Control of Electromechanical Systems using Sliding Mode Techniques

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Abstract— **This article proposes a sliding mode control for electromechanical systems, for instance a DC motor with an inverted pendulum as load is considered. In contrast to conventional cascade control structures not only the variables of the mechanical system but also the electrical variables are part of the control law and voltage is used as discontinuous control input. The new control approach offers better performance, minimial implementation complexity, provides robustness, and a decrease of power consumption. The performance of the presented approach is demonstrated via numerical simulations and a real experiment.**

I. Introduction

It is common to design control for mechanical systems with torque or force as the control action. It is assumed that there exists a fast inner control loop providing a desired current i^*. Therefore, for the speed controller in the outer loop the current control loop is treated as an ideal current source, which means a given reference current i^* will be tracked ideally. An example for such a control scheme is shown in fig. 1 for a 2nd order mechanical system driven by a DC motor. There is a low-level feedback loop using a pulse width modulated (PWM) signal or linear amplifier providing the desired current or torque. The desired current is given by the control law for the mechanical system.

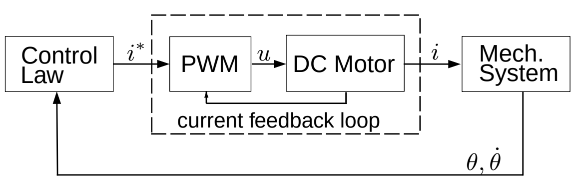

Fig. 1. Conventional cascade control structure for a 2nd order mechanical system driven by a DC motor

For high performance systems there are limits of this control scheme. The bandwidth of the inner control loop is limited, because the desired current i^* is an integrated PWM signal. Hence, the performance of the outer control loop, the performance of the mechanical system, is limited by this bandwidth of the current control loop. Particularly due to a very slowly moving mechanical system, position sensor data are limited and therefore a sufficient estimation of the speed signal is not possible and the accurate control of the mechanical system is restricted. An additional sensor for the electrical variables of the system could offer better estimation of the not measured speed variable of the mechanical system. If a PWM signal is used, current control is based on an exactly defined switching frequency. In consequence, independent of the control objective this extremely high switching frequence using maximal power is always applied. If the mechanical variables θ and $\dot{\theta}$ are also taken into account for design of control law, reduction of energy can be achieved. To overcome the above described problems, this article investigates a control scheme for electromechanical systems using voltage as the discontinuous control input. Additional to the mechanical variables, the variable of the electrical system, the current, influences the control law. Sliding mode control is chosen because it offers robustness as well as fast dynamics. Furthermore implementation of sliding mode control as fast switching control is also practicable.

Several applications of sliding mode control of DC motors, induction motors and synchronous motors have been proposed, e.g. in [1].In the outer control loop of the control scheme shown in fig. 1 PD or PID control is usually implemented. Moreover, in order to improve robustness, tracking problems for position and angular speed of a DC motor also have been solved based on a sliding mode control approach [2]. Improvement of robustnes by adding sliding mode control of mechanical system for an induction motor drive with forced dynamics has been shown [3]. Nevertheless, this approach still is based on a cascade control structure assuming fast ideal low-level feedback loops.

The control scheme for an electromechanical system which is proposed in this article uses advantages of sliding mode control and at the same time chattering effects are decreased because the variables of the electric drive are part of the control law. The electric motor acts as filter for high-frequency signals. Compared to the shown cascade control using sliding mode control structure system dynamics becomes faster. The system performance is characterized by insensitivity to parameter variations and rejection of disturbances due to sliding mode control characteristics as well as minimial implementation complexity and reduction of energy.

This article analyzes sliding mode control of electromechanical systems. In section II the proposed control scheme explained for arbitrary electromechanical systems receives priority consideration. Afterwards it is developed for a sample system, an inverted pendulum driven by a DC motor. Section III discusses the results of numerical simulations and the experimental results. Performance of the proposed sliding mode control is compared to that of a conventional control method.

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II. Description of the Control Algorithm

In this article nonlinear n-dimensional control affine systems

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}) + \boldsymbol{g}(\boldsymbol{x})\,\boldsymbol{u} \qquad \boldsymbol{x} \in \Re^n\,, \boldsymbol{u} \in \Re^m \tag{1}$$

are considered. For electromechanical systems the system state $\boldsymbol{x}$ constists of the state variables of the electrical subsystem $\boldsymbol{x}_{electr}$ and the variables of the mechanical subsystem $\boldsymbol{x}_{mech}$. For the system (1) the idea of the proposed sliding mode control scheme is shown in fig. 2. In contrast to fig. 1 for control design of the mechanical system additionally to the mechanical dynamics, the dynamics of the DC motor are taken into account.

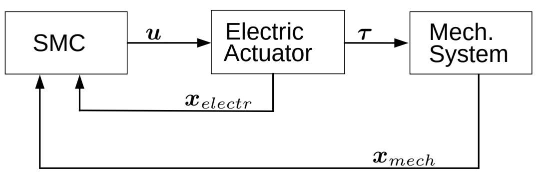

Fig. 2. Schematic diagram of the proposed control scheme for electromechanical systems.

Following the idea of sliding mode control, the control input $\boldsymbol{u}$ is selected as a discontinuous function of the system state

$$\boldsymbol{u}(\boldsymbol{x}) = \begin{cases} \boldsymbol{u}^+(\boldsymbol{x}) & \text{if} \quad s(\boldsymbol{x}) > 0 \\ \boldsymbol{u}^-(\boldsymbol{x}) & \text{if} \quad s(\boldsymbol{x}) < 0 \end{cases} \qquad \boldsymbol{u}(\boldsymbol{x}) \in \Re\,. \tag{2}$$

in order to enforce desired dynamics of the mechanical system which are given by $s(\boldsymbol{x}) = \boldsymbol{x}^*(t) - \boldsymbol{x}(t) = 0$ with $\boldsymbol{x}^*(t)$ as reference input.

The control scheme will be derived for a sample system which consists of an inverted pendulum driven by a DC motor (fig. 3). The control input of the electromechanical system of third order is a scalar variable, the applied voltage to the DC motor u_a. The sliding manifold given by $s(\boldsymbol{x}) = 0$ divides the state space into two subspaces. The control input $u(\boldsymbol{x}) = u_a$, which is defined everywhere in the state space except for the sliding manifold, is designed in such a way that the tangent vectors of the state trajectory point towards the sliding manifold. Hence, there exists a neighborhood of the sliding manifold, such that once the trajectory enters the neighborhood, it stays within this neighborhood for all subsequent time. More precisely, finite sampling time is assumed within this neighborhood, the system state moves from one side of the sliding manifold to the other. Finally, switching at high frequencies, theoretically infinitely fast switching leads to a sliding motion of the system along the sliding manifold. The system follows the dynamics given by $s(\boldsymbol{x}) = 0$.

To make sure that the system reaches the sliding manifold independent of the initial condition, the sliding mode condition

$$\lim_{s(\boldsymbol{x})\to\boldsymbol{0}^+} \dot{s}(\boldsymbol{x}) < 0 \quad \text{and} \quad \lim_{s(\boldsymbol{x})\to\boldsymbol{0}^-} \dot{s}(\boldsymbol{x}) > 0 \tag{3}$$

must be fulfilled.[4]

A. Mathematical Model of the considered Electromechanical System

The dynamics of the electrical system are given by

$$L\dot{i} = u_a - R_a i - K_n \dot{\theta} \tag{4}$$

$$J\ddot{\theta} = K_m i - T_l \tag{5}$$

where i is the armature current, u_a the supplied voltage, R_a the armature resistance and L the armature inductance; K_m represents the torque constant and K_n the induction constant of the DC motor; $\dot{\theta}$ is the angular speed, J is the moment of inertia of the system and T_l is the load.

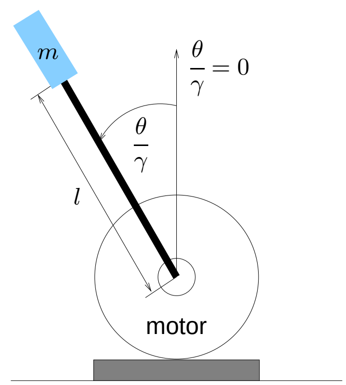

Fig. 3. Schematic diagram of the considered electromechanical sample system, an inverted pendulum actuated by a DC motor.

The mechanical system shown in fig. 3 defines the load on motor side

$$T_l = c_1\dot{\theta} - \frac{1}{\gamma} mgl \sin(\frac{\theta}{\gamma}) \tag{6}$$

where c_1 is a frictional constant ($\frac{\text{Nms}}{\text{rad}}$), γ represents the gear reduction of the motor, m is the pendulum mass, g the gravitational constant, l the pendulum length and θ the angle of the pendulum with the upright position being zero. Angle θ and angular speed $\dot{\theta}$ are considered to be on the motor side before the gear.

With $[x_1, x_2, x_3] = [\theta, \dot{\theta}, i]$ and the manipulated variable $u = u_a$, the voltage supply, from (4), (5) and (6) the state description of the system is given by

$$\dot{x}_1 = x_2 \tag{7}$$

$$\dot{x}_2 = \frac{1}{J}(K_m x_3 - c_1 x_2 + \frac{1}{\gamma} mgl \sin(\frac{x_1}{\gamma})) \tag{8}$$

$$\dot{x}_3 = \frac{1}{L}(u - R_a x_3 - K_n x_2) \tag{9}$$

For dynamic analysis of the dynamics of the system a linear state description of the system is desired. With $a_1 = \frac{1}{J\gamma} mgl$ the following calculation can be done:

$$a_1 \sin(\frac{x_1}{\gamma}) = \frac{a_1}{\gamma} \frac{\sin(\frac{x_1}{\gamma})}{\frac{x_1}{\gamma}} x_1 = \frac{a_1}{\gamma} \xi x_1$$
$$\text{with } \xi = \frac{\sin(\frac{x_1}{\gamma})}{\frac{x_1}{\gamma}} = \mathrm{si}(\frac{x_1}{\gamma}) \quad (10)$$

The function $\xi(x) = \mathrm{si}(x)$ is bounded. $\forall x \in \Re : \xi(x) \in \langle -0.2172; 1 \rangle$. That means the nonlinear part of the differential equation (8) can be approximated by a linear term with a bounded coefficient:

$$a_1 \sin(\frac{x_1}{\gamma}) = (\frac{a_1}{\gamma} + \Delta) x_1$$
$$\text{with } \Delta \in \left\langle -1.2173 \frac{a_1}{\gamma}; 0 \right\rangle \quad (11)$$

The controller for the system is selected as

$$u = u_0 \mathrm{sign}(s(\boldsymbol{x})) \quad (12)$$

with $s(\boldsymbol{x}) = k_0 x_1 + k_1 x_2 + k_2 x_3,\ k_0, k_1, k_2 \in \Re$. In order to use this controller, it must be guaranteed that the sliding mode condition (3) is fulfilled.

B. Observer Design

Since the calculation of load torque is not accurate enough, due to unknown friction torque of the motor and gear, a non negligible error occurs in the angular speed $\dot{\theta}$. In order to rectify this error as well as to reduce the number of sensors a sliding mode observer is used to estimate the angular speed $\dot{\theta}$ (fig. 4).

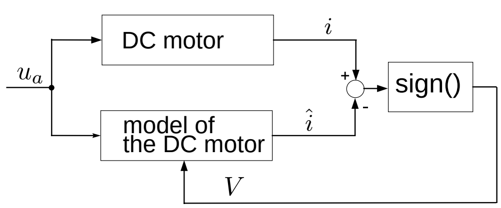

Fig. 4. Schematic diagram of the observer

Assuming that the current i is measurable, based on one of the equations of the DC motor (4), the observer is designed as follows:

$$L \frac{d\hat{i}}{dt} = u_a - R_a \hat{i} - V \quad (13)$$

The term V, which represents the unknown term $K_n \dot{\theta}$, is defined as a switching function of the tracking error of the observer

$$V = V_o \mathrm{sign}\,(\hat{i} - i) \quad (14)$$

where V_o is a constant factor. The constant V_o is chosen in such a way that sliding mode is enforced in the manifold $s_i = \hat{i} - i = 0$. Once sliding mode is enforced, the differential equations (4) and (13) have the same solution and the terms $R_a i$ and $R_a \hat{i}$ are equivalent. Therefore the terms V and $K_n \dot{\theta}$ have to be equal. The unknown angular speed $\dot{\theta}$ can be estimated.

Sliding mode is then achieved in a finite time if the sliding mode condition (3) is satisfied, which means s_i and $\dot{s}_i$ have to have opposite algebraic signs and $\dot{s}_i \neq 0$ for $s_i = 0$. Therefore for a stability analysis the differential equation

$$L \dot{s} = K_n \dot{\theta} - V_0 \mathrm{sign}(s_i) - R s_i \quad (15)$$

has to be analyzed. The condition $\dot{s}_i \neq 0$ for $s_i = 0$ is satisfied. For $s_i \neq 0$ the worst case will be considered, that is, Rs is so small that it can be neglected. The following conditions are then obtained for V_o :

$$V_o > K_n \dot{\theta} \quad \text{if} \quad s_i > 0$$
$$V_o > -K_n \dot{\theta} \quad \text{if} \quad s_i < 0$$

To summarize, $V_o > |K_n \dot{\theta}|$ ensures asymptotic behavior of the observer. To determine the value of V_o worst case is considered again and the biggest possible value is taken for $\dot{\theta}$.

During application a low pass filter has to be used to gain the average value $\overline{V} = K_n \dot{\theta}$ of the discontinuous time function $V = V_o \mathrm{sign}\,(\hat{i} - i)$. So far the term $K_n \dot{\theta}$ is observed, to gain the shaft speed $\dot{\theta}$ the result of filtering has to be divided by the factor K_n.

C. Control Parameter Design

In general the design of a sliding mode control can be divided into two problems. At first the switching manifold with sliding mode in order to design the desired dynamics of the motion equation is selected. Second objective is to find a discontinuous control function such that the state reaches the manifold and sliding mode exists in that manifold . In this section an idea of control parameter design for the elected sliding mode control (12) is presented. Once a sliding mode manifold is defined and the system behavior on it is analyzed, finding optimal control parameters shall be aimed. Afterwards the existence of sliding mode is proved.

a) Definition of the Sliding Manifold: Dynamics of the system can be defined using a sliding surface $s = 0$ din the following way:

$$s = 0 \quad \leftrightarrow \quad \frac{k_0}{k_2} x_1 + \frac{k_1}{k_2} x_2 + x_3 = 0 \quad (16)$$

with $k_0, k_1, k_2 > 0$. Then, without loss of generality let $k_2 = 1$. In the case of $x_3 = 0$, for all $x_1 = \theta$ an angular speed $x_2 = \dot{\theta}$ with opposite sign is assigned. In consequence the system moves towards the unstable equilibrium position $[x_1, x_2] = [\theta, \dot{\theta}] = \mathbf{0}$.

b) System Behavior on the Sliding Manifold: Once sliding mode is enforced, the system loses its own dynamics and the new dynamics are only defined by the definition of the sliding manifold. In our case this is the position of the sliding plane in three dimensional state space. Characteristics of u also are not relevant to dynamics of the controlled system on the sliding surface.

Observing at the dynamics on the sliding manifold can help to find the optimal sliding mode control parameters. Solving $s = 0$ using (9) the current providing the desired dynamics for the mechanical systems is given by

$$x_3 = -k_0 x_1 - k_1 x_2 \tag{17}$$

Replacing x_3 in (8) and (10) leads to a state description of a 2nd order system

$$\begin{aligned} \dot{x_1} &= x_2 \\ \dot{x_2} &= (\frac{a_1}{\gamma}\xi - \frac{K_m k_0}{J})x_1 - (\frac{c_1}{J} + k_1)x_2\,. \end{aligned} \tag{18}$$

The nonlinear function $\frac{a_1}{\gamma}\xi$ can be neglected in comparision to $\frac{K_m k_0}{J}$ for $k_0 > 0.3$ since $\frac{a_1}{\gamma}\xi << \frac{K_m k_0}{J}$. The characteristic polynomial of the system is then given by

$$s^2 + \frac{k_0 K_m}{J}s + \left(\frac{c_1}{J} + \frac{k_1 K_m}{J}\right) \tag{19}$$

Besides, the standard form of a characteristic polynomial of a 2nd order system is given by $s^2 + 2D\omega_0 + \omega_0^2$ where D is the damping ratio and ω_0 is the characteristic frequency. It means if sliding mode is enforced according to (19) dynamics of the system can be designed as dynamics of a 2nd order system. By tuning the parameter D and ω_0 desired dynamics can be chosen by

$$\begin{aligned} k_0 &= \frac{J}{K_m}{\omega_0}^2 \\ k_1 &= \frac{2JD\omega_0 - c_1}{K_m} \end{aligned} \tag{20}$$

Control parameter k_0 is proportional to the second power of the frequency ω_0 of the system. Once k_0 has been chosen, k_1 based on the desired damping of the system can be assigned.

c) Existence of Sliding Mode: Using the manipulated variable $u = -\bar{u}\,\text{sign}(s)$ the system state reaches the sliding manifold (16) starting from every initital condition in finite time, because

$$\begin{aligned} s\dot{s} &= s(k_0\dot{x}_1 + k_1\dot{x}_2 + \dot{x}_3) \\ &= s(\frac{k_1 a_1 \xi}{\gamma}x_1 + (k_0 - \frac{k_1 c_1}{J} - \frac{K_n}{L})x_2 + \ldots \\ &\quad (\frac{k_1 K_m}{J} - \frac{R_a}{L})x_3) - s\frac{\bar{u}\,\text{sign}(s)}{L} < 0 \end{aligned} \tag{21}$$

With known initial values x_{10}, x_{20} and x_{30} and defined parameters k_0 and k_1 the first three terms of (21) are bounded. Since $s\,\text{sign}(s) = |s| > 0$, there always exists a $\bar{u} > 0$ fulfilling inequation (21). The inequality (21) eventually is guaranteed if the sum of the first three terms is smaller than $\frac{u_0}{L}|s|$.

Large control inputs accelerate system dynamics. Therefore large amplitudes of the manipulated variable influence the performance of the system before reaching sliding mode. The experimental setup allows amplitude values of $\bar{u} = \pm 24\,\text{V}$.

D. Defining a Benchmark Control

In this article the proposed sliding mode control is compared to a control scheme described in fig. 1. In the outer control loop for the mechanical system only the state variables representing the angle and angular speed are part of the control law. The third variable, the current, is considered as manipulated variable. In the inner electrical control loop the current is controlled with PWM. Control law for the mechanical system is implemented as a feedback linearization control.

The reduced system is then given by

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \frac{a_1}{\gamma}\xi x_1 - \frac{c}{J}x_2 + \frac{K_m}{J}i \\ y &= x_1 \end{aligned} \tag{22}$$

and the feedback linearization by

$$\begin{aligned} y &= x_1 \\ \dot{y} &= x_2 \\ \ddot{y} &= \dot{x}_2 \end{aligned} \tag{23}$$

The behavior of the system will be considerably simplified through the feedback linearization. If the Input-Output behavior is analyzed, a simple integrator chain is seen, then it is possible to use a conventional feedback loop control. In this case the ITAE (Integral Time Multiplied Absolute Error) criterion was employed to design the feedback gains, the poles of the system. Poles are designed to be $p_{1/2} = -\omega_0\,(0.7071 \pm j\,0.7071)$, where ω_0 is a scaling factor. It should be taken into account that this factor has an impact on the transfer function of the system. Therefore feedback has to be multiplied by a factor K, which assures steady state accuracy.

The reduced system is a 2nd order system whose transfer function is represented by

$$F(s) = \frac{K}{s^2 + \sqrt{2}\,\omega_0\,s + \omega_0^2} \tag{24}$$

Hence, $K = \omega_0^2$ is obtained.

III. Evaluation of the proposed Control Scheme

The performance of the derived sliding mode control is validated in numerical simulations and applied to an experimental setup.

A. Numerical Simulations

Numerical simulations are done with Matlab/ Simulink using variable stepsize, minimal stepsize is $T_a = 10^{-8}\,\text{s}$. In order to provide comparability of simulation results of the sliding mode control system to those of the benchmark control system, the same dynamics for both control methods were specified. That means for both control strategies the dynamics of the closed loop were characterized by $\omega_0 = 500$ and $D = \frac{1}{\sqrt{2}}$. Using (19) as parameter of the sliding mode control $k_0 = 176$ and $k_1 = 0.4$ were obtained. In the benchmark system the inner control loop for the current is simulated as PWM control based on 20 kHz sampling rate. For both systems the control objective is $\theta = 0$ and the initial angle is $\theta_0 = 0.3$ rad. A disturbance of 2 Nm is added at the time $t_D = 0.2$ s for a time period of 0.4 s. A zero order hold, sampling time $T_S = 0.0001$ s was added in order to simulate discrete control. The observer is not used.

DC motor:	pendulum:
$R_a = 0.316\,\Omega$	$m_{min} = 0\,\text{kg}$
$L = 0.00008\,\text{H}$	$m_{max} = 0.3\,\text{kg}$
$K_m = 0.0302\,\frac{\text{Nm}}{\text{A}}$	$g = 9.81\,\frac{\text{m}}{\text{s}^2}$
$K_n = 60/317\,\text{Vs}$	$l_{min} = 0\,\text{m}$
$J_m = 1.3400e-005\,\text{kg}\,\text{m}^2$	$l_{max} = 0.5\,\text{m}$
$u_A = 24\,\text{V}$	
$c_1 = 0.003\,\frac{\text{Nms}}{\text{rad}}$ (estimated)	
$\gamma = 91$	

Table 1. Parameter of the experimental setup used for control design and in numerical simulations. By changing mass and length of the pendulum different loads can be realized for the experimental setup. In numerical simulations $m = m_{max}$ and $l = l_{max}$ are used.

Fig. 5 shows the trajectories of angle and angular speed for simulations of the sliding mode control and the benchmark control. Detailed trajectories of angle and angular speed can be seen in fig. 6. Fig. 7 demonstrates influences of the control parameters k_0 and k_1 on the transient response of the system using sliding mode control.

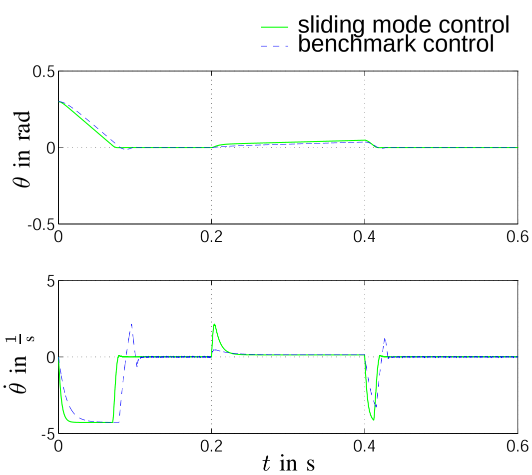

Fig. 5. Simulation results: Sliding mode control of the electromechanical system and benchmark control with disturbances.

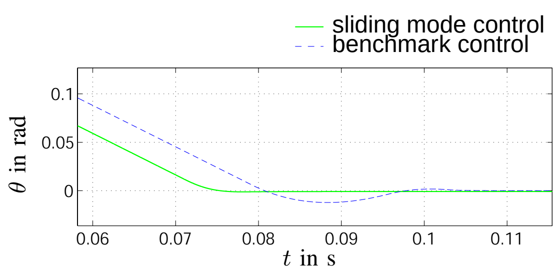

Fig. 6. Simulation results: Sliding mode control of the electromechanical system and benchmark control with disturbances- Close up.

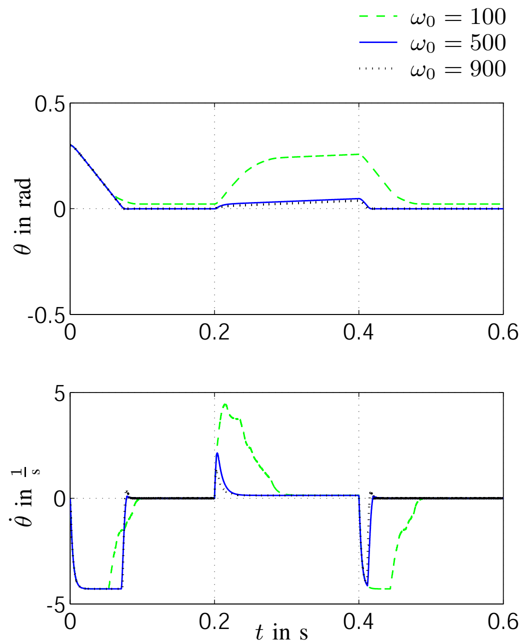

Fig. 7. Simulation Results: Sliding mode control of the electromechanical system with disturbances. Transient response for different design parameters. Increasing parameters k_0 and k_1 go together with increasing ω_0 and faster transient responses.

B. Experimental Setup

The proposed control algorithm was applied to the sample system (fig. 3). The actuator is a 150 W Maxon DC motor with gear. The mass and length of the pendulum can be modified and so different loads can be realized. An H-Bridge provides the required discontinuous control input for the sliding mode control. In the benchmark control system the DC motor is powered by a Copley PWM-amplifier. As framework for the control system Matlab/ Simulink Real Time Workshop is used. The controller runs under RT-Linux with a sampling time of 0.1 ms. Detailed parametric values of the mechanical and electrical subsystem can be seen in table 1.

Fig. 8 and 9 present the trajectories of angle as well as measured current if the proposed sliding mode control is applied to the electromechanical system. Measurements were repeated for different loads.

C. Results

The efficiency of the controller was proved by means of numerical simulations as well as experiments. The derived sliding mode control of the electromechanical system offers robustness, fast dynamics and compared to a benchmark control it uses less power.

d) Fast Performance: As shown in fig. 6 based on simulations the sliding mode control is faster than the benchmark control system. Using sliding mode control the control objective $\theta = 0$ is achieved without overshooting after 80 ms whereas the benchmark control needs 100 ms (see fig. 6) This is a 25% faster transient response. Delayed reaction of the conventional controlled system is caused by

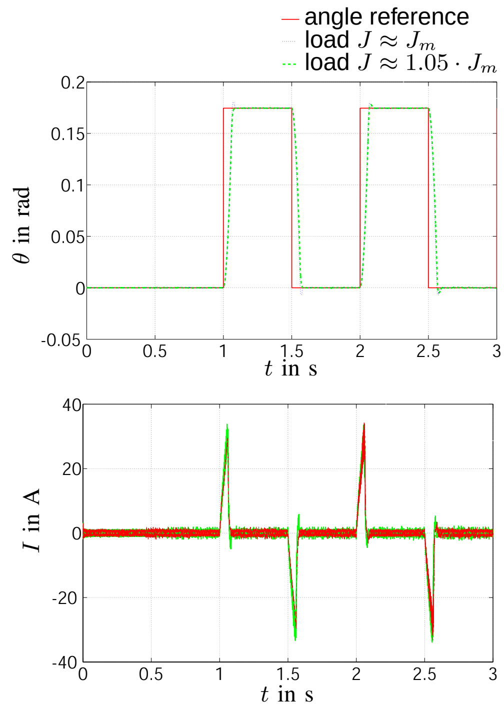

Fig. 8. Experimental results: Sliding mode control of the electromechanical system. Position control with different, not assignable loads.

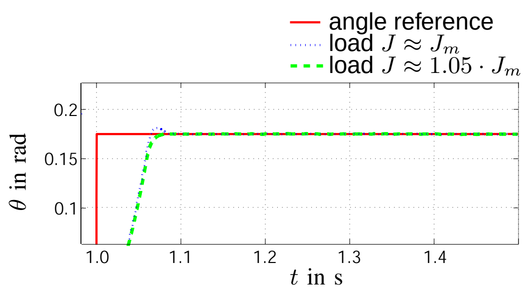

Fig. 9. Experimental results: Sliding mode control of the electromechanical system. Position control with different, not assignable loads- Close up.

the inner control loop providing the desired current given by the control in the outer control loop, which is not always of maximal amplitude. The time constant of the DC motor used in the experimental setup is $T_m = \frac{L}{R_a} \approx 0.25\,\text{ms}$. Therefore in order to prove the advantages of complete state feedback control, sampling rates of at least $T_S = 0.1\,\text{ms}$ are nessecary to be able to demonstrate faster control performances of the sliding mode control. Experimental results underline the accurancy

e) Robustness: The sliding mode controlled system proved to be very robust against parameter variations. Changing the load about approximately 5% does not effect performance considerably as demonstrated in fig. 8 and 9. The control objective is achieved without steady state error and the absolute accuracy of the measured angle is $\pm 0.5e-3\,\text{rad}$. In contrast, feedback linearization as well as pole placement with the help of the ITAE criterion require well known models. Therefore while using sliding mode control, it is easier to compensate a perturbation of the torque load. The benchmark control can generate a steady state error.

f) Simple Implementation: Implementation of the proposed sliding mode control is simple and stability analysis can be made without problems using the sliding mode condition (3). Nevertheless, fast hardware is required: A control unit offering at least 1 kHz sampling rate is necessary to get acceptable results concerning current and angle ripple.

g) Chattering Problem: Since switching is always required, the ideal sliding mode ($s = 0$) is never hold. Regarding (16), k_2 is the feedback gain of the armature current. If $k_2 \to 0$, which equals to $k_0, k_1 \to \infty$, the sliding surface will nearly lay on the plane spread by x_1 and x_2. This will cause chattering. Hence, k_2 cannot be infinitesimal small and therefore, aside from physical constraints, using this method the system cannot be made infinitely fast. Due to a sampling rate of only $0.1\,\text{ms}$ compared to the time constant of $\approx 0.25\,\text{ms}$ of the electrical system in fig. 8 the inductance of the motor cannot totally filter out chattering before it reaches the mechanical subsystem and a current ripple of $\pm 1\,\text{A}$ is observed.

h) Power Reduction: Control based on PWM signals is not as flexible as sliding mode control because performance depends on the defined sampling rate of the PWM unit. High switching frequencies cause high current ripples. This includes large power losses. For the szenario presented in fig. 5 energy consumption of the benchmark control in steady state is $360\frac{\text{Ws}}{\text{s}}$ whereas it is only $40\frac{\text{Ws}}{\text{s}}$ for the sliding mode control.

IV. Conclusion

In this article a sliding mode control for electromechanical systems was developed and experimentally tested. Results show that the proposed control scheme improves performance of electromechanical systems compared to conventional control schemes. If the dynamics of the electric drive are taken into account, the phenomenon of chattering can be avoided and power consumption can be decreased. Because the input voltage of the electromechanical system is switched depending on the mechanical and electrical variables the control is very robust with regard to disturbances and different initial states. First experimental results indicate, that the proposed approach improves performance of mechanical systems driven by different electric actuators, such as DC motors, synchronous and induction machines with not exactly known parameters and which are operating under unknown conditions.

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