}})$. The Luenberger-type state observer is represented by

$$\frac{d}{dt}\begin{bmatrix} \hat{q} \\ \hat{\dot{q}} \end{bmatrix} = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix}\begin{bmatrix} \hat{q} \\ \hat{\dot{q}} \end{bmatrix} + \begin{bmatrix} 0 \\ I \end{bmatrix}(\ddot{q}_d - u) + \begin{bmatrix} L_p \\ L_v \end{bmatrix}(q - \hat{q}) \tag{12}$$

where L_p and L_v are diagonal and positive definite matrices. Substituting (9) and (12) into (1) leads to

$$\frac{d}{dt}\begin{bmatrix} \tilde{q} \\ \tilde{\dot{q}} \end{bmatrix} = \begin{bmatrix} -L_p & I \\ -L_v & 0 \end{bmatrix}\begin{bmatrix} \tilde{q} \\ \tilde{\dot{q}} \end{bmatrix} - \begin{bmatrix} 0 \\ I \end{bmatrix} w_o \tag{13}$$

with $\tilde{q} := q - \hat{q}$. Finally, by combining (11) and (13), we obtain the state-space equation described by

$$\frac{d}{dt}\begin{bmatrix} e \\ \dot{e} \\ \tilde{q} \\ \tilde{\dot{q}} \end{bmatrix} = \begin{bmatrix} 0 & I & 0 & 0 \\ -K_p & -K_v & 0 & -K_v \\ 0 & 0 & -L_p & I \\ 0 & 0 & -L_v & 0 \end{bmatrix}\begin{bmatrix} e \\ \dot{e} \\ \tilde{q} \\ \tilde{\dot{q}} \end{bmatrix} + \begin{bmatrix} 0 \\ I \\ 0 \\ -I \end{bmatrix} w_o. \tag{14}$$

Note that w_o in (14) affects not only the tracking error $(e,\dot{e})$ but also the estimation error $(\tilde{q},\tilde{\dot{q}})$, although w in (8) for the case with accurate velocity measurements is related with only to the tracking error. With this in mind, the following section establishes another control structure to make the observer-based CTM be more sophisticated by reducing the effects of w_o on both the tracking performances and estimation accuracies simultaneously.

IV. DUAL-LOOP CONTROL SCHEME

This section proposes a new structure of the CTM of robot manipulators by taking the so-called dual-loop control scheme [10], [11]. The dual-loop controller is a 2-*degrees-of-freedom* (DOF) controller consisting of nominal and robust controllers. The former is in the form of the standard observer-based controller as described in Section III, and the latter brings robustness to the closed-loop system. More precisely, the dual-loop control structure is constructed by

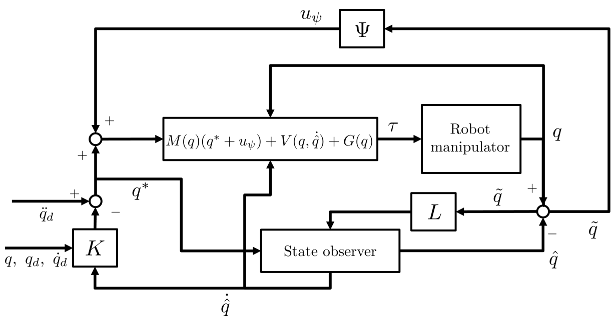


Fig. 1. Proposed dual-loop control for CTM of robot manipulators

adding another feedback loop to the observer-based controller. This ancillary loop suppresses the effects of disturbances by using the deviation between the plant output and estimation output.

A. Control Structure

The conventional dual-loop control scheme [10], [11] primarily aims at improving the robustness against the disturbance, but no argument on reducing the estimation error $(\tilde{q}, \dot{\tilde{q}})$ is discussed. The existing structure cannot suppress the effect of w_o on the estimation error $(\tilde{q},\ \dot{\tilde{q}})$ even if the robust controller produces an appropriate signal (which will be denoted by u_ψ) to improve the robustness against the disturbance. More importantly, the estimation accuracy with respect to $(\tilde{q}, \dot{\tilde{q}})$ in the conventional dual-loop control structure [10], [11] could be regarded as quantitatively equivalent to that of the observer-based control without the robust control loop discussed in the preceding section.

Motivated by this, we provide a new structure of the dual-loop control scheme on the top of the observer-based CTM architecture, as shown in Fig. 1. In other words, the torque input and the state observer are described respectively by

$$\tau = M(q)(\ddot{q}_d - u + u_\psi) + V(q, \dot{\hat{q}}) + G(q) \tag{15}$$

$$\frac{d}{dt}\begin{bmatrix}\hat{q}\\ \dot{\hat{q}}\end{bmatrix} = \begin{bmatrix}0 & I\\ 0 & 0\end{bmatrix}\begin{bmatrix}\hat{q}\\ \dot{\hat{q}}\end{bmatrix} + \begin{bmatrix}0\\ I\end{bmatrix}(\ddot{q}_d - u) + \begin{bmatrix}L_p\\ L_v\end{bmatrix}(q - \hat{q}) \tag{16}$$

where u_ψ is the robust control input generated by the robust controller Ψ in Fig. 1; Ψ is designed to improve the robustness against the disturbance by using the information of $\tilde{q}$. Combining (15), (16) and (1) derives

$$\frac{d}{dt}\begin{bmatrix}e\\ \dot{e}\\ \tilde{q}\\ \dot{\tilde{q}}\end{bmatrix} = \begin{bmatrix}0 & I & 0 & 0\\ -K_p & -K_v & 0 & -K_v\\ 0 & 0 & -L_p & I\\ 0 & 0 & -L_v & 0\end{bmatrix}\begin{bmatrix}e\\ \dot{e}\\ \tilde{q}\\ \dot{\tilde{q}}\end{bmatrix} + \begin{bmatrix}0 & 0\\ I & -I\\ 0 & 0\\ -I & I\end{bmatrix}\begin{bmatrix}w_o\\ u_\psi\end{bmatrix} \tag{17}$$

It can be observed from (17) that this additional robust control input u_ψ makes it possible to reduce the effects of w_o on both the tracking error $(e, \dot{e})$ and estimation error $(\tilde{q}, \dot{\tilde{q}})$ simultaneously, in contrast to the existing dual-loop control method [10], [11]. This new structure of the dual-loop control scheme brings a potential ability for the trajectory tracking problem of robot manipulators without velocity measurements.

B. Guideline for Taking Robust Controller Ψ with respect to Stabilization

There might be a number of methods for designing the robust controller Ψ, but such an issue does not lie in the scope of this paper since the main objectives of the present study are to propose the new framework for the observer-based CTM of robot manipulators by modifying the conventional dual-loop control structure [10], [11] and to verify its practical effectiveness. With this in mind, we take Ψ by a readily implementable controller, and give a guideline for taking the relevant parameters with respect to the stabilization of the overall closed-loop systems.

To this end, we consider a simple integrator as an effective candidate of Ψ given by

$$\Psi : u_\psi = -L_\psi \int \tilde{q} \tag{18}$$

where L_ψ is a diagonal positive matrix.

Remark 1: Due to the structural difference between the conventional methods [10], [11] and the method proposed in this paper, it is quite difficult to obtain a robust controller Ψ of a first-order integrator such as (18) to ensure the asymptotic stability of the corresponding closed-loop systems in the former structure.

Then, the closed-loop form of (17) admits the representation given by

$$\frac{d}{dt}\begin{bmatrix}e\\ \dot{e}\\ \tilde{q}\\ \dot{\tilde{q}}\\ u_\psi\end{bmatrix} = \begin{bmatrix}0 & I & 0 & 0 & 0\\ -K_p & -K_v & 0 & -K_v & -I\\ 0 & 0 & -L_p & I & 0\\ 0 & 0 & -L_v & 0 & I\\ 0 & 0 & -L_\psi & 0 & 0\end{bmatrix}\begin{bmatrix}e\\ \dot{e}\\ \tilde{q}\\ \dot{\tilde{q}}\\ u_\psi\end{bmatrix} + \begin{bmatrix}0\\ I\\ 0\\ -I\\ 0\end{bmatrix} w_o \tag{19}$$

It is obvious from (19) that the set of eigenvalues of the state-transition matrix in (19) coincide with the union of the eigenvalues of its submatrices A_F and A_L, i.e.,

$$A_F = \begin{bmatrix}0 & I\\ -K_p & -K_v\end{bmatrix}, \quad A_L = \begin{bmatrix}-L_p & I & 0\\ -L_v & 0 & I\\ -L_\psi & 0 & 0\end{bmatrix} \tag{20}$$

Because the control parameters $(K_p, K_v, L_p, L_v, L_\psi)$ can be taken arbitrarily in the proposed control structure, both the matrices A_F and A_L can be asymptotically stable. This is nothing but the asymptotic stability of the resulting closed-loop systems. For instance, if the control parameters (K_p, K_v, L_p, L_v) with respect to the nominal controller and the state observer can be parameterized respectively as

$$(K_p, K_v) = (\omega_c^2 I_{n\times n},\ 2\omega_c I_{n\times n}) \tag{21}$$

$$(L_p, L_v) = (2\omega_o I_{n\times n},\ \omega_o^2 I_{n\times n}) \tag{22}$$

with the cut-off frequency (ω_c, ω_o) relevant to the nominal performance, then the robust control parameter can be determined as $L_\psi = \gamma I_{n\times n}$ $(\gamma < 2\omega_0^3)$, with which A_L becomes Hurwitz stable.

To summarize, we can obtain the following theorem.

Theorem 1: The closed-loop system given by (19) is to be asymptotically stable by taking the control parameters

$(K_p, K_v, L_p, L_v, L_\psi)$ leading to the asymptotic stability of both the matrices A_F and A_L described by (20). Furthermore, it is ensured with such control parameters that both the tracking errors $(e, \dot{e})$ and the estimation errors $(\tilde{q}, \dot{\tilde{q}})$ are bounded for an arbitrary w.

On the other hand, it would be worthwhile to note that even though the synthesis issue on a robust controller Ψ does not lie in the scope of this paper, it could be obtained by using the conventional schemes of robust linear quadratic regulator (LQR) [12], $\mathcal{L}_{p/q}$ optimal control schemes [13], [14], sliding mode control (SMC) [15], and so on. Hence, the proposed control structure is undoubtedly regarded as a practically effective framework for the observer-based CTM of robot manipulators since it could be immediately implemented to real robot manipulators by taking various existing control schemes.

V. SIMULATION AND EXPERIMENT

This section is devoted to verifying the practical effectiveness and the theoretical validity of the proposed structure through some simulation and experimental results with a 2-linked and a 6-linked robot manipulators, respectively. More precisely, we examine accuracies for the velocity estimations by comparing the proposed dual-loop architecture and the observer-based CTM without the robust control loop discussed in Section III. This evaluation could be done rigorously only by simulations since the velocity measurements in experiments often contain noises. Meanwhile, the practical effectiveness associated with the tracking performances as well as the theoretical validity relevant to the stability are demonstrated through experiments.

A. Simulation Result

Because the estimation accuracies with respect to $(\tilde{q}, \dot{\tilde{q}})$ in the conventional dual-loop control structure [10], [11] is quantitatively equivalent to that of the observer-based control without the robust control loop in Section III, their comparison study conducted in this subsection can be interpreted as indirectly showing the effectiveness of the proposed structure in improving the estimation accuracies rather than the existing dual-loop control structure.

Remark 2: Regarding the comparison between the proposed dual-loop control structure and conventional structure [10], [11] with respect to the tracking performance, it should be noted that their direct comparison in a fair fashion is a non-trivial task because of the structural differences as discussed in *Remark* 1.

Let us consider the 2-linked robot manipulator as shown in Fig. 2, whose equation of motion is described by

$$M(q(t)) = \begin{bmatrix} \theta_1 + 2\theta_3\mathcal{C}_2 & \theta_2 + \theta_3\mathcal{C}_2 \\ \theta_2 + \theta_3\mathcal{C}_2 & \theta_2 \end{bmatrix}$$

$$V(q(t), \dot{q}(t)) = \begin{bmatrix} -\theta_3\mathcal{S}_2\dot{q}_1(t)\dot{q}_2(t) & \theta_3\mathcal{S}_2(\dot{q}_1(t) - \dot{q}_2(t))\dot{q}_2(t) \\ -\theta_3\mathcal{S}_2\dot{q}_1^2(t) & 0 \end{bmatrix}$$

$$G(q(t)) = \begin{bmatrix} \theta_4\mathcal{S}_{12} + \theta_5\mathcal{S}_1 \\ \theta_4\mathcal{S}_{12} \end{bmatrix}$$

TABLE I

RMS VALUES OF VELOCITY ESTIMATION ERRORS IN SIMULATIONS

Link	1	2
PM	0.1364	0.1466
OB	0.2221	0.3452

where $\theta_1 = 0.0710$[kg·m^2], $\theta_2 = 0.01266$ [kg·m^2], $\theta_3 = 0.001569$ [kg·m^2], $\theta_4 = 0.07575$ [kg·m^2/s^2], $\theta_5 = 0.7871$ [kg·m^2/s^2], $\mathcal{C}_2 := \cos(q_2(t))$, $\mathcal{S}_1 := \sin(q_1(t))$, $\mathcal{S}_2 := \sin(q_2(t))$, and $\mathcal{S}_{12} := \sin(q_1(t) - q_2(t))$ with the initial condition $q(0) = \begin{bmatrix} 0.1 & 0 \end{bmatrix}^T$ and $\dot{q}(0) = \ddot{q}(0) = 0$. It is assumed that the value of joint angle $q(t)$ is exactly known in real-time, but the value of joint velocity $\dot{q}(t)$ cannot be measured directly due to the absence of velocity sensors. We also consider the case where the external torque $\tau_d(t)$ is an arbitrary signal with a magnitude of up to 4.0 [N·m]. The desired trajectory $q_d(t)$ are described by 5th-order polynomials with zero initial condition, $q_d(0) = \dot{q}_d(0) = \ddot{q}_d(0) = 0$ as shown in Fig. 3. The control parameters (K_p, K_v, L_p, L_v) are taken by (21) and (22) with the cut-off frequency $(10, 30)$, and we determine the robust control gain $L_\psi = 21600$ such that A_L is asymptotically stable. The observer-based control without the robust control loop is also considered with the same control parameters taken in the proposed method. For the notational simplicity, the proposed method and the observer-based controller without the robust control loop are denoted by PM and OB, respectively, throughout this section.

Fig. 4 shows that the simulation results of the velocity estimation errors $\dot{\tilde{q}}$ and their root-mean-square (RMS) values (of the estimation error $\dot{\tilde{q}}$) for each joint are given in Table. I. We can observe from Fig. 4 and Table. I that the proposed method with the robust control loop leads to more improved estimation accuracies than the observer-based control without the robust control loop for both joints. The proposed method reduces the RMS errors for each joint by 38% and 57%, respectively, and it can readily be seen that the estimation errors of the proposed method converge to 0 much faster. These observations clearly demonstrate that the proposed structure is more effective in reducing the estimation errors than the conventional structure.

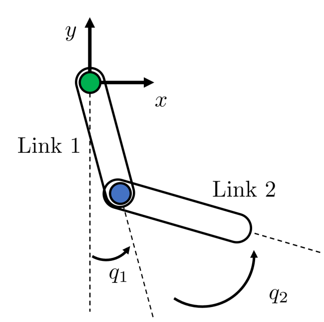


Fig. 2. Robot manipulator used in simulations

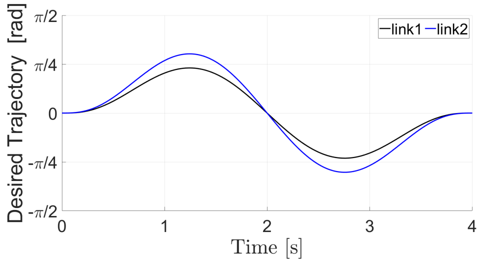
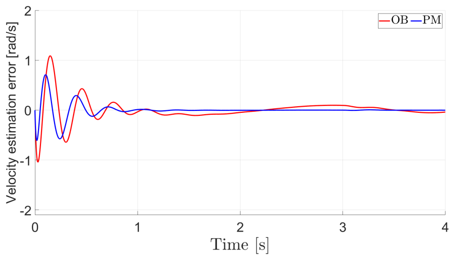
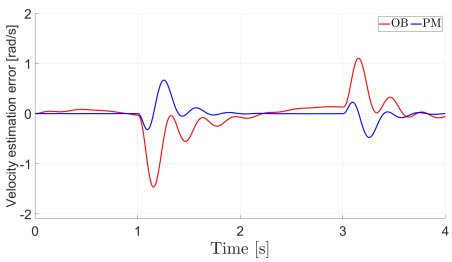


Fig. 3. Desired trajectory used in simulations



(a) Velocity estimation error of link 1



(b) Velocity estimation error of link 2

Fig. 4. Result for velocity estimation errors in simulations (red: observer-based control without the robust control loop, blue: proposed method)

B. Experimental Validation

This subsection demonstrates the practical effectiveness and the theoretical validity of the proposed structure through some experiments with the 6-linked robot manipulator as shown in Fig. 5, whose the model information is given in Table II. The experiments would be conducted in the operating frequency 1 kHz with comparisons between the proposed method, the conventional CTM method with velocity measurements from tachometers, and the observer-based controller without the robust control loop. We denote the conventional CTM method with velocity measurements by CV to simplify the notation.

First of all, assume that the joint angle can be measured without measurement errors in real-time and the initial joint angle is exactly known. With this assumption, we take $\hat{q}(0) = q(0)$. The desired trajectories $q_d(t)$ are shown in Fig 6, which correspond to exponential functions with the initial conditions $q_d(0) = q(0)$ and $\dot{q}_d(0) = \ddot{q}_d(0) = 0$. The control parameters (K_p, K_v, L_p, L_v) are taken by (21) and (22) with the cut-off frequency $(30, 50)$ and $(60, 110)$ for the links 1–4 and the links 5–6, respectively. Furthermore, we assign the robust control parameters by $L_\psi = 10000$ and $L_\psi = 50000$ for the links 1–4 and the links 5–6, respectively. The control parameters of CV and OB are taken as the same as those of (K_p, K_v, L_p, L_v) in the proposed method. The trajectory tracking errors of the three methods are shown in Fig. 7, and their RMS and steady-state values are given in Tables III and IV, respectively.

Fig. 5. Robot manipulator used in experiments

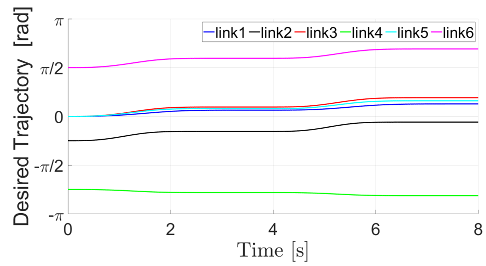
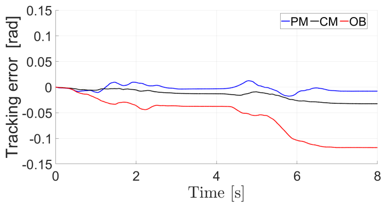


Fig. 6. Desired trajectory used in experiments

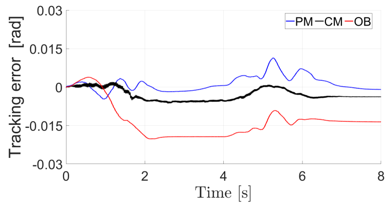
It can be clearly observed from Fig. 7 and Tables III and IV that the overall tracking performances of the proposed method are much superior to those of the other methods. The RMS values for the proposed method (PM) are reduced up to 76% and 91% from 13% and 77% compared to the conventional method (CV) and the observer-based method (OB), respectively. More importantly, the proposed method is effective in reducing steady-state trajectory tracking errors. The steady-state errors for the PM are reduced up to 99% and 99% from 75% and 93% compared to the CV and OB, respectively. Furthermore, we can observe from Fig. 7(b) that the CV exhibits unstable fluctuations due to sensor noises affecting the derivative parameter K_v, while the PM shows smooth joint angle movements. It is also worth noting that the PM leads to better performances at reducing the RMS and steady-state values than the CM even if the PM does not require velocity measurements/sensors. These observations of the experimental results clearly demonstrate that the proposed structure can be effectively used for the CTM of robot manipulators without velocity measurements.

VI. CONCLUSIONS

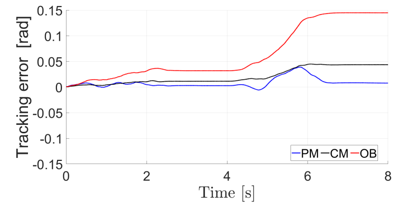
This paper developed a modified dual-loop control scheme for the CTM of robot manipulators without velocity measurements. When the CTM generates a torque input without velocity measurements, the estimation errors could yield the



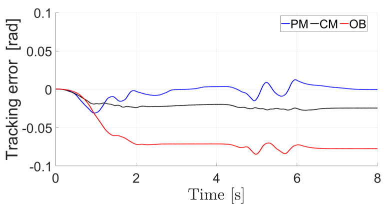
(a) Tracking error for link 1



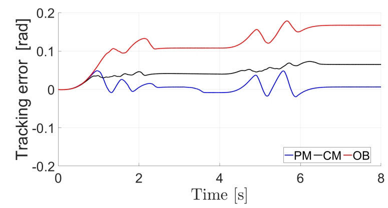
(b) Tracking error for link 2



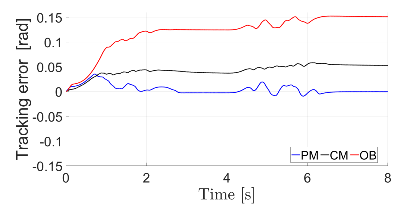
(c) Tracking error for link 3



(d) Tracking error for link 4



(e) Tracking error for link 5



(f) Tracking error for link 6

Fig. 7. Result for trajectory tracking error (red: Luenberger-observer-based controller, blue: proposed method)

TABLE II

MODEL INFORMATION OF ROBOT MANIPULATOR USED IN EXPERIMENTS

Link	1	2	3	4	5	6
Mass [kg]	5.6175	3.2286	3.5878	1.2259	1.6665	0.7355
Length [m]	0.3330	0.1660	0.1500	0.1600	0.1240	0.0880

TABLE III

RMS OF TRACKING ERRORS IN EXPERIMENTS

Link	1	2	3	4	5	6
PM	0.0068	0.0033	0.0123	0.0091	0.0155	0.0103
CV	0.0184	0.0038	0.0261	0.0220	0.0489	0.0444
OB	0.0694	0.0148	0.0831	0.0681	0.1268	0.1256

TABLE IV

STEADY-STATE TRAJECTORY TRACKING ERRORS IN EXPERIMENTS

Link	1	2	3	4	5	6
PM	0.0080	0.0009	0.0077	0.0003	0.0062	0.0004
CV	0.0326	0.0038	0.0436	0.0244	0.0648	0.0531
OB	0.1181	0.0136	0.1448	0.0773	0.1671	0.1511

tracking performance degradation. To address this problem, we employed the dual-loop robust control scheme. We then clarified that the conventional structure of the dual-loop control scheme could not reduce the effect of the disturbances on the estimation errors. Thus, we provided a new architecture for the dual-loop control scheme that can suppress the effect of the disturbances on the tracking and estimation errors simultaneously. Furthermore, a guideline for taking the relevant control parameters with respect to the stability issues was also provided. Finally, the simulation and experimental results demonstrated the effectiveness and validity of the proposed structure.

Beyond the practical effectiveness and the theoretical validity of the proposed method discussed in this paper, a more sophisticated study on controller synthesis for this new architecture is left for an interesting future works. Such future studies could include the synthesis of advanced controllers for the proposed structure and a direct comparison between the conventional and proposed structures with the similar controller forms.

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