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Consensus Control for Networked Manipulators With Switched Parameters and Topologies

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ABSTRACT To solve abruptly occurrence of parameters jumping and directed communication topologies changing in the control process of networked manipulators, in this paper, distributed switched consensus control algorithms are formulated for a group of robot manipulators in realizing cooperative consensus performance. In fact, networked Lagrange systems are modeled as switched systems regarding the different parameters and topologies. Namely, the dynamic models switch when the system parameters or the topology structures change. The consensus control strategy is constructed by resorting to (improved) average dwell time (ADT) method and sliding-mode control technique, and a unified analysis methodology is developed to perform the convergence analysis for the closed-loop system by Lyapunov stable theory. The main contribution of this paper is the development of a systematically adaptive consensus algorithm by simultaneously considering shifting parameters and switching communication network (as two unavoidable key factors) in the process of communication interaction among robots. A distinctive feature of the developed consensus protocol is to introduce the directed network topology characterizing the local communication interaction among robots, which is especially suitable for representing the the structures and features of the realistic cooperative multi-robotic systems. Accordingly, the developed consensus tracking strategy for manipulators possess prominent advantages including robustness,stability and effectiveness over the existing concentrated on single robot counterparts. Finally, numerical simulations of two-link manipulators are performed to illustrate the effectiveness of the obtained control algorithm.

INDEX TERMS Networked manipulators, switching control, parameters jump, communication topologies change, cooperative consensus, (improved) average dwell time method.

I. INTRODUCTION

Coordination of multi-agents systems has spawned widespread attention over the last two decades, which is partly aroused by the vast applications in assembly lines, rescue, reconnaissance, etc [1]–[7]. Compared to single robot, multiple robots can operate more complex tasks effectively with high flexibility and reliable performance [8]–[10]. As a matter of fact, diverse control techniques such as adaptive control, slide mode control, tracking control, backstepping scheme for multi-agent systems have been proposed to solve the problem of network flocking, consensus, formation control over the last decades, please see [11]–[13]. In particular, one of the typical cases regarding consensus for a team of robots is to cooperatively transport large and heavy loads, they even need to lay down and carry up different loads repeatedly. Accordingly, the mass center and the inertia for each robot change with the shifting load, which leads to the system parameters for all the agents keep switching among several values [14]. In this paper, the two link robotic manipulators are taken as typical research object to investigate the coordinated consensus control problems.

In practical applications, robot systems inevitably possess various uncertainty because of a large volume of complicated factors, such as unstructured dynamics, external disturbances and varying environments as well as the changing loads, etc [15], [16]. Consequently, it is difficult to find accurate dynamic models, and impractical to use basic control methods that are highly dependent on accurate model parameters in the industry assembly lines. It is well known that

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robust control and adaptive control are very effective methods for dealing with system uncertainties [17]. Nevertheless, the uncertainty caused by loads change is more prominent compared to other uncertainties [18]. This is mainly because the uncertainty caused by the switching loads will greatly expand its upper bound, which results in the high energy consumption [19]. In order to solve the above problems, an autonomous switched control algorithm is proposed to perform tracking control for single manipulator with shifting loads in the reference [20], besides, a switched mode is constructed with respect to each different load, the model switched if the load shifts.

For another, switched system, which is composed of subsystems and switching rules, is a typical hybrid system, and plays an important role in the era of intelligence [21]–[26]. Accordingly, the switched systems have attracted increasing attention owing to the ability to deal with a variety of dynamics behaviour including logic commands, varying structures, parameters jump, etc [27]–[30]. Apart from the loads change, the communication topologies may be unstable in the process of coordinated control for networked robot systems. The main reasons are originated from the failure of information transmission among some agents, message dropouts of the communication and external disturbance and so on [31]–[33]. Therefore, new communication connections will be created among the nearby agents [34]–[36]. Generally speaking, cases including loads change or the communication structures change of the robotic manipulators can be dealt with the switched Lagrange dynamic model. That is, the model switches when the loads shift or the directed graphs transform. In conclusion, the switching control algorithm is meaningful both in system switching and topology switching for multiple mobile robots.

Inspired in part by the aforementioned backgrounds, the coordinated consensus for the switched multiple Lagrangian systems are studied in the presence of the parameters changing and directed topologies switching for a team of manipulators governed by Euler-Lagrange systems. Specifically, a novel distributed consensus algorithm is proposed based on the integration of sliding-mode control scheme and (average) ADT method to solve consensus problem, where a smaller average dwell time is derived to guarantee the stable of the closed-loop system. In particular, each different load or communication topology corresponds to one subsystem whose sub-controllers have designed beforehand. It is noted that the switched controllers are given under the condition that sub-controllers switch synchronously with the switched sub-systems. The merits and novelty of this work are summarized in the three aspects:

(i) a simple yet general analysis framework regarding the proposed switching control algorithm is presented to develop a unified methodology for the cooperative switching control in the point view of multi-agent systems.

(ii) the problems of model parameters jump and the switching communication topologies are all considered in the control protocol, a smaller average dwell time is derived by ADT and improved ADT methods.

(iii) the information interaction among the manipulators is appropriately characterized by communication topology under the graph theory.

The remainder of this paper is organized as follows. The problem preliminaries are briefly provided in Section 2. Section 3 describes switched multiple Euler-Lagrange systems. Section 4 gives the control design for multi-mobile robots. In Section 5, examples and simulations are presented to validate the proposed control scheme. Finally, the conclusion is drawn in Section 6.

II. PROBLEM PRELIMINARIES

A. GRAPH THEORY

The information exchange connections of n robots can be represented by a weighted directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E}, \mathcal{W})$, where $\mathcal{V} = \{1, 2, \cdots n\}$, $\mathcal{E} \in \mathcal{V} \times \mathcal{V}$ and $\mathcal{W} = [w_{ij}]_{n\times n}$ are the node set, edge set and the weight adjacency matrix, respectively. $(i, j) \in \mathcal{V}$ denotes that robot j can receive the information form robot i. Where $w_{ij} = 0$ if $(i, j) \notin \mathcal{E}$, otherwise, $w_{ij} \neq 0$, and $w_{ii} \equiv 0$ means that there is no self-loop. A directed spanning tree is that a root node has a directed path to other path. In general, we define the Laplacian matrix $L_w = [l_{ij}]_{n\times n}$ as $l_{ii} = \sum_{j=1}^{n} w_{ij}$ if $i = j$, and $l_{ij} = -w_{ij}$ if $i \neq j$.

The switching connected topologies will be described below. For any switching signal $\sigma(t) \in \Lambda = \{1, 2, \cdots\}$, $t \in [t_r, t_{r+1})$, $r = 0, 1, 3\cdots$, the switching time sequence $\{t_r\}_{r=0}^{+\infty}$ is assumed satisfy $t_0 < t_1 < t_2 < \cdots < \infty$, where the map $\sigma(t) : [0, +\infty)$ is right continuous piecewise and constant stochastic. The time subsequence r_m with $[t_r, t_{r+1})$ can be expressed as $[t_r, t_{r+1}) = \bigcup_{m=1}^{n_m+1}[t_{r_m}, t_{r_{m+1}})$, and $t_{r_{m+1}} - t_{r_m} < \delta$, $\delta > 0$. The switched topology is fixed with $t \in [t_{r_m}, t_{r_{m+1}})$ such that every robot $i \in \Xi$ is reachable in the union graph $\bigcup_{m=1}^{n_m+1} \mathcal{G}^{\sigma(t_m)}$ instead of every $\mathcal{G}^{\sigma(t_m)}$ is required to be strongly connected, then the switched topology $\mathcal{G}_{\sigma(t)}$ is jointly connected. Note that, the corresponding adjacency matrix $\mathcal{W}^{\sigma(t)}$ and Laplace matrix $L_w^{\sigma(t)}$ are time varying.

B. SWITCHED SYSTEMS

For the switched systems, it is commonly known that the ADT scheme describes a large class of stable switching signals. Consider the switched systems [38]

$$\dot{x}(t) = f_{\sigma(t)}(x) \tag{1}$$

where $x \in \mathbb{R}^n$ is the state, the switching signal $\sigma(t) : [0, \infty) \rightarrow \Lambda = \{1, 2, \cdots d\}$ is is right continuous piecewise, and $\sigma(t) = p$ means that the pth subsystem is active. Then, we give the switched rules regarding average dwell time for nonlinear systems.

Let $\tau_l = t_l - t_{l-1}$ denotes the dwell time, the definition and lemmas of (improved) ADT method are given:

Definition 1: A switching signal $\sigma(t)$ has average dwell time τ_l, if there are numbers N_0, τ_l such that

$$N_\sigma(T, t_0) \leq N_0 + \frac{T - t_0}{\tau_l}, \forall T \geq t_0 \geq 0 \tag{2}$$

Lemma 1: [23] For the nonlinear switched system (1), if there exist function $U_i = x^T P_i x$, $i, j \in \Lambda$ and two class K_∞ functions α_1 and α_2, a positive number λ such that

$$\alpha_1 \|x(t)\|^2 \leq U_i(x) \leq \alpha_2 \|x(t)\|^2, \tag{3}$$

$$\frac{\partial U_i(x)}{\partial x} f_i(x) \leq -\lambda U_i(x), \tag{4}$$

$$U_i(x) \leq \mu U_j(x). \tag{5}$$

(i) [ADT approach] for some positive number μ, then the switched system is globally asymptotically stable under any switching signal with the ADT:

$$\check{\tau} > \check{\tau}^* = \frac{\ln \mu}{\lambda}; \tag{6}$$

(ii) [improved ADT approach (IADT)] [38] if the inequalities (3)(4) hold, for some positive number μ^*, then the switched system is globally asymptotically stable under any switching signal with the ADT:

$$\check{\tau} \geq \check{\tau}^* = \frac{\ln \mu^*}{\lambda}, \mu^* = \sup_{p \in \Lambda} \frac{\alpha_{i2}}{\alpha_{i1}}. \tag{7}$$

Remark 1: The Lemma 1 (i) and (ii) are the classical ADT approach and improved ADT (IADT) approach, respectively. For convenience, we combine them together here. Obviously, both ADT and IADT methods need to satisfy conditions (3) and (4), and ADT approach also require condition (5) that IADT approach doesn't. As state in [38], the IADT criterion to some extend is simpler and more significant in theoretical analysis and control application. Especially, for linear switching systems, the minimum average dwell time required for the IADT method is smaller than the ADT method.

C. SWITCHED EULER-LAGRANGE SYSTEMS

As known to us all, a group of robots are usually used to coordinated carry heavy or large objects in modern factory. And sometimes, they need to repeatedly lay down and pick up different kinds of goods mechanically, which leads to the uncertainties in the value of system parameters. Moreover, the communication topology structures maybe unstable and changeable for various factors including equipment limitation, external disturbance, etc. Now, the switching construction of networked manipulators will be introduced to characterize the switching behaviour. Supposed that there exist N manipulators, and the ith robot is described by following switched Lagrange systems:

$$M_{i\sigma(t)}(q_i)\ddot{q}_i + C_{i\sigma(t)}(q_i, \dot{q}_i)\dot{q}_i + G_{i\sigma(t)}(q_i) = \tau_{i\sigma(t)}, \tag{8}$$

where $\sigma(t)$ is the switching signal, $\sigma(t) = p$ means that the pth subsystem of the ith robot is active, $i \in \Xi = \{1, 2, \cdots, N\}$, $q_i, \dot{q}_i \in \mathbb{R}^n$ are the vectors of generalized coordinates and velocities, respectively, $M_{i\sigma(t)}(q_i) \in \mathbb{R}^{n\times n}$ is a symmetric and positive definite inertia matrix, $C_{i\sigma(t)}(q_i, \dot{q}_i) \in \mathbb{R}^{n\times n}$ represents the coriolis and centrifugal force matrix and $G_{i\sigma(t)}(q_i) \in \mathbb{R}^n$ represents the gravitational force, $\tau_{i\sigma(t)} \in \mathbb{R}^n$ is the control input of the robot i.

Remark 2: The mechanism of switching model (8) is that when the parameters or topology change, the switching system switches from one subsystem to another, and all subsystems in the switching model are different. It is practical to assume that the times of parameter and topology shifting is limited, which means that the number of subsystems is also limited. Moreover, we only consider the case that all the subsystems are stable subsystems for the switching Lagrange system, then, corresponding sub-controller for each subsystem is designed beforehand to make it stable.

For the sequel applications, several properties, definitions and lemmas are given to facilitate the control process. First, suppose that the Lagrange system has following properties:

Property 1: (Boundedness) [16] $M_{ip}(q_i)$ and $C_{ip}(q_i, \dot{q}_i)$ are bounded, and $\alpha_{i1}^p \|x_i\| \leq x_i^T M_{ip}(q_i) x_i \leq \alpha_{i2}^p \|x_i\|$, $i \in \Xi$, $p \in \Lambda$.

Property 2: (Skew symmetric) [15] $\dot{M}_{ip}(q_i) - 2C_{ip}(q_i, \dot{q}_i)$ is skew symmetric.

Lemma 2: [4]If a directed topology graph has a directed spanning tree, then the corresponding Laplacian matrix $\mathcal{L}_w$ has only one zero eigenvalue and the other eigenvalues have positive real parts.

Definition 2: [4] The switched control torque $\tau_{i\sigma(t)}(i = 1, 2, \cdots N)$ for a group of agents with parameter and topologies changing is said to solve consensus problem, if $\lim_{t\to\infty} \|q_i - q_j\| = 0$, $\lim_{t\to\infty} \|\dot{q}_i - \dot{q}_j\| = 0$.

Assumption 1: Assume that the switching communication topology $\mathcal{G}_{\sigma(t)}$ has a directed spanning tree in each interval $[t_k, t_{k+1}]$. If not, assume that every node is connected in the union graph $\bigcup_{m=1}^{n_m+1} \mathcal{G}_{\sigma(t_m)}$.

III. SWITCHED CONSENSUS OF EL SYSTEMS

A. CONTROL DESIGN

In this section, we deal with the adaptive switched consensus control problems for multi-mobile robots. Assume that the sub-controller match the active subsystem simultaneously when the loads (parameters) shifting. Before moving on, an auxiliary slide-mode reference variable $\dot{q}_{ri}$ regarding position error information is presented,

$$\dot{q}_{ri}^p = -\sum_{j\in\mathcal{N}_i} \omega_{ij}^p (q_i - q_j), \tag{9}$$

and its derivative along time t is given by:

$$\ddot{q}_{ri}^p = -\sum_{j\in\mathcal{N}_i} \omega_{ij}^p (\dot{q}_i - \dot{q}_j), \tag{10}$$

then, a slide mode vector $s_i^p \in \mathbb{R}^n$ containing topological information can be designed as:

$$s_i^p = \dot{q}_i - \dot{q}_{ri}^p. \tag{11}$$

Accordingly, the distributed switched subcontroller is formulated by

$$\tau_{ip} = M_{ip}(q_i)\ddot{q}^p_{ri} + C_{ip}(q_i, \dot{q}_i)\dot{q}^p_{ri} + G_{ip}(q_i) - K_{ip}s^p_i, \quad (12)$$

where K_{ip} is a positive definite matrix, $i \in \Xi$, $\sigma(t) = p \in \Lambda$. Combining the Eq. (12) with (8), one can obtain the following closed-loop system:

$$M_{ip}(q_i)\dot{s}^p_i = -C_{ip}(q_i, \dot{q}_i)s^p_i - K_{ip}s^p_i. \quad (13)$$

B. CONVERGENCE ANALYSIS

Based on above preparations, here, we give the following theorems regarding switched consensus control by ADT method and improved ADT method for multiple mobile manipulators.

Theorem 1: Under Assumption 1, the switched multi-Lagrange systems (8) can reach consensus $q_i \to q_j$ as $t \to \infty$ by adaptive switched control protocol (12) under arbitrary switching path $\sigma(t)$ with the average dwell time:

$$\check{\tau}_{ia} > \check{\tau}^*_{ia} = \frac{\ln \mu_{i\min}}{\lambda_{i\min}}, \quad (14)$$

where

$$\mu_{i\min} = \min\{\mu_i, \mu^*_i\}, \lambda_{i\min} = \min_{i\in\Xi, p\in\Lambda} \lambda_{ip},$$

$$\mu_i = \sup_{s^p_i \neq 0, p,q\in\Lambda} \frac{\alpha^p_{i2}}{\alpha^q_{i1}}, \mu^*_i = \sup_{s^p_i \neq 0, p\in\Lambda} \frac{\alpha^p_{i2}}{\alpha^p_{i1}}$$

Proof: The proof procedure of Theorem 1 in this part involves two steps by adopting ADT and improved ADT method, together with lyapunov-like analysis approach. In the first step, the minimum average dwell time by ADT and IADT methods will be calculated to guarantee the stability of the switched system. In the second step, the specific trajectory tracking for all the manipulators will be further proved.

Step 1: (1) ADT method

For the closed loop system (13), one considers following Lyapunov function candidate:

$$V_{ip} = \frac{1}{2}s^{pT}_i M_{ip} s^p_i, i \in \Xi, \quad p \in \Lambda, \quad (15)$$

differentiating the Eq. (15) along Eq.(13) yields:

$$\frac{dV_{ip}(s^p_i(t))}{dt} = \dot{V}_{ip}(s^p_i(t)) = -s^{pT}_i K_{ip} s^p_i. \quad (16)$$

For any $t \in [t_k, t_{k+1})$, $i \in \Lambda$, by using Property 1 and Eq (15), we have:

$$\begin{aligned}\frac{\min_{i\in\Xi,p\in\Lambda} \alpha^p_{i1}}{2}\|s^p_i\|^2 &\leq \frac{\alpha^p_{i1}}{2}\|s^p_i\|^2 \leq V_{ip}(s^p_i) \\ &\leq \frac{\alpha^p_{i2}}{2}\|s^p_i\|^2 \leq \frac{\max_{i\in\Xi,p\in\Lambda} \alpha^p_{i2}}{2}\|s^p_i\|^2. \quad (17)\end{aligned}$$

Combining Eqs.(16) and (17), one can obtain:

$$\begin{aligned}\dot{V}_{ip}(s^p_i) &\leq -\lambda_{\min}(K_{ip})\|s^p_i\|^2 \\ &\leq -\frac{2}{\alpha^p_{i2}}\lambda_{\min}(K_{ip})V_{ip}(s^p_i) \\ &= -\lambda_{ip}V_{ip}(s^p_i), i \in \Xi, \quad p \in \Lambda, \quad (18)\end{aligned}$$

where $\lambda_{ip} = \frac{2}{\alpha^p_{i2}}$. Moreover, from Eq (17) we have:

$$\begin{aligned}V_{ip}(s^p_i) &\leq \frac{\alpha^p_{i2}}{\alpha^q_{i1}}V_{iq}(s^p_i) \leq \mu_{ipq}V_{iq}(s^p_i) \\ &\leq \max_{p,q\in\Lambda}(\mu_{ipq})V_{iq}(s^p_i) \\ &= \mu_i V_{iq}(s^p_i), \forall i \in \Xi, \quad p, q \in \Lambda \quad (19)\end{aligned}$$

Taken together, the inequations (17), (18) and (19) hold when the subcontrollers switching synchronously with the subsystems in the presence of the known $\sigma(t)$, which satisfy the conditions (3), (4) and (5), where $\lambda_{i\min} = \min_{i\in\Xi,p\in\Lambda}(\lambda_{ip})$. Accordingly, the switched Lagrange systems are global asymptotic stability with the ADT $\check{\tau}_{ia} > \check{\tau}^*_{ia} = \frac{\ln \mu_i}{\lambda_{i\min}}$, $\mu_i = \sup_{s^p_i\neq 0, p,q\in\Lambda} \frac{\alpha^p_{i2}}{\alpha^q_{i1}}$.

(2) IADT method

Now, we further to calculate another average dwell time by improved ADT method.

The Lyapunov function is chosen same as (15), and let $t_1, t_2, \cdots, t_{N_\sigma}$ denote the switching instant during $(0, T)$, for $\forall T > 0$, and p_k be the value of $\sigma(t)$ on the time interval $[t_{k-1}, t_k)$. Integrate Eq.(18) over time $[t_{k-1}, t_k)$, we have:

$$\ln V_{ip_k}[s^p_i(t_k)] - \ln V_{ip_k}[s^p_i(t_{k-1})] \leq \lambda_{ip_k}\check{\tau}_k \quad (20)$$

$$V_{ip_k}[s^p_i(t_k)] \leq e^{-\lambda_{ip_k}\check{\tau}_k}V_{ip_k}[s^p_i(t_{k-1})] \quad (21)$$

Combining Property 1 and Eq.(27) give

$$\begin{aligned}\alpha^p_{i1}\|s^p_i(t_k)\|^2 &\leq V_{ip_k}[s^p_i(t_k)] \leq e^{-\lambda_{ip_k}\check{\tau}_k}V_{ip_k}[s^p_i(t_{k-1})] \\ &\leq \alpha^p_{i2}e^{-\lambda_{ip_k}\check{\tau}_k}\|s^p_i(t_{k-1})\|^2\|s^p_i(t_k)\|^2 \\ &\leq \frac{1}{\alpha^p_{i1}}V_{ip_k}[s^p_i(t_k)] \leq \frac{\alpha^p_{i2}}{\alpha^p_{i1}}e^{-\lambda_{ip_k}\check{\tau}_k}\|s^p_i(t_{k-1})\|^2 \\ &\leq \mu^*_i e^{-\lambda_{ip_k}\check{\tau}_k}\|s^p_i(t_{k-1})\|^2 \quad (22)\end{aligned}$$

Therefore, for arbitrary t satisfying $t_0 < t_1 < t_2 <, \cdots, t_m \leq t < t_{m+1}$, one can have:

$$\begin{aligned}\|s^p_i(t)\|^2 &\leq \frac{1}{\alpha^{\sigma(t_m)}_{i1}}V_{i\sigma(t)} \\ &\leq \frac{1}{\alpha^{\sigma(t_m)}_{i1}}e^{-\lambda_{i\sigma(t_m)}(t-t_m)}V_{i\sigma(t)}[s^p_i(t_m)] \\ &\leq \frac{\alpha^{\sigma(t_m)}_{i2}}{\alpha^{\sigma(t_m)}_{i1}}e^{-\lambda_{i\sigma(t_m)}(t-t_m)}\|s^p_i(t_m)\|^2 \\ &= \mu^*_{i\sigma(t_m)}e^{-\lambda_{i\sigma(t_m)}(t-t_m)}\|s^p_i(t_m)\|^2 \\ &\leq \mu^*_{i\sigma(t_m)}\mu^*_{i\sigma(t_{m-1})}e^{-\lambda_{i\sigma(t)}(t-t_m)-\lambda_{i\sigma(t_m)}(t_m-t_{m-1})} \\ &\quad \times\|s^p_i(t_{m-1})\|^2 \\ &\quad \vdots\end{aligned}$$

$$\leq \mu_i^* \prod_{m=1}^{N} e^{a_{im}N_{\sigma_m}(t_0,t)-\lambda_{im}T_{im}(t_0,t)} \|s_i^p(0)\|^2, \quad (23)$$

where $a_{im} = \ln \mu_{im}^*$.

Since the Lyapunov function $V_{ip} > 0$, and its derivative $\dot{V}_{ip} < 0$, then we can get s_i is bounded. Moreover, it is obvious that $\mu_{im} \geq 1$, $a_{im} \geq 0$.

(i) If $a_{im} = 0$, i.e., $u_{im} = 1$, from the inequality (23), we can have:

$$\|s_i^p(t)\|^2 \leq \prod_{m=1}^{N} e^{-\lambda_{im}T_{im}(t_0,t)} \|s_i^p(0)\|^2$$
$$\leq e^{-\lambda_{i\min}(t-t_0)} \|s_i^p(0)\|^2 \quad (24)$$

where $\lambda_{i\min} = \min_{i\in\Xi, p\in\Lambda}(\lambda_{ip})$, which indicates that the closed loop Lagrange systems (13) are global asymptotic stability under arbitrary average dwell time.

(ii) If $a_{im} \neq 0$, together with the inequality (2), we get:

$$a_{im}N_{\sigma_m}(t_0,t) - \lambda_{im}T_{im}(t_0,t)$$
$$\leq a_{im}N_{0im} + (\frac{a_{im}}{\breve{\tau}_{ia*}} - \lambda_{im})T_{im(t_0,t)}. \quad (25)$$

By combining Eq.(23) with (25), then, one can obtain:

$$\|s_i^p(t)\|^2 \leq \mu_i^* \prod_{m=1}^{N} e^{a_{im}N_{0im}(t_0,t)+(a_{im}/\breve{\tau}_{ia*}-\lambda_{im})T_{im}(t_0,t)}$$
$$\times \|s_i^p(0)\|^2$$
$$= \mu_i^* \bar{h}_i e^{\lambda_{\min}(t-t_0)} \|s_i^p(0)\|^2, \quad (26)$$

where $\bar{h}_i = \prod_{m=1}^{N} e^{a_{im}N_{0im}}$, $\lambda_{\min} = \min_{m=1}^{N}\{\lambda_{im} - \frac{a_{im}}{\breve{\tau}_{ia*}}\}$, as a result, the systems (13) are global asymptotic stability with the average dwell time $\breve{\tau}_{ia} > \breve{\tau}_{ia}^* = \frac{\ln \mu_i^*}{\lambda_{i\min}}$, $\mu_i^* = \sup_{s_i^p\neq 0, p\in\Lambda} \frac{\alpha_{i2}^p}{\alpha_{i1}^p}$.

It is worth mentioning that the closed loop system (13) can be stabilized by both ADT and IADT method, but the obtained ADT is different since the different μ_i, μ_i^*. Therefore, we take the smaller average dwell time with (14).

Step 2: Now, we further to verify that the networked manipulators can reach consensus $q_i \to q_j$ as $t \to \infty$ from the point view of multi-agent systems. For convenience, the sliding-mode variables (11) can be written as a vector form:

$$\dot{\mathbf{q}} = \mathbf{S}^p + \dot{\mathbf{q}}_r^p = \mathbf{S^p} - (\mathcal{L}_w^p \otimes I_m)\mathbf{q}, \quad (27)$$

where $\otimes$ denotes Kronecker product, $\mathbf{q} = (q_1^T, q_2^T, \cdots, q_N^T)^T$, $\mathbf{S}^p = (s_1^{pT}, s_2^{pT}, \cdot, s_N^{pT})^T$, $\mathbf{q_r} = (\dot{q}_{r1}^{pT}, \dot{q}_{r2}^{pT}, \cdots, \dot{q}_{rN}^{pT})^T$. Here, we construct a decomposition transform matrix D,

$$D = \begin{bmatrix} r_1 & r_2 & \cdots & r_{N-1} & r_N \\ -1 & 1 & \cdots & 0 & 0 \\ 0 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & -1 & 1 \end{bmatrix}, \quad (28)$$

which makes that $D^{-1}\mathcal{L}_{wp}D = diag(0, -\mathcal{L}_r)$, where $-\mathcal{L}_r \in R^{(N-1)\times(N-1)}$ is Hurwitz stable. Consider the coordinate transformation:

$$\zeta = (D \otimes I_m)\mathbf{q} \quad (29)$$

Note that the matrix D is independent of inertia of the agents, and ζ can be described as $\zeta = [\zeta_1^T, \zeta_R^T]^T$, where $\zeta_1 = \sum_{i=1}^{N} r_i q_i$, $\zeta_R = [(q_2 - q_1)^T, (q_3 - q_2)^T, \cdots, (q_N - q_{N-1})^T]^T$. Differentiating the system (29) and in combination with Eq.(27), we have:

$$\dot{\zeta} = -(D\mathcal{L}_w^p D^{-1} \otimes I_m)\zeta + (D \otimes I_m)\mathbf{S}^p \quad (30)$$

we can rewrite Eq. (30) as following two parts:

$$\dot{\zeta}_1 = (\mathbf{r} \otimes I_m)\mathbf{S}^p \quad (31)$$
$$\dot{\zeta}_R = -(\mathcal{L}_w^p \otimes I_m)\zeta_R + \mathbf{s}_R^p \quad (32)$$

where $\mathbf{r} = [r_1, r_2, \cdots, r_N]^T$, $\mathbf{s}_R^p = [(s_2^p - s_1^p)^T, (s_3^p - s_2^p)^T, \cdots, (s_N^p - s_{N-1}^p)^T]^T$.

It follows form (15)(16) that $V_{ip} > 0$, and its derivative $\dot{V}_{ip} < 0$, which indicates that $s_i^p \in L_2 \cap L_\infty$. From Eq. (31) we obtain that $\dot{\zeta}_1$ is bounded. Since $-\mathcal{L}_w^p$ is Hurwitz stable, the Eq. (32) is input-to-state stable with respect to $\mathbf{s}_R^p$ and ζ_R. Since the motion trajectories of robots are bounded, then s_i^p and $\mathbf{s}_R^p$ are bounded, one can get from Eqs. (31), (32) that ζ_R is bounded, and $\dot{\zeta}_R \in L_\infty$, $\dot{\zeta}_1$ is bounded. Differentiating Eq. (29), that is, $\dot{\zeta} = (D \otimes I_m)\dot{\mathbf{q}}$, so, $\dot{\mathbf{q}}$ is bounded. In the light of Eqs. (11) and (10), one can get $\dot{q}_{ri}^p$ and $\ddot{q}_{ri}^p$ are bounded. From the closed-loop system (13), one have $\dot{s}_i$ is bounded. Since $\ddot{V}_{ip} = -2\dot{s}_i^T K_{ip}\ddot{s}_i$ is bounded, $\dot{V}_{ip}$ is uniformly continuous. By Barbalat's lemma, one can get $s_i^p \to 0$ as $t \to \infty$, which reveals that $q_i \to q_j$ as $t \to \infty$.

By above discussion, if the ADT (14) holds, the cooperative consensus is ensured by the control protocol (12) for arbitrary switching signal, and $\lim_{t\to\infty} \|q_i - q_j\| = 0$.

Remark 3: As discussed in above section, both ADT and improved ADT approaches are utilized to calculate the minimum average dwell time for guaranteeing the stability of the switched multi-EL-systems. Moreover, the differences between the ADT and IADT method in Theorem 1 are: (i) ADT method needs to satisfy the condition $V_{ip} \leq \mu_i V_{iq}$, $i \in \Xi, p, q \in \Lambda$, that IADT approach doesn't require; (2) it is obviously that the difference of $\mu_i = \sup_{s_i\neq 0, p, q\in\Lambda} \frac{\alpha_{ip2}}{\alpha_{iq1}}$ and $\mu_i^* = \sup_{s_i\neq 0, p\in\Lambda} \frac{\alpha_{ip2}}{\alpha_{ip1}}$ leads to the different average dwell time. In deed, the conditions (3), (4), (5) are all satisfied in the EL switching model investigated in this paper, we select the smaller dwell time. In particular, if there exist the case that the condition (5) can be ensured, the improved ADT method can be applied.

Remark 4: It is worth mentioning that the cases parameter jumping and topology switching are all considered for a team of manipulators in the designing of the distributed consensus tracking strategies from the point of view of multi-agent systems. It is obvious that the occurrence of suddenly parameters and communication structures changes in the control process can result in the whole systems unstable within finite time. The proposed switching adaptive control algorithm can perfectly deal with these problems. Actually, we only consider the condition that the switched Lagrange systems autonomous match the corresponding sub-controllers once the parameters or the communications change, the mismatch case will study in the later works. Further more, the system parameters and shifting loads (switching parameters) is known.

Remark 5: So far, numerous significant switching control techniques have been proposed for general linear and nonlinear switched systems for its widespread potential applications in various fields [21], [22], [38], [39]. But for single manipulator, there are only few works have been down [14], [20], [27], let alone a team of manipulators. Accordingly, networked lagrange systems in the presence of changing parameters (loads) and switching topologies are investigated in this technique paper. Note that there have been a lot of studies on switching topology for multi-agent systems, and considerable meaningful results have been obtained [32], [34], [35], so this paper does not take it as a key problem to investigate.

IV. ILLUSTRATIVE EXAMPLES

In this section, numerical simulations are given to illustrate the effectiveness and validity of our results. For ease of calculating, we study five two-link revolute manipulators, and assume that the parameters (loads) change and communication constructs switch occur at the same time. Here, the switching system (8) we consider contains two subsystems, and the detailed parameters and communication structures are given as:

$$\begin{aligned} M_{ip}(q_i) &= \begin{bmatrix} u_{i1p} + 2u_{i2p}\cos q_{i2} & u_{i3p} + u_{i2p}\cos q_{i2} \\ u_{i3p} + 2u_{i2p}\cos q_{i2} & u_{i3p} \end{bmatrix}, \\ C_{ip}(q_i, \dot{q}_i) &= \begin{bmatrix} -u_{i2p}\dot{q}_{i2}\sin q_{i2} & -u_{i2}(\dot{q}_{i1} + \dot{q}_{i2}\sin q_{i2}) \\ u_{i2p}\dot{q}_{i1}\sin q_{i2} & 0 \end{bmatrix}, \\ g_{ip} &= \begin{bmatrix} u_{i4p}g\dot{q}_{i2}\cos q_{i1} + u_{i5p}g\cos(q_{i1+q_{i2}}) \\ u_{i5p}g\cos(q_{i1} + q_{i2}) \end{bmatrix}, \end{aligned}$$

where $g = 9.8\ m/s^2$, $q_i = (q_{i1}, q_{i1})^T$, $u_{i1p} = m_{i1p}l_{ai1}^2 + m_{i2p}(l_{i1}^2 + l_{ai2}^2) + J_{i1p} + J_{i2p}$, $u_{i2p} = m_{i2p}l_{i1p}l_{ai1}$, $u_{i3p} = m_{i2p}l_{ai2}^2 + J_{i2}$, $u_{i4p} = m_{i1p}l_{ai1} + m_{i2p}l_{i1p}$, $u_{i5p} = m_{i2p}l_{ai2}$, $J_{i1p} = m_{i1p}l_{ai1}^2/3\ kg \cdot m^2$, $J_{i2p} = m_{i2p}l_{ai2}^2/3\ kg \cdot m^2$, $l_{ai1} = l_{i1p}/2$, $l_{ai2} = l_{i2p}/3$. $\theta_{ip} = [u_{i1p}, u_{i2p}, u_{i3p}, u_{i4p}, u_{i5p}]^T$, $p \in \Lambda = \{1, 2\}$, $i \in \Xi$.

$p = 1$, $m_{i11} = 2.2\ kg$, $m_{i21} = 2.0\ kg$, $l_{i11} = 2.2\ m$, $l_{i21} = 2.5\ m$.

$p = 2$, $m_{i12} = 1.2 + 0.2ikg$, $m_{i22} = 1.4 + 0.12ikg$, $l_{i12} = 1.8 + 0.08im$, $l_{i22} = 2.3 + 0.04im$.

Example 1: The switched communication topology is connected. The initial conditions are chosen as $q_1(0) = [2, -3]^T$, $q_2(0) = [-4, 2.1]^T$, $q_3(0) = [4, -2]^T$, $q_4(0) = [5, 2]^T$, $q_5(0) = [3, -2]^T$; $\dot{q}_1(0) = [4, -2]^T$, $\dot{q}_2(0) = [-4, -2]^T$, $\dot{q}_3(0) = [3, 5]^T$, $\dot{q}_4(0) = [2.1, 1.4]^T$, $\dot{q}_5(0) = [2.8, -2]^T$. The switching communication topology and switching path are presented in Figure 1 and 2, respectively. Besides, the relevant Laplacian matrix is:

$$\mathcal{L}_1 = \begin{bmatrix} 2 & -1 & -1 & 0 & 0 \\ 0 & 2 & 0 & -1 & -1 \\ 0 & 0 & 2 & -1 & -1 \\ 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

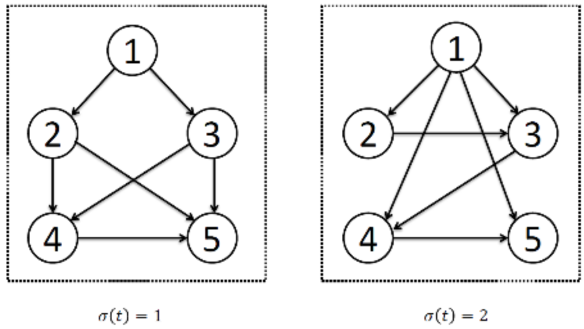

FIGURE 1. Switching communication topology.

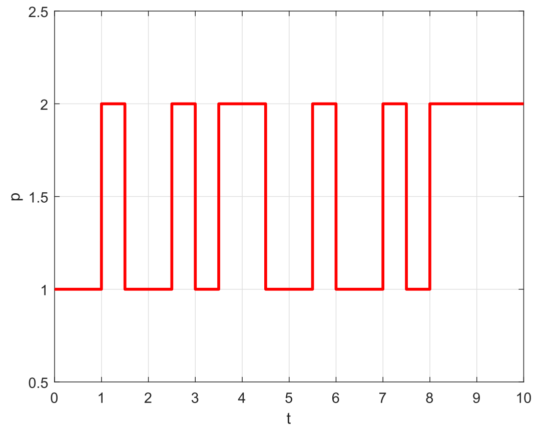

FIGURE 2. Switching signal.

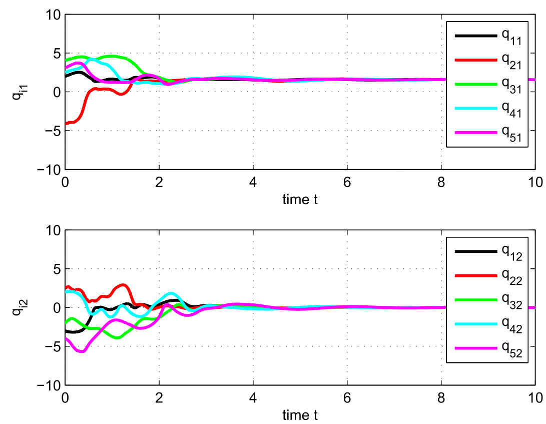

FIGURE 3. The position q_{i1}, q_{i2} regarding time t of the five manipulators.

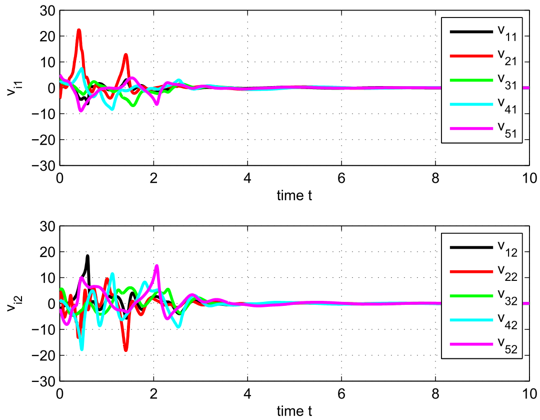

FIGURE 4. The velocities $\dot{q}_{i1}, \dot{q}_{i2}$ of the five manipulators.

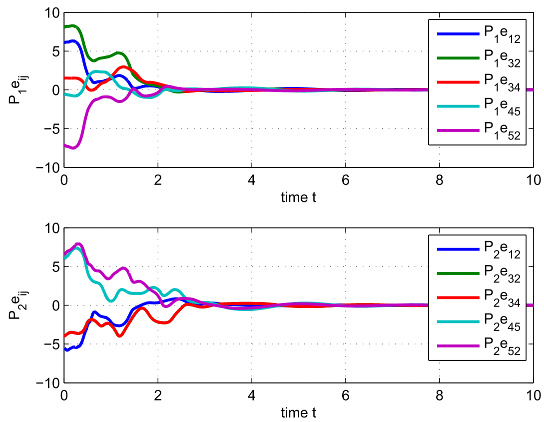

FIGURE 5. The position synchronization error P_1e_{ij}, P_2e_{ij} of the five manipulators.

$$\mathcal{L}_2 = \begin{bmatrix} 4 & -1 & -1 & -1 & -1 \\ 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

Obviously, Assumption 1 of Theorem 1 is satisfied, and average dwell time is chosen as $\check{\tau}_{ia} = 1 > \check{\tau}_{ia}^*$.

The detailed simulation results are shown from Figure 1 to 6. Figure 3 shows the state of q_{i1}, q_{i2} about time t, which indicates that the five manipulators achieve position synchronization quickly with the proposed switched adaptive algorithm. Noting that, the five manipulators have the jump parameters and unstable communication structures will lead to unstable state during the synchronization process, which is difficult to realize the control objective by applying general control approach. The velocities $\dot{q}_{i1}$, $\dot{q}_{i2}$ of each manipulator is described in Figure 4. The position synchronization errors and velocity errors are given in Figure 5 and Figure 6, respectively. According to the simulation results above, we can see that the synchronization process of the five manipulators is not affected even if there is parameter change and communication instability by the control protocol of Theorem 1.

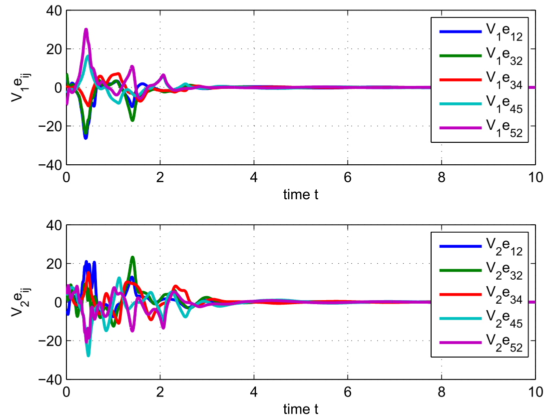

FIGURE 6. The velocity error V_1e_{ij}, V_2e_{ij} regarding time t of the five manipulators.

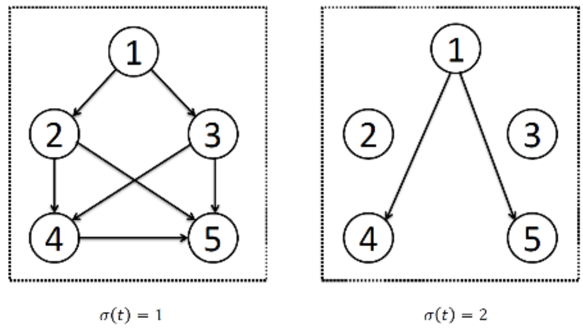

FIGURE 7. Switching communication topology.

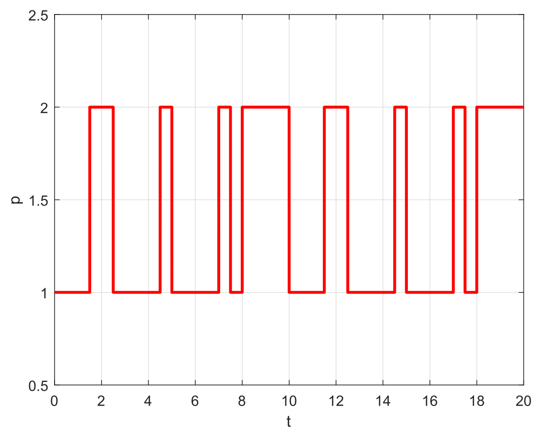

FIGURE 8. Switching signal.

Example 2: The switched topology is jointly connected.

With respect to the condition that switched topology $\mathcal{G}_p$ is jointly connected, our results are also valid. For convenience, the system parameters and initial conditions are chosen same as example 1.

As shown in Figure 7, the communication topology is jointly connected, the switching path is given in Figure 8. It's is easy to prove that all the conditions of Theorem 1 are satisfied. Figure 9 and Figure 10 show the position q_{i1}, q_{i2} and

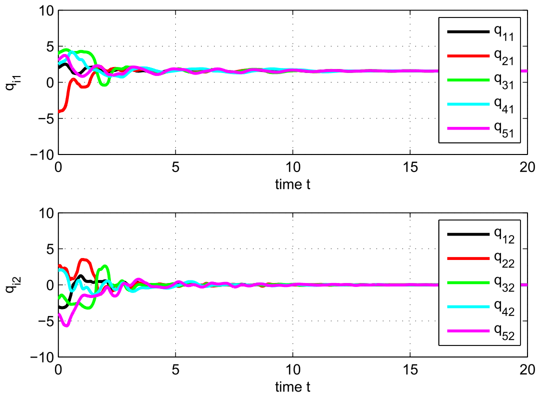

FIGURE 9. The state trajectory q_{i1}, q_{i2} of the five robots.

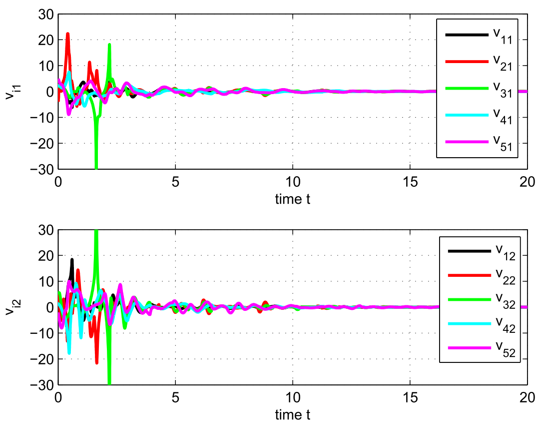

FIGURE 10. The velocities $\dot{q}_{i1}, \dot{q}_{i2}$ of the five robots.

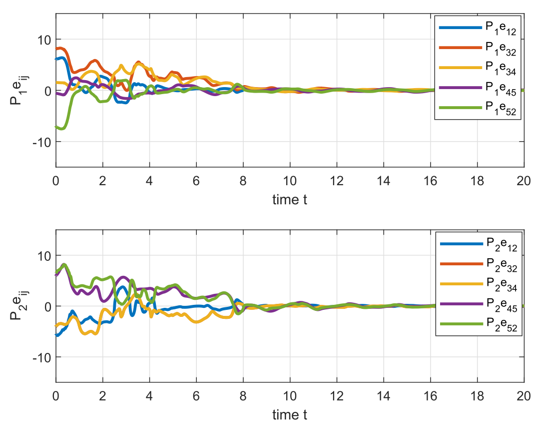

FIGURE 11. The position error P_1e_{ij}, P_2e_{ij} regarding time t of the five robots.

the velocities $\dot{q}_{i1}, \dot{q}_{i2}$ for the five manipulators, respectively. Finally, the position synchronization error and velocity error are described in Figure 11 and Figure 12, respectively. Example 2 reveals that our obtained control technique is effective for jointly connected switching communication graph. Since the proof process is similar to Theorem 1, we omit it and only give the simulation results.

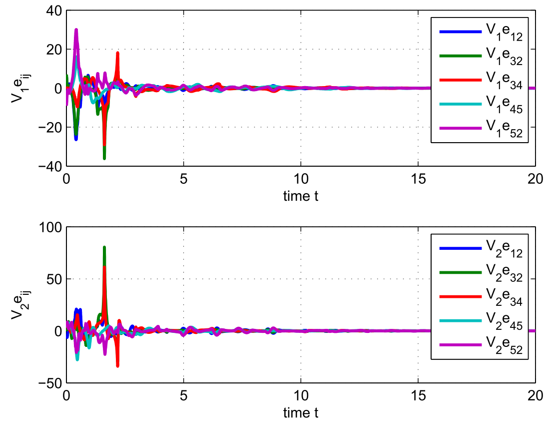

FIGURE 12. The velocity error V_1e_{ij}, V_2e_{ij} regarding time t of the five robots.

V. CONCLUSION

In this paper, we have studied coordinated consensus of the switched networked Lagrangian systems under the conditions of both loads shifting and directed topologies switching. Adaptive switched control protocols have been obtained in combination with the sliding-mode surface including the switching communication information. Further more, both ADT and improved ADT approaches are utilized to calculate the smaller average dwell time, Lyapunov-like analysis together with slide mode technique have been applied to guarantee the convergence analysis for the a group of switched EL systems. Finally, the effectiveness of the proposed approaches have been illustrated by numerical simulations.

In our further research work, some effective control strategies for a group of robot systems, such as topology-dependent average dwell time method, adaptive fuzzy output-feedback control, should be further investigated and fully to reduce the conservatism [40]–[43].

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