Integral Sliding Mode Based Switched Structure Control Scheme for Robot Manipulators

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Abstract— **This paper deals with the design of a switching control scheme for robot manipulators. The key elements of the proposed scheme are the inverse dynamics based centralized controller and a set of decentralized controllers. They enable to realize two possible control structures: one of centralized type, the other of decentralized type. All the controllers are based on Integral Sliding Mode (ISM), so that matched disturbances and uncertain terms, due to unmodeled dynamics or couplings effects, are suitably compensated. The idea of using ISM, apart from its feature of providing robustness in front of a wide class of uncertainties, is motivated by its capability of acting as a "perturbation estimator", which is a clear advantage in the considered case. In fact, it allows one to define a switching rule in order to choose one of the two control structures featured in the scheme, depending on the requested performances. As a consequence, the resulting control scheme is more efficient from computational viewpoint, while maintaining the advantages in terms of stability and robustness of the conventional standalone control schemes. In addition, the scheme can accommodate a variety of velocity and acceleration requirements, in contrast with the capability of the genuine decentralized or centralized control structures. The verification and the validation of our proposal have been carried out in simulation, relying on a model of an industrial robot manipulator COMAU SMART3-S2, with injected noise to better emulate a realistic setup.**

I. INTRODUCTION

Sliding Mode Control (SMC) [1]–[3] have been used in robotics from the early 1980's [4]–[7]. However, the necessity of implementing discontinuous control laws, in practical cases, can generate unacceptable vibrations (the so-called chattering) and cause a significant wear of the actuators. This is particularly critical in presence of gear boxes. In [4], [8] a continuous approximation of the discontinuous control has been proposed, which however could only guarantee practical sliding mode and the ultimately boundedness of the tracking error. Furthermore, since a "pseudo-sliding mode" is enabled, the robustness properties of this approach could be lost.

In the last decade, Higher Order Sliding Mode (HOSM) controllers have been introduced in order to alleviate the chattering problem without losing robustness [9]–[12]. HOSM control algorithms allow one to confine the effects of discontinuity of the control law to higher order derivatives of the sliding variable, feeding into the plant a continuous control signal. By virtue of this beneficial effect, HOSM controllers have been applied even to robotic systems. For instance, in [13], [14], a Suboptimal Second Order Sliding Mode (SSOSM) control algorithm has been successfully designed for a robot manipulator. For the same class of systems, in [15] a third order switched SMC scheme is proposed. In that paper, the control gain is suitably adapted depending on the sliding variable and its derivatives. In [16], a supervisory SMC is proposed for cooperative robot manipulators.

Another alternative in terms of chattering alleviation properties is Integral Sliding Mode (ISM) [17]. This is the approach used in this paper. The main feature of ISM is to enforce robustness to the controlled system since the initial time instant. It also provides other interesting features which will be suitably revised in this paper. Note that, recently, ISM control has been applied in combination to Model Predictive Control (MPC) in [18], [19]. In [20] an Integral SSOSM has been also proposed to improve the robustness properties of the SSOSM law, while maintaining the good properties in terms of chattering alleviation.

Apart from the specific control law which is used to control the robot, one has to consider that motion control of robot manipulators is generally based on two different control approaches: the decentralized method, if the aim is to control each joint independently, or the centralized one, if the robot is controlled as a Multi-Input-Multi-Output (MIMO) system [8], [21]. The decentralized control scheme is typically used when manipulators present higher transmission ratios and high performances in terms of velocity and acceleration are not required. In this case, each joint is controlled as a Single-Input-Single-Output (SISO) system and the manipulator is seen as a composition of linear and decoupled systems, one for each joint of the robot, where nonlinearities and coupling effects among joints are regarded as disturbances acting on the single joint. On the other hand, centralized control schemes have to be used when manipulators do not present gear boxes at the joints and higher performances in terms of velocity and acceleration are required. In this case, nonlinearities and couplings among the joints are not negligible anymore and have to be explicitly taken into account during the design of the control. If, on one hand, the decentralized scheme is light from a computational viewpoint and it is an easy-to-implement solution, the need to perform high velocity and acceleration often requires to adopt a centralized approach. In [21] these two approaches are presented relying on Proportional-Derivative (PD) controllers with the centralized method based on the so-called inverse dynamics control approach. If a

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perfect estimation of the robot parameters could be achieved, this allowed one to perform a global feedback linearization and a decoupling of the controlled system.

In this paper a switched structure control scheme based on ISM control [17] is designed to get the most out of the decentralized and centralized control approaches taken separately. More specifically, the whole scheme contains two loops. The first loop is closed relying on a decentralized ISM controller, able to compensate the coupling disturbances acting on the joints. The second loop is based on a centralized ISM controller in order to reject matched disturbances due to the unmodeled dynamics, which are not compensated by the inverse dynamics approach. A switching rule is designed based on a performance index depending on the coupling dynamics and matched disturbance signals, suitably estimated by exploiting the so-called "perturbation estimator" property of the ISM controllers [17]. The main contribution of this work is the introduction of a smart switching rule able to take into account the task operated by the manipulator, suitably selecting the most efficient control structure for the current request in terms of performances. Furthermore, this methodology has the advantage to switch from a decentralized control architecture, which typically requires high control gains, to a centralized one with reduced control gains and beneficial effects in terms of chattering and actuator saturation. The paper is organized as follows. In Section II the robot model is presented and some preliminary elements are reported. In Section III the proposed control scheme is described, while in Section IV the ISM control is discussed and theoretically analyzed. Simulation results obtained relying on the model of a real robot manipulator COMAU-SMART3-S2 are illustrated in Section V. Some conclusions are gathered in Section VI.

II. Preliminaries and Problem Formulation

In this section, some preliminary elements will be introduced: first, a canonical form for the state model of the plant, which enables to describe the dynamics of the tracking error in a suitable form for control design, then the model of the robot manipulator and considerations about the error definition. Finally, the control problem is formulated.

A. Preliminary on Sliding Mode Control

In order to formulate the control problem it is convenient to make reference to a canonical form frequently used in the development of SMC laws. To this end, consider a SISO perturbed double integrator as follows

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = v(t) + h(t) \\ y(t) = \sigma(x(t)) \end{cases} \tag{1}$$

where $x \in \Omega \subset \mathbb{R}^2$ is the state vector with $x(t_0) = x_0$, $v(t) \in \mathbb{R}$ is the input and $h(t) \in \mathbb{R}$ is a bounded matched uncertainty such that $|h(t)| \in \mathcal{H}$, with $\mathcal{H}$ being a compact set containing the origin, and $\mathcal{H}^{\sup} \equiv \sup_{h\in\mathcal{H}}\{|h|\}$. The output function $\sigma(x) : \Omega \to \mathbb{R}$ is of class $\mathrm{C}(\Omega)$ and is referred to as "sliding variable" in the following, that is $\sigma(x)$ is the variable to steer to zero in a finite time in order to solve the control problem, according to classical sliding mode control theory [1], [3]. The sliding variable $\sigma(x)$ has to be selected such that if $v(t)$ is designed so that, in a finite time t_{r} (ideal reaching time), $\sigma(x(t_{\mathrm{r}})) = 0 \ \forall x_0 \in \Omega$ and $\sigma(x(t)) = 0 \ \forall t > t_{\mathrm{r}}$, then $\forall t \geq t_{\mathrm{r}}$ the origin is an asymptotically stable equilibrium point of (1) constrained to $\sigma(x(t)) = 0$.

In the following sections it will be illustrated how to make the formulation of the robot control problem under consideration fit the structure (1), and be therefore eligible to be solved via a SMC solution.

B. The Robot Model

The dynamics of a n-joints robot can be described as

$$B(q)\ddot{q} + n(q,\dot{q}) = \tau \tag{2}$$

$$n(q,\dot{q}) = C(q,\dot{q})\dot{q} + F_{\mathrm{v}}\dot{q} + g(q) \tag{3}$$

where $B(q) \in \mathbb{R}^{n\times n}$ is the inertia matrix, $C(q,\dot{q}) \in \mathbb{R}^{n\times n}$ represents centripetal and Coriolis torques, $F_{\mathrm{v}} \in \mathbb{R}^{n\times n}$ is the viscous friction matrix, while the static friction, which is typically difficult to estimate, is not considered, $g(q) \in \mathbb{R}^n$ is the vector of gravitational torques, and $\tau \in \mathbb{R}^n$ represents the motor torques. Note that the considered robot model (2)-(3) is a MIMO nonlinear coupled model. Also note that the time dependence has been omitted for the sake of simplicity, but $q = q(t)$ and $\dot{q} = \dot{q}(t)$.

C. Problem Formulation

Given the robot manipulator model in (2)-(3), assume that q_{ref} and $\dot{q}_{\mathrm{ref}} \in \mathbb{R}^n$ are prespecified reference signals for the joint variables and their first time derivative. We assume that the components of q_{ref} are bounded and $\dot{q}_{\mathrm{ref}}$ is Lipschitz continuous. Now, define the tracking errors:

$$e_1(t) = q_{\mathrm{ref}} - q \tag{4}$$

$$e_2(t) = \dot{q}_{\mathrm{ref}} - \dot{q} \tag{5}$$

so that $e = \begin{bmatrix} e_1 & \dot{e}_1 \end{bmatrix}^\top = \begin{bmatrix} e_1 & e_2 \end{bmatrix}^\top$. In the following, e_{1_j} and e_{2_j} will be used to indicate the position error and the velocity error of joint j, with $e_j = \begin{bmatrix} e_{1_j} & e_{2_j} \end{bmatrix}^\top$. The control problem solved in this paper is a classical robot motion control problem [21].

III. The proposed ISM based Switched Structure Control Scheme

In order to solve the control problem formulated in the previous section, the control architecture in Figure 1 is proposed. It consists of two loops: the first loop is characterized by a decentralized control structure (Mode 1) as described in Subsection III-A; the second loop, instead, is based on the inverse dynamics based control structure (Mode 2) illustrated in Subsection III-B. For the sake of simplicity, without loss of generality, a control scheme designed in the joint space is considered. Both the control loops include a control block based on an ISM law which receives the errors e_1, e_2. The two control blocks send the control signals

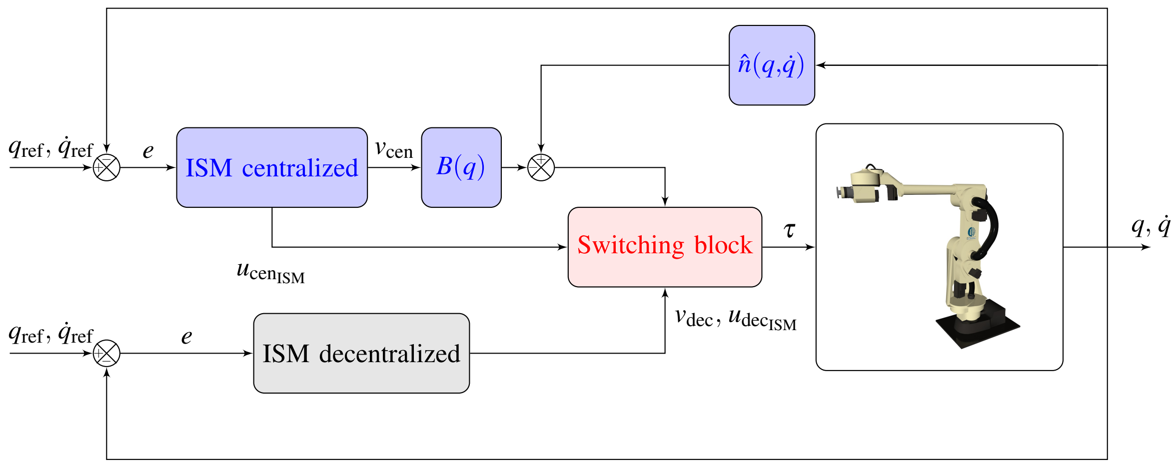

Fig. 1. The proposed multi-loop switching ISM control scheme

$u_{{\rm dec}_{{\rm ISM}\,j}}(t)$ and $u_{{\rm cen}_{{\rm ISM}\,j}}(t)$ to the so-called switching block, described hereafter.

A. Decentralized Control Structure

Let $K_{\rm r} \in \mathbb{R}^{n\times n}$ be the matrix of the gear ratios on the motor shafts such that the motor positions are $K_{\rm r}q = q_{\rm m}$, and the shaft torques are $K_{\rm r}^{-1}\tau = \tau_{\rm m}$. Moreover, let $F_{\rm m} = K_{\rm r}^{-1}F_{\rm v}K_{\rm r}^{-1}$ be the matrix of the viscous friction coefficients referred to the motor shafts, and consider the inertia matrix $B(q)$ composed of a nominal component $\bar{B}$ and an unknown term $\Delta B(q)$, such that $B(q) = \bar{B} + \Delta B(q)$. The dynamic model (2)-(3) can be rewritten as

$$\ddot{q} = (K_{\rm r}\bar{B}^{-1}K_{\rm r})\tau_{\rm m} - (K_{\rm r}\bar{B}^{-1}K_{\rm r})F_{\rm m}\dot{q} - (K_{\rm r}\bar{B}^{-1}K_{\rm r})d(q,\dot{q},\ddot{q}) \quad (6)$$

where the term that accounts for nonlinearities and coupling is

$$d = K_{\rm r}^{-1}\Delta B(q)K_{\rm r}^{-1}\ddot{q} + K_{\rm r}^{-1}C(q,\dot{q})K_{\rm r}^{-1}\dot{q} + K_{\rm r}^{-1}g(q)\ . \quad (7)$$

Now we can introduce the error model. To this end, we write

$$\dot{e}_2 = \ddot{q}_{\rm ref} - \ddot{q}\ . \quad (8)$$

By posing $h_{\rm dec} = \ddot{q}_{\rm ref} + (K_{\rm r}\bar{B}^{-1}K_{\rm r})F_{\rm m}\dot{q} + (K_{\rm r}\bar{B}^{-1}K_{\rm r})d(q,\dot{q},\ddot{q})$ and $v_{\rm dec} = -(K_{\rm r}\bar{B}^{-1}K_{\rm r})\tau_{\rm m}$, one obtains

$$\begin{cases} \dot{e}_{1_j}(t) = e_{2_j}(t) \\ \dot{e}_{2_j}(t) = v_{{\rm dec}_j}(t) + h_{{\rm dec}_j}(t) \\ y_j(t) = \sigma_j(e_j(t)) \end{cases} \quad (9)$$

with $v_{{\rm dec}_j}$ and $h_{{\rm dec}_j}$ being the j-th component of the vectors $v_{\rm dec}$ and $h_{\rm dec}$, respectively. Note that one can assume $h_{\rm dec} \in \mathcal{H}_{\rm dec}$, with $\mathcal{H}_{\rm dec}$ being a compact set containing the origin and $\mathcal{H}_{\rm dec}^{\rm sup} \equiv \sup_{h_{\rm dec}\in\mathcal{H}_{\rm dec}}\{|h_{\rm dec}|\}$ known.

B. Centralized Control Structure

The second architecture dealt with in this paper is the so-called inverse dynamics based centralized control scheme. Assume the ability to exactly estimate the inertia matrix $B(q)$ and to have a quite accurate replica of the vector $n(q,\dot{q})$, such that $\hat{n}(q,\dot{q}) \neq n(q,\dot{q})$. Moreover, let $v_{\rm cen}$ be an auxiliary control vector such that the control torque is selected as

$$\tau = -B(q)v_{\rm cen} + \hat{n}(q,\dot{q})\ . \quad (10)$$

Substituting (10) into model (2)-(3), one has

$$B(q)\ddot{q} + n(q,\dot{q}) = -B(q)v_{\rm cen} + \hat{n}(q,\dot{q})\,, \quad (11)$$

writing again $\dot{e}_2$ as in (8), one obtains

$$\begin{cases} \dot{e}_{1_j}(t) = e_{j_2}(t) \\ \dot{e}_{2_j}(t) = v_{{\rm cen}_j}(t) + h_{{\rm cen}_j}(t) \\ y_j(t) = \sigma_j(e_j(t)) \end{cases} \quad (12)$$

with $v_{{\rm cen}_j}$ and $h_{{\rm cen}_j}$ being the j-th component of the vectors $v_{\rm cen}$ and $h_{\rm cen} = \ddot{q}_{\rm ref} - B(q)^{-1}(\hat{n}(q,\dot{q}) - n(q,\dot{q}))$, respectively. Moreover, analogously to the decentralized case, one can assume $h_{\rm cen} \in \mathcal{H}_{\rm cen}$, with $\mathcal{H}_{\rm cen}$ being a compact set containing the origin and $\mathcal{H}_{\rm cen}^{\rm sup} \equiv \sup_{h_{\rm cen}\in\mathcal{H}_{\rm cen}}\{|h_{\rm cen}|\}$ known.

C. Switching Block

In order to switch from Mode 1 to Mode 2 and vice versa, the switching block contains the following rule based on a performance index $p_{\rm sw}(\hat{h})$ depending on an estimate of the uncertain terms and coupling effects $\hat{h}$, i.e.,

$$p_{\rm sw}(\hat{h}) \gtrless \bar{P}\ . \quad (13)$$

Depending on the current active mode, both the index and the threshold are alternatively defined as

$$p_{\rm sw}(\hat{h}) = \begin{cases} p_{\rm sw}(\hat{h}_{\rm dec}), & \text{if Mode 1 is active} \\ p_{\rm sw}(\hat{h}_{\rm cen}), & \text{if Mode 2 is active} \end{cases} \quad (14)$$

and

$$\bar{P} = \begin{cases} \mathcal{T}_{\rm max}, & \text{if Mode 1 is active} \\ \mathcal{A}_{\rm min}, & \text{if Mode 2 is active} \end{cases} \quad (15)$$

with $\mathcal{T}_{\rm max}$ and $\mathcal{A}_{\rm min}$ being the thresholds in terms of maximum torque and minimum acceleration, respectively. The logic of the switching rule is: *if Mode 1 is active and the* *coupling terms are greater than $\mathcal{T}_{\max}$ (i.e., high velocity and acceleration performance are required), switch to Mode 2. Vice versa, if Mode 2 is active and the uncertain terms are less than $\mathcal{A}_{\min}$ (i.e., high velocity and acceleration performance are not required) switch to Mode 1.*

Now, we will consider the following question: how to estimate the uncertain and coupling terms, i.e., the term $\hat{h}$? This question can be answered thanks to the properties of ISM control [17].

IV. ISM Control Design

Consider the j-th joint of the robot. Now the aim is to design the ISM control laws to be used in the decentralized and centralized case, respectively. ISM is typically characterized by a control variable $v_j(t)$ split into two parts, i.e.,

$$v_j(t) = u_j(t) + u_{\mathrm{ISM}_j}(t) \tag{16}$$

where $u_j(t)$ is generated by a suitable controller designed relying on the nominal model (i.e., the model of the plant assuming that no uncertainty is present), and $u_{\mathrm{ISM}_j}(t)$ is the sliding mode control action in order to reject the uncertainties affecting the system.

The $u_{\mathrm{ISM}_j}(t)$ component has to be designed relying on the errors e_{1_j}, e_{2_j} previously defined. The error model describing the dynamics of such errors can be written in compact form as follows

$$\dot{e}_j(t) = A_j e_j(t) + B_j\left(v_j(t) + h_j(t)\right) \tag{17}$$

where matrices A_j, B_j can be easily deduced in the decentralized and centralized cases making reference to (9) and (12), respectively. In system (17), $v_j(t)$ and $h_j(t)$ contain the components v_{dec_j} and h_{dec_j} or v_{cen_j} and h_{cen_j}, for $j = 1, \ldots, n$, depending on the case.

The so-called integral sliding manifold is defined as

$$\Sigma_j(t) = \sigma_j(t) + \varphi_j(t) = 0 \tag{18}$$

where Σ_j is the auxiliary sliding variable, $\sigma_j = me_{1_j} + e_{2_j}$ is the actual sliding variable, with m being a positive constant, and the integral term φ_j given by

$$\varphi_j(t) = -\sigma_j(t_0) - \int_{t_0}^{t} me_{2_j}(\zeta) + u_j(\zeta)d\zeta \tag{19}$$

with the initial condition $\varphi_j(t_0) = -\sigma_j(e_j(t_0))$. Then, the discontinuous control law is defined as

$$u_{\mathrm{ISM}_j}(t) = -K_j \operatorname{sgn}\left(\Sigma_j(t)\right) \,. \tag{20}$$

After the design of the control law (20), one needs to answer the question reported at the end of Subsection III-C.

Note that the ISM controller is able to estimate the uncertain and coupling terms if the equivalent control is available [17]. As claimed in [17], it is shown that an approximation of the equivalent control can be obtained via a first order linear filter with the real discontinuous control (20) as input signal, i.e.,

$$\tilde{u}_{\mathrm{ISM}_{\mathrm{eq}\,j}}(t) = \frac{1}{\mu}\int_{t_0}^{t} \mathrm{e}^{-\frac{1}{\mu}(t-\zeta)} u_{\mathrm{ISM}_j}(\zeta)d\zeta \tag{21}$$

where $\tilde{u}_{\mathrm{ISM}_{\mathrm{eq}\,j}}(t_0) = 0$ and μ is the time constant of the filter, that should be set such that the linear filter does not distort the slow component of the switching action, which is $u_{\mathrm{ISM}_{\mathrm{eq}}}$. Furthermore, the integral term has to be redesigned as

$$\begin{aligned}\varphi_j(t) = &-\sigma_j(t_0) + \\ &-\int_{t_0}^{t} me_{2_j}(\zeta) + u_j(\zeta) + \tilde{u}_{\mathrm{ISM}_{\mathrm{eq}\,j}}(\zeta) - u_{\mathrm{ISM}_j}(\zeta)d\zeta\end{aligned} \tag{22}$$

with initial condition $\varphi_j(t_0) = \sigma_j(e(t_0))$. It can be proved that $\tilde{u}_{\mathrm{ISM}_{\mathrm{eq}\,j}} \simeq -h_j$, i.e., $\tilde{u}_{\mathrm{ISM}_{\mathrm{eq}\,j}} = \hat{h}_j$. This quantity can be used to compute the performance index $p_{\mathrm{sw}}(\hat{h})$ in (13), which allows to realize the switching mechanism illustrated in subsection III-C.

V. Case Study

In this section, simulation results carried out relying on a realistic model of a robot manipulator COMAU SMART3-S2 are presented. In this paper, for the sake of simplicity, only vertical planar motions of the robot have been enabled for the simulation tests. Simulations have been run using a model of the actual robot identified on the basis of real data. The goal of the proposed control scheme is to track a pick-and-place trajectory in the operative state space, providing to each joint a Trapezoidal Velocity Profile (TVP) trajectory with initial point equal to $q_{\mathrm{ref}_0} = [0,\, 0,\, \pi/2]'$ rad and final target equal to $q_{\mathrm{ref}_\mathrm{f}} = [\pi/8,\, \pi/8,\, \pi/4]'$ rad, with each angle obtained respectively at 6.7 s for joint 1 and 2 and 5 s for joint 3, and cruising velocity $\dot{q} = [0.0648,\, 0.0648,\, -0.1728]'$ rad s^{-1}. The initial conditions of the robot are $q(0) = [\pi/15,\, 0,\, \pi/2]'$ rad, while the sampling time is $T = 5\times10^{-5}$ s. Note that, we assume that the joint velocity $\dot{q}$ is measurable. If this is not the case, one can use an estimate of $\dot{q}$, for instance, by using a Levant's differentiator [9], as successfully shown in [22].

The nominal control law, both in the decentralized and the centralized loop is chosen as a Proportional-Derivative (PD) controller, with control parameters equal to $K_{\mathrm{P_{dec}}} = 2.5\times10^4$, $K_{\mathrm{D_{dec}}} = 5\times10^3$ and $K_{\mathrm{P_{cen}}} = 200$ and $K_{\mathrm{D_{cen}}} = 100$, respectively. On the other hand, the control gain of the discontinuous component of the controllers has been set as reported in Table I, with the constant $m = 1$. In our case, the performance index $p_{\mathrm{sw}}(\hat{h})$ (see (13)) has been chosen as the Root-Mean-Square (RMS) value of the uncertainty estimates in both modes. Figure 2 illustrates the operative space trajectory when the switching control scheme is used (top-left) and the control torque (bottom-left) fed into the plant. In Figure 2 the logic of the proposed control scheme is also graphically explained

TABLE I

ISM CONTROL GAINS K_j.

Joint i	Mode 1	Mode 2
1	1000	2
2	500	2
3	500	2

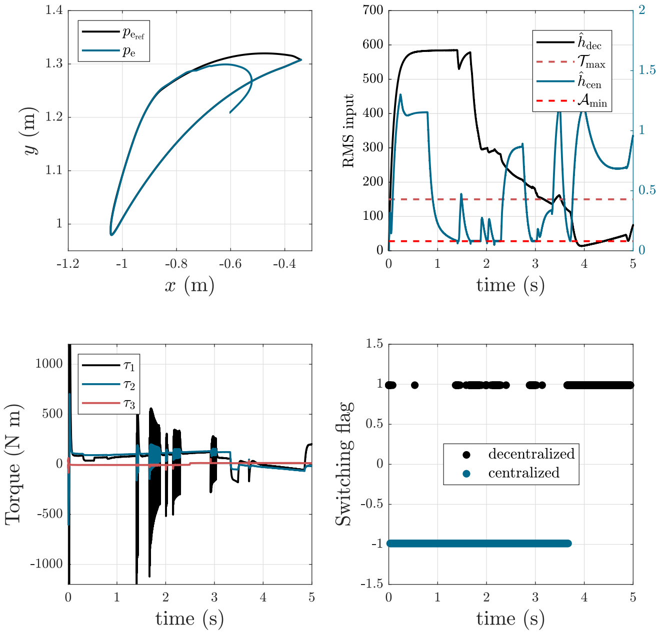

Fig. 2. From the top-left. Trajectory tracking in the operative space. RMS input of the switching block $\hat{h}_{\text{dec}}$ (left-axis, black line), $\hat{h}_{\text{cen}}$ (right-axis, blue line) and switching thresholds ($\mathcal{T}_{\text{max}}$ in dashed dark-red line, $\mathcal{A}_{\text{min}}$ in dashed light-red line). Control torques τ for each joint. Switching flag, equal to 1 and -1 when Mode 1 (decentralized loop) or Mode 2 (centralized loop) is active

TABLE II

RMS VALUES FOR EACH JOINT

	Joint i	e_{RMS_i}	τ_{RMS_i}	h_{decRMS_i}	h_{cenRMS_i}
	1	0.0462	302.78	214.272	0.927
Sw.	2	0.00077	103.51	55.274	0.328
	3	0.001	10.397	34.339	0.580
	1	0.034	253.266	104.294	–
Dec.	2	0.00051	98.079	90.550	–
	3	0.00005	10.853	9.804	–
	1	0.0468	156.105	–	0.476
Cen.	2	0.00027	94.436	–	0.317
	3	0.00043	10.164	–	0.541

(top-right). The estimates of the coupling effects in Mode 1 (left axis, black line) and matched uncertainty in Mode 2 (right-axis, blue line), obtained through the sliding mode component of the controller, are shown with the maximum and minimum thresholds ($\mathcal{T}_{\text{max}}$ in dashed dark-red line, $\mathcal{A}_{\text{min}}$ in dashed light-red line) to switch from one loop to the other one. More specifically, these values have been set equal to $\mathcal{T}_{\text{max}} = 150$ and $\mathcal{A}_{\text{min}} = 0.08$, on the basis of the real data of the robot and through a trial and error procedure. On the bottom, a flag function equal to 1 or -1 when Mode 1 or Mode 2 is active, respectively, is reported. Figure 3 shows instead the time evolution of the sliding variables. It is possible to notice that the sliding mode is always guaranteed in spite of the switches between the two control architectures. Finally, Figure 4 shows the time evolution of the joint variables q and their derivatives (left-axes), together with the corresponding error signals (right-axes).

The proposed switched structure control approach (indicated as strategy "Sw.") has been also tested in comparison with the classical standalone decentralized (indicated as strategy "Dec.") and centralized (indicated as strategy "Cen.") control schemes. To this aim, the RMS values of the position error e_{RMS}, of the torque τ_{RMS}, and of the uncertainties $h_{\text{dec}_{\text{RMS}}}$ and $h_{\text{cen}_{\text{RMS}}}$ have been computed for each joint and are reported in Table II. Note that the RMS values obtained through the switching scheme are comparable with the other ones. Then, the proposed approach allows one to track varying trajectories which require both high and low performances in terms of velocity and acceleration, using alternatively higher and lower control gains with benefits in terms of saturation or wear of the actuators.

VI. CONCLUSIONS

In this paper a switched structure control scheme, based on the combination of a decentralized control structure and a centralized inverse dynamics based control structure, has been proposed to solve a motion control problem for robot manipulators. A ISM control law is used in order to determine a switching rule to alternatively activate one of the two control structures: the one which at the current time instant is the most suitable to obtain better performances, taking into account the role of coupling effects among joints and nonlinearities. In fact, apart from its robustness property, ISM allows one to estimate the matched and coupling uncertainty affecting the system, directly related to the required tracking performance of the robot. The proposal ensures benefits from a computational viewpoint, extending the operative velocity and acceleration range in which the robot manipulator can work. The proposed approach has been theoretically analyzed and validated in simulation relying on a model of an industrial COMAU SMART3-S2 anthropomorphic robot manipulator identified on the basis of real data.

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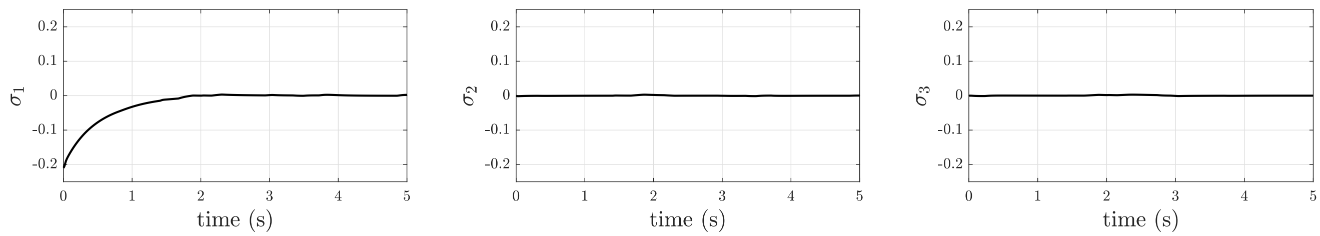

Fig. 3. Time evolution of the sliding variables σ_j, $j = 1, 2, 3$

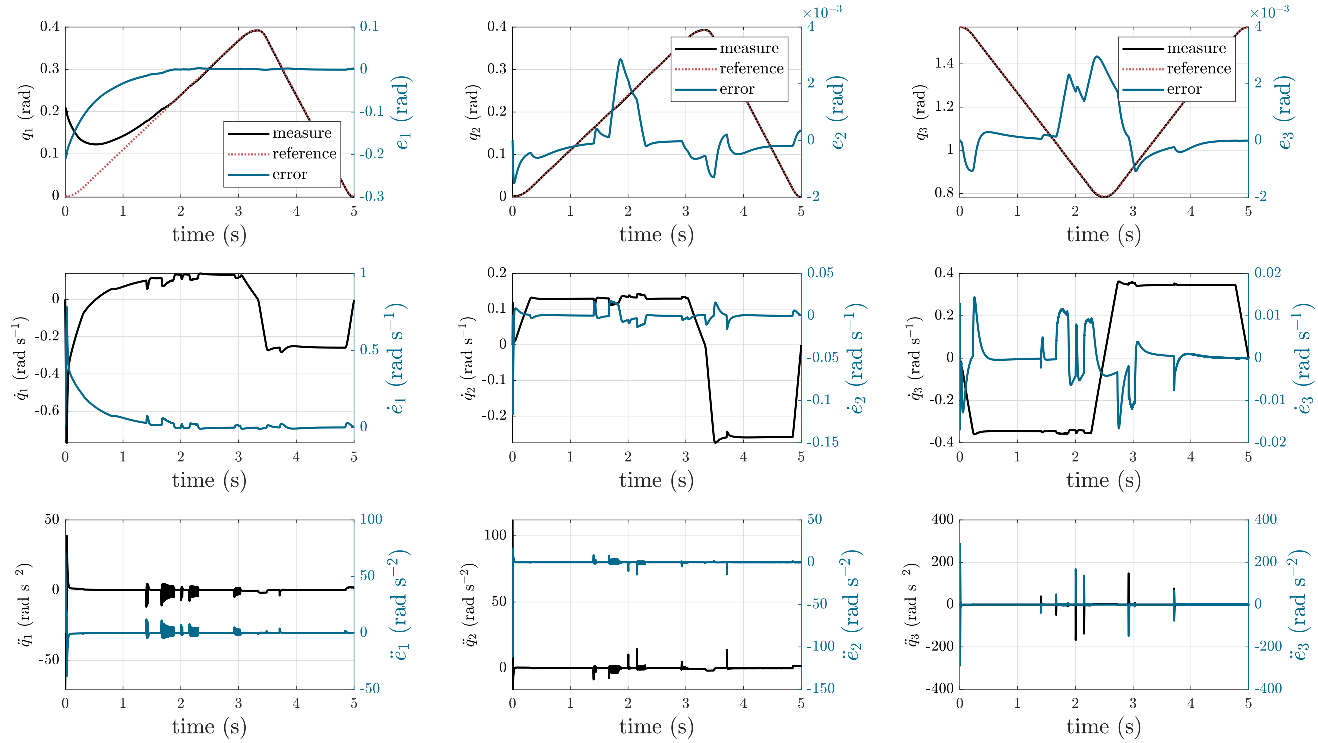

Fig. 4. Time evolution of the joint variables q, velocity $\dot{q}$, acceleration $\ddot{q}$ and corresponding errors e, $\dot{e}$, $\ddot{e}$ for each joint

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