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Published in:
SEFI 2022 - 50th Annual Conference of the European Society for Engineering Education, Proceedings

DOI:
10.5821/conference-9788412322262.1454

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

AN INTRODUCTION TO SLIDING MODE CONTROL FOR INTERDISCIPLINARY EDUCATION

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Conference Key Areas: *Interdisciplinary engineering education, Mathematics at the heart of Engineering, Co-creation with students*
Keywords: *Interdisciplinary engineering education, practice-based learning concepts, theory-based engineering course, design for non-engineering students*

ABSTRACT

This paper proposes a new lecture structure for an introduction to Sliding Mode Control (SMC) for a wider audience of undergraduate students. In particular, the intuitive derivation of the sliding variable and choice of the sliding surface is emphasized in order to obtain an intuitive understanding in a gradual manner. The structure of the lecture is conceived in an inclusive way, considering only the common mathematical high school background and basic knowledge about simple differential equations and their solutions. In this sense, SMC can represent a possible application of the already acquired knowledge and in the meantime provide contact with one of the most important control techniques in theory and application. The paper intends to give a possible structure of an interdisciplinary lecture in SMC for teachers and students (in particular, non-technical students). By presenting the research-based approach and the results of the implementation, the paper contributes to the discourse on interdisciplinary education in engineering.

1 INTRODUCTION

Global transformation processes lead to challenges and changed framework conditions that the engineering and education sciences have to face. In view of digitalization and increased demands for the efficient use of resources, the challenges for control engineering solutions are constantly growing. These new issues are characterized by a high degree of complexity and responsibility as well as the need for broad knowledge at the interfaces of the disciplines. Graduates must be prepared to develop adequate solutions in diverse teams in order to contribute to change processes towards a smart and sustainable future [1–3]. On the one hand, this requires interdisciplinary approaches and an increasing awareness of the automatic control importance in our society. On the other hand, there is a massive shortage of qualified specialists in the technical field. Against this background, engineering sciences have to face the challenge of offering suitable engineering programmes for a broader target group (e.g. non-technical students) and an interdisciplinary education. The aim is to prepare the students for creative and responsible action in today's society in which the concept of complementarity, which means interdisciplinarity and transdisciplinarity, is essential for most leading positions in our complex society. This ambitious program calls for new lectures: inclusive, interdisciplinary and more based on the common background of the students. This paper contributes to this research discourse by presenting an innovative theory-based lecture

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doi:10.5821/conference-9788412322262.1454

structure for introducing the concept of Sliding Mode Control (SMC) to undergraduate students in non-technical fields and the related empirical findings on implementation.

1.1 Research-based didactic framework

Our objectives are standing for both theoretical understanding and educational practice. Therefore, we have chosen Design Based Research (DBR) as multi-faceted approach that provides valuable results for both, [4]. With a focus on engineering education for a sustainable and smart future, our contribution specifically addresses the theory-based approach for students who do not come from an engineering background. The very heterogeneous group of students requires an innovative teaching and learning concept to integrate different disciplinary cultures and to specifically support these *non-traditional* students in acquiring competences, as in [5]. The student-centered course design is based on Educational Reconstruction [6] as the research framework. In [7], this framework is further developed with a focus on engineering education. In order to take students seriously as an active starting point for the construction of knowledge, the Educational Reconstruction model can be of great help, see [6], especially for the special target group of non-technical students. In the Educational Reconstruction model, scientific concepts and the learners' perspective are related to each other, and from the comparison a conclusion is drawn for the design of student-centred learning environments. From this it can be concluded that teaching content must not simply be dictated scientifically, but must be created pedagogically meaningful through the conception of the learners themselves, as in [8]. With this framework, implementation results for heterogeneous student groups are available [9, 10], which have been incorporated into the new concept of the control lecture.

1.2 Institutional implementation and math. requirements

The newly developed lecture addresses the challenges for teaching in the engineering sciences described at the beginning. The lecture is offered at the Leuphana University Lüneburg in Lüneburg, Germany, which provides a conducive setting. Bachelor studies at Leuphana not only lays a solid foundation for the future professional career, but also aims at providing access to a university that values interdisciplinarity and emphasizes wide-ranging practical and theoretical competence. At Leuphana College, the individual study programme is created from major, minor and complementary studies, see Fig. 1. It forms a gateway to the academic world by exposing students to a wide range of scientific methods and offering a holistic education through individual choice of a major, minor, and complementary study electives. The College programme encourages students of all disciplines to look for solutions beyond the boundaries of academic discourse and to build a personalized and inclusive path of study. Therefore, such liberal education demands and encourages the intellectual and personal development of each and every specific student profile, in which new ideas to teach and to connect naturally or technically with human sciences represent a prerequisite. In addition, studies with a view to gender aspects underline the positive effects of an interdisciplinary design of study programmes on the selection of women [11,12]. Offering a control engineering lecture for an interdisciplinary target group can also contribute to securing and increasing young talent in the field. The presented lecture can be used in different contexts: in Bachelor courses for engineers as well as for courses dedicated to non-engineers (non-engineering minor programs, complementary study). In this way, the paper provides important insights into how to teach the first and only control course in non-control engineering programs. The lecture requires mathematical high school knowledge. Nevertheless, it is important that these courses start recalling basic knowledge of differential equations and, before starting with this lecture dedicated to SMC, the courses should introduce elements of nonlinear differential equations considering the fundamental direct method of Lyapunov related to the stability of a solution of a differential equation. Figure 1 shows the structure of the proposed course in which this lecture in included. In fact, as is visible there, the lecture closes by recalling Lyapunov's direct method in the context of sliding mode control. The goal of this contribution is to present a possible structure of a lecture concerning SMC which is held in the programs of study described above, and which realizes the possibility of an inclusive lecture in which just basic high school knowledge, such as computation of derivatives

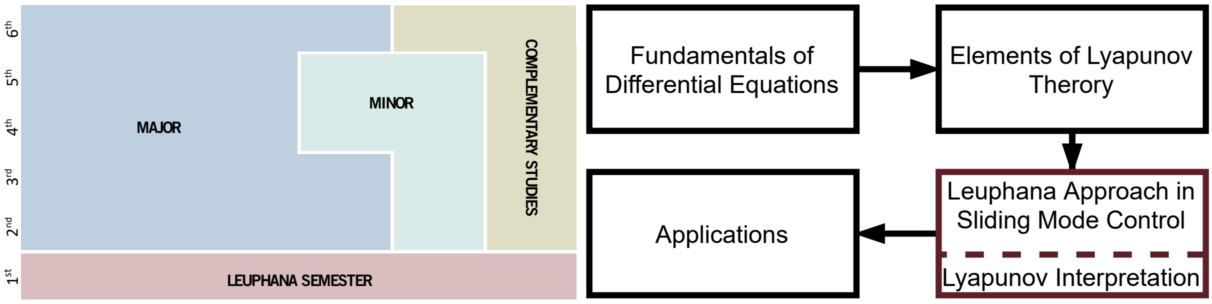

Fig. 1. Leuphana College model, see `https://www.leuphana.de/en/college` *(left) and structure of the proposed course (right)*

and integrals is necessary. The intuitive nature of the lecture and in the meantime the formal and rigorous explanation of some fundamental concepts of control realize an important contribution in the context of a new didactic treadoff between natural and human sciences. The course focuses on a broad-based education and at the same time developing individual essential skills, such as analytical and reactive thinking, clear and convincing argumentation, well-founded and perspective assessment. This takes place through intensive interactions with teachers and fellow students as well as in self-study, both during university events and extra-curricular activities. The protagonists of these lectures are the students. Therefore, this paper is written in collaborations with some of the students who attended these lectures and this emphasizes the inclusive nature of the course.

The paper is organized in the following way. Section 2 introduces the concept of Sliding Mode Control (SMC) in an intuitive way. Section 3 introduces the concept of an integral sliding surface for first-order systems. In Section 4, related empirical findings on implementation and future perspectives are presented for the engineering research and education community. Conclusions close the paper.

2 SLIDING MODE CONTROL

SMC is a robust control method which can handle both linear and nonlinear systems with uncertainties and unmeasurable disturbances.

2.1 Preliminary and Fundamental Aspects

Considering a plant with one state variable x and control input u, the goal is to steer the state to zero:

$$\frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} = u(t) \tag{1}$$

with $x(0) = \pm x_0$, where $x_0 > 0$ is the absolute value of the initial condition.

2.2 Obvious strategy

The intuitive solution is to select

$$x(t) > 0 \rightarrow \frac{\mathrm{d}\,x}{\mathrm{d}\,t} \overset{!}{<} 0, \qquad x(t) < 0 \rightarrow \frac{\mathrm{d}\,x}{\mathrm{d}\,t} \overset{!}{>} 0. \tag{2}$$

From this consideration, a control law $u(t)$ should arise.

2.3 First strategy

A surmisable first approach is to use a linear state-feedback control $u(t) = -kx(t)$ in which $k > 0$. Using this controller,

$$\lim_{t\to+\infty} x(t) = 0. \tag{3}$$

In fact, the simple closed-loop system

$$\frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} = -kx(t) \tag{4}$$

yields the well-known solution

$$x(t) = \pm x_0 \exp(-kt). \tag{5}$$

2.4 Second strategy

Since eq. (5) converges to zero only in infinite time, another strategy is to set $u(t) = -k\,\mathrm{sgn}(x(t))$, which renders the closed-loop system nonlinear

$$\frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} = u(t) = -k\,\mathrm{sgn}(x(t)). \tag{6}$$

The solution depends on the sign of the state,

$$x(t) = x_0 - kt \text{ for } x(t) > 0 \tag{7}$$
$$x(t) = x_0 - kt > 0 \rightarrow t < \frac{x_0}{k},$$
$$x(t) = -x_0 + kt \text{ for } x(t) < 0 \tag{8}$$
$$x(t) = -x_0 + kt < 0 \rightarrow t < \frac{x_0}{k}.$$

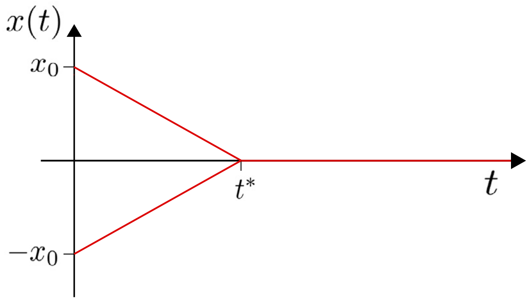

Fig. 2. Finite time dynamics

Considering $t > 0$, the solutions are valid as long as $0 < t \leq \frac{x_0}{k}$. Figure 2 shows the obtained finite time dynamics using the *static-friction-like* nonlinear component $\mathrm{sgn}(x(t))$. We obtain $x(t) = 0$ for $t = \frac{x_0}{k}$. For $t = \frac{x_0}{k} \rightarrow \mathrm{sgn}(0) = 0 \rightarrow \frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} = 0$. This means that we do not have variations, and thus we remain at zero $(x(t) = 0)$ – at least in a mathematical sense. This generates the following solution for $x(t) > 0$:

$$x(t) = \begin{cases} x_0 - kt & \text{if } t \leq \dfrac{x_0}{k} \\ 0 & \text{if } t > \dfrac{x_0}{k}. \end{cases} \tag{9}$$

For $x(t) < 0$, the solution is

$$x(t) = \begin{cases} -x_0 + kt & \text{if } t \leq \dfrac{x_0}{k} \\ 0 & \text{if } t > \dfrac{x_0}{k}. \end{cases} \tag{10}$$

Often, the discontinuous function sgn is approximated as $\mathrm{sgn}(x(t)) \approx \mathrm{sat}\left(\frac{x(t)}{\phi}\right)$, see Fig. 3, where $\phi > 0$ is the *thickness* of a boundary layer in which we may remain without switching:

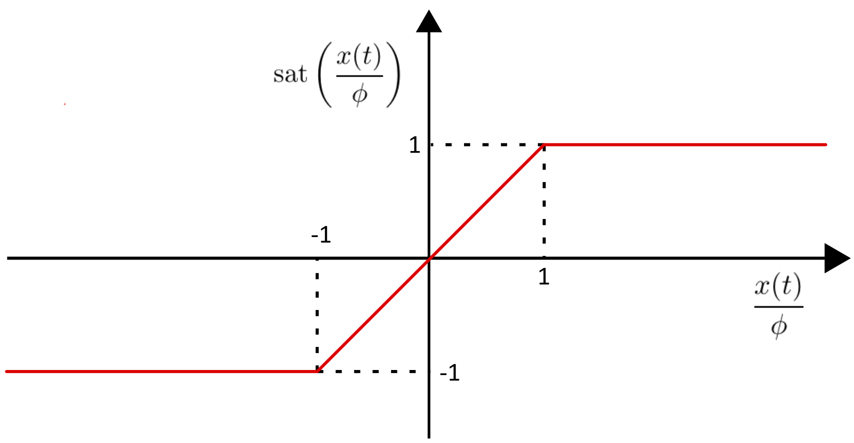

Fig. 3. Saturation function

$$\operatorname{sat}\left(\frac{x(t)}{\phi}\right) = \begin{cases} \frac{x(t)}{\phi} & \text{if } \left|\frac{x(t)}{\phi}\right| \leq 1 \\ \operatorname{sgn}\left(\frac{x(t)}{\phi}\right) & \text{otherwise.} \end{cases} \tag{11}$$

Considering an uncertainty Δ in the system model,

$$\frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} = u(t) + \Delta(x(t), t) \text{ with } |\Delta(x(t), t)| \leq \Delta_{\text{max}}. \tag{12}$$

If we apply the first strategy to this uncertain system,

$$\frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} = -kx(t) + \Delta(x(t), t). \tag{13}$$

In this case, we do not have the possibility to steer the state to zero. If we apply the second strategy, however,

$$\frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} = -k\operatorname{sgn}(x(t)) + \Delta(x(t), t). \tag{14}$$

We simply need to choose $k > \Delta_{\text{max}}$ i.e. $k = \Delta_{\text{max}} + \eta$ with a positive η. If this expression is placed in (12):

$$\begin{cases} x(t) > 0: \frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} = -\eta - \Delta_{\text{max}} + \Delta(x(t), t) \\ x(t) < 0: \frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} = \eta + \Delta_{\text{max}} + \Delta(x(t), t), \end{cases} \tag{15}$$

which is now manipulated as

$$\begin{cases} x(t) > 0: \frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} + \Delta_{\text{max}} - \Delta(x(t), t) = -\eta \\ x(t) < 0: \frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} - \Delta_{\text{max}} - \Delta(x(t), t) = \eta. \end{cases} \tag{16}$$

If we consider that

$$\Delta_{\text{max}} - \Delta(x(t), t) \geq 0, \tag{17}$$

$$-\Delta_{\text{max}} - \Delta(x(t), t) \leq 0, \tag{18}$$

the following inequalities can be derived

$$\begin{cases} x(t) > 0: \frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} \leq -\eta, \\ x(t) < 0: \frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} \geq \eta. \end{cases} \tag{19}$$

Thus, η represents the minimal convergence rate. We can write this expression in a more compact form by multiplying both sides with $\operatorname{sgn}(x)$:

$$\begin{cases} x(t) > 0: \operatorname{sgn}(x)\frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} \leq -\eta\operatorname{sgn}(x) \\ x(t) < 0: \operatorname{sgn}(x)\frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} \geq \eta\operatorname{sgn}(x) \end{cases} \Rightarrow \begin{cases} x(t) > 0: \frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} \leq -\eta\operatorname{sgn}(x) \\ x(t) < 0: \frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} \leq -\eta\operatorname{sgn}(x). \end{cases} \tag{20}$$

So, in general the closed-loop system results as

$$\frac{\mathrm{d}\,x(t)}{\mathrm{d}\,t} \leq -\eta\operatorname{sgn}(x(t)), \tag{21}$$

where η represents the reachability condition.

2.5 SMC for higher-order systems

Now a system with two states is considered:

$$\frac{\mathrm{d}\,x_1(t)}{\mathrm{d}\,t} = x_2(t), \quad \frac{\mathrm{d}\,x_2(t)}{\mathrm{d}\,t} = u(t), \quad x_0 = \begin{bmatrix} x_{1,0} \\ x_{2,0} \end{bmatrix} = \begin{bmatrix} x_1(0) \\ x_2(0) \end{bmatrix}. \tag{22}$$

The goal is the same as before: steer the state to zero. Assuming that we can apply a state-feedback controller to achieve $x_2(t) = -c_1 x_1(t)$ with $c_1 > 0$, the dynamics result as

$$\frac{\mathrm{d}\,x_1(t)}{\mathrm{d}\,t} = -c_1 x_1(t). \tag{23}$$

If this is possible, $x_1(t) = x_{1,0} \exp(-c_1 t)$. This yields

$$\lim_{t \to +\infty} x_1(t) = 0, \quad \lim_{t \to +\infty} x_2(t) = 0. \tag{24}$$

However, it is problematic to assume the relationship $x_2(t) = -c_1 x_1(t)$. We are not able to set this condition through linear state-feedback control. In fact, if we consider a mechanical system, this means that the velocity must be proportional to the position. To remedy this, we introduce an abstract **sliding variable** $s(t)$ defined in the following way:

$$s(t) = x_2(t) + c_1 x_1(t) \quad \text{with } c_1 > 0. \tag{25}$$

Now, if we reach $s(t) = 0$, we have

$$0 = x_2(t) + c_1 x_1(t) \tag{26}$$

and thus $x_2(t) = -c_1 x_1(t)$, which is exactly what we wanted to obtain. Now the goal is to steer the system to $s(t) = 0$. Recalling system (22), if we differentiate s(t), we obtain

$$\frac{\mathrm{d}\,s(x_1(t), x_2(t))}{\mathrm{d}\,t} = \frac{\mathrm{d}\,x_2(t)}{\mathrm{d}\,t} + c_1 \frac{\mathrm{d}\,x_1(t)}{\mathrm{d}\,t} = u(t) + c_1 x_2(t). \tag{27}$$

Since we want to obtain

$$\frac{\mathrm{d}\,s(x_1(t), x_2(t))}{\mathrm{d}\,t} = -k\,\mathrm{sgn}(s(t)), \tag{28}$$

similar to (21), it is easy to see from (27) that we require

$$u(t) + c_1 x_2(t) \stackrel{!}{=} -k\,\mathrm{sgn}(s(t)) \tag{29}$$

which means that the controller *to stabilize* $s(t)$ is

$$u(x_1(t), x_2(t)) = -c_1 x_2(t) - k\,\mathrm{sgn}(s(t)) \tag{30}$$

The graphical interpretation of the dynamics is represented in Fig. 4. If we consider a saturation function with boundary layer instead of function sgn, we obtain the behaviour described in Fig. 5.

2.6 Recalling Lyapunov point of view

The proposed solution is now considered in a Lyapunov sense. The obtained sliding surface dynamics (28) can be multiplied by $s(t)$, yielding

$$s(t)\frac{\mathrm{d}\,s(x_1(t), x_2(t))}{\mathrm{d}\,t} = -k s(t)\,\mathrm{sgn}(s(t)) \tag{31}$$

and thus

$$\frac{1}{2}\frac{\mathrm{d}\,s^2(x_1(t), x_2(t))}{\mathrm{d}\,t} = -k|s(t)|. \tag{32}$$

Equation (32) is the Lyapunov stability condition, which the students are taught earlier in the course (see Fig. 1), and can be obtained starting from

$$V(s(t)) = \frac{1}{2}s^2(t) \tag{33}$$

and thus [13]

$$\frac{\mathrm{d}\,V(s(t))}{\mathrm{d}\,t} = s(t)\frac{\mathrm{d}\,s(t)}{\mathrm{d}\,t} = s(t)[-k\,\mathrm{sgn}(s(t))] = -k|s(t)| < 0. \tag{34}$$

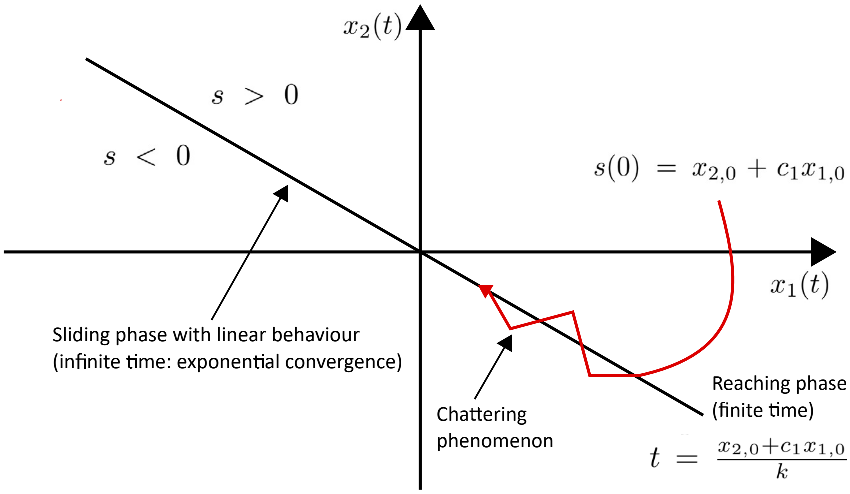

Fig. 4. Sliding phase

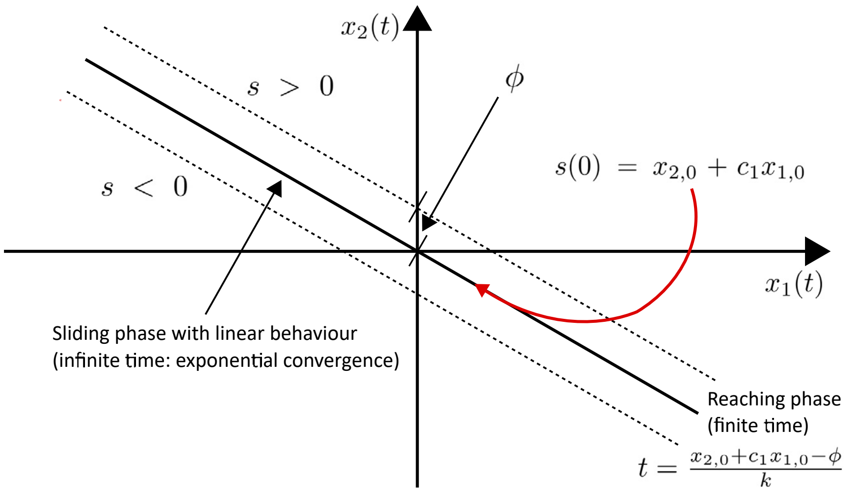

Fig. 5. Graphical representation of the dynamics in the presence of a boundary layer

3 INTEGRAL SLIDING SURFACES

Let us consider the following sliding surface structure as proposed in [13] and a system with just one state x (i.e. $n = 1$). The conventional sliding surface, based on an error $e(t) = x(t) - x_d(t)$, can be chosen as

$$s(t) = \left(\frac{\mathrm{d}}{\mathrm{d}\,t} + \lambda\right)^{n-1} e(t), \tag{35}$$

in which $n \in \mathbb{N}$ represents the number of states of the system. The exponent of this expression represents the derivative order as well as the *polynomial exponent*. If $n = 1$, then $s(t) = e(t)$. This is the simplest possible surface which is exactly the state error. This surface allows to reach error $e(t) = 0$ at a finite time ($s(t^*) = 0 \to e(t^*) = 0$). Let us now consider the following sliding surface, with the assumption of a non-impulsive control error $e(t)$

$$s(t) = e(t) + \lambda \int_0^t e(\tau)d\tau - e(0), \tag{36}$$

with $\lambda > 0$. Assuming that the trajectory reaches condition $s(t) = 0$ at $t = t^*$, then for $t > t^*$

$$0 = e(t) + \lambda \int_0^t e(\tau)d\tau - e(0), \tag{37}$$

and thus

$$e(t) = e(0) - \lambda \int_0^t e(\tau)d\tau. \tag{38}$$

Equation (38) is a linear one and admits just one unique solution, which is

$$e(t) = e(0)\exp(-\lambda t). \tag{39}$$

The trajectory remains on the surface, but the convergence is obtained in infinite time. This implies that, if the initial condition of the system state error is known and $e(0) = 0$, then $s(0) = 0$. In this case, the duration of the reaching phase is reduced to zero, but we introduce an infinite sliding time with respect to the sliding surface $s(t) = e(t)$.

Let us compare this result with those obtained using a slightly different surface:

$$s(t) = e(t) + \lambda \int_0^t e(\tau)d\tau. \tag{40}$$

Considering that (40) is obtained if $e(0) = 0$, the unique solution results as (39) with $e(t) = 0$. Using surface (40) instead of surface (36), the reaching phase cannot be reduced to zero because $s(0) = e(0)$, but once the surface is reached at t^* ($s(t^*) = 0$), then $e(t) = 0$.

Remark 1 *Another interesting consideration is that both surfaces (40) and (36) guarantee the invariant condition $\dot{s}(t) = 0$ (to remain at $s(t) = 0\ \forall t$) for each initial condition. In fact, both cases*

$$\dot{s}(t) = \dot{e}(t) + \lambda e(t) = 0 \tag{41}$$

admit the solution

$$e(t) = e(0)\exp(-\lambda t). \tag{42}$$

From a mathematical point of view, when $s(t) = 0$, then $\operatorname{sgn}(s(t)) = 0$ and considering (42), $s(t) = 0$ and $\dot{s}(t) = 0$, $\forall$ initial conditions $e(0)$.

4 FEEDBACK FROM STUDENTS AND FROM THE SCIENTIFIC COMMUNITY

Introducing the basic concept of sliding mode control, we received positive feedback from our scientific community which accepted our communications in different conferences and journals, see [14–18]. In an interview of a student from Arkansas University [19], who has published a paper in [14], it emerges that the students appreciated the intuitive idea to introduce this effective and robust (and in this sense, practical) method, despite the difficulty of the courses. Moreover, our community appreciated the contributions of our students which in some cases received best paper awards in the student papers competition [15]. In one case, a paper was selected as one of the best papers of the conference [16] and, in another one, a paper was selected for an extension within a reputable journal, see [17].

5 CONCLUSION

This paper deals with a new structure of an introductional lecture in the context of Sliding Mode Control for undergraduate students. SMC is one of the most used control techniques in industrial applications. This is due to its robustness and its straightforward structure to be implemented, at least in its basic form. Therefore it is worthwhile to introduce this techniques directly in the Bachelor's-level lectures together with the classical basic knowledge of control systems, such as control in Laplace domain and linear state space methods. In fact, concepts like differential calculus and integrals are already known when the students start lectures in control system.

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