Robot Manipulators

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I-Tech

Published by In-Teh

In-Teh is Croatian branch of I-Tech Education and Publishing KG, Vienna, Austria.

www.in-teh.org
Additional copies can be obtained from:
publication@ars-journal.com

First published September 2008
Printed in Croatia

A catalogue record for this book is available from the University Library Rijeka under no. 111222001
Robot Manipulators, Edited by Marco Ceccarelli
p. cm.
ISBN 978-953-7619-06-0
1. Robot Manipulators. I. Marco Ceccarelli

Preface

Robots can be considered as the most advanced automatic systems and robotics, as a technique and scientific discipline, can be considered as the evolution of automation with interdisciplinary integration with other technological fields.

A robot can be defined as a system which is able to perform several manipulative tasks with objects, tools, and even its extremity (end-effector) with the capability of being reprogrammed for several types of operations. There is an integration of mechanical and control counterparts, but it even includes additional equipment and components, concerned with sensorial capabilities and artificial intelligence. Therefore, the simultaneous operation and design integration of all the above-mentioned systems will provide a robotic system

The State-of-Art of Robotics already refers to solutions of early 70s as very obsolete designs, although they are not yet worthy to be considered as pertaining to History. The fact that the progress in the field of Robotics has grown very quickly has given a shorten of the time period for the events being historical, although in many cases they cannot be yet accepted as pertaining to the History of Science and Technology.

It is well known that the word "robot" was coined by Karel Capek in 1921 for a theatre play dealing with cybernetic workers, who/which replace humans in heavy work. Indeed, even in today life-time robots are intended with a wide meaning that includes any system that can operate autonomously for given class of tasks. Sometimes intelligent capability is included as a fundamental property of a robot, as shown in many fiction works and movies, although many current robots, mostly in industrial applications, have only flexible programming and are very far to be intelligent machines.

From technical viewpoint a unique definition of robot has taken time for being universally accepted.

In 1988 the International Standard Organization gives: "An industrial robot is an automatic, servo-controlled, freely programmable, multipurpose manipulator, with several axes, for the handling of work pieces, tools or special devices. Variably programmed operations make possible the execution of a multiplicity of tasks".

However, still in 1991 for example, the IFToMM International Federation for the Promotion and Mechanism and Machine Science (formerly International Federation for the Theory of Machines and Mechanisms) gives its own definitions: Robot as "Mechanical system under automatic control that performs operations such as handling and locomotion"; and Manipulator as "Device for gripping and controlled movements of objects".

Even roboticists use their own definition for robots to emphasize some peculiarities, as for example from IEEE Community: "a robot is a machine constructed as an assemblage of joined links so that they can be articulated into desired positions by a programmable controller and precision actuators to perform a variety of tasks".

However, different meanings for robots are still persistent from nation to nation, from technical field to technical field, from application to application.

Nevertheless, a robot or robotic system can be recognized when it has the three main characteristics: mechanical versatility, reprogramming capacity, and intelligent capability.

Summarizing briefly the concepts, one can understand the above-mentioned terms as follows; mechanical versatility refers to the ability of the mechanical design to perform several different manipulative tasks; reprogramming capacity concerns with the possibility to update the operation timing and sequence, even for different tasks, by means of software programming; intelligent capability refers to the skill of a robot to recognize its owns state and neighbour environment by using sensors and human-like reasoning, even to update automatically the operation.

Therefore, a robot can be considered as a complex system that is composed of several systems and devices to give:

- mechanical capabilities (motion and force);
- sensorial capabilities (similar to human beings and/or specific others);
- intellectual capabilities (for control, decision, and memory).

In this book we have grouped contributions in 28 chapters from several authors all around the world on the several aspects and challenges of research and applications of robots with the aim to show the recent advances and problems that still need to be considered for future improvements of robot success in worldwide frames. Each chapter addresses a specific area of modeling, design, and application of robots but with an eye to give an integrated view of what make a robot a unique modern system for many different uses and future potential applications.

Main attention has been focused on design issues as thought challenging for improving capabilities and further possibilities of robots for new and old applications, as seen from today technologies and research programs. Thus, great attention has been addressed to control aspects that are strongly evolving also as function of the improvements in robot modeling, sensors, servo-power systems, and informatics. But even other aspects are considered as of fundamental challenge both in design and use of robots with improved performance and capabilities, like for example kinematic design, dynamics, vision integration.

Maybe some aspects have received not a proper attention or discussion as an indication of the fecundity that Robotics can still express for a future benefit of Society improvement both in term of labor environment and productivity, but also for a better quality of life even in other fields than working places.

Thus, I believe that a reader will take advantage of the chapters in this edited book with further satisfaction and motivation for her or his work in professional applications as well as in research activity.

I thank the authors who have contributed with very interesting chapters in several subjects, covering the many fields of Robotics. I thank the editor I-Tech Education and Publishing KG in Wien and its Scientific Manager prof Aleksandar Lazinica for having supported this editorial initiative and having offered a very kind editorial support to all the authors in elaborating and delivering the chapters in proper format in time.

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Contents

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Experimental Results on Variable Structure Control for an Uncertain Robot Model

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1. Introduction

To reduce computational complexity and the necessity of utilizing highly nonlinear and strongly coupled dynamical models in designing robot manipulator controllers, one of the solutions is to employ robust control techniques that do not require an exact knowledge of the system. Among these control techniques, the sliding mode variable structure control (SM-VSC) is one that has been successfully applied to systems with uncertainties and strong coupling effects.

The sliding mode principle is basically to drive the nonlinear plant operating point along or nearby the vicinity of the specified and user-chosen hyperplane where it 'slides' until it reaches the origin, by means of certain high-frequency switching control law. Once the system reaches the hyperplane, its order is reduced since it depends only on the hyperplane dynamics.

The existence of the sliding mode in a manifold is due to the discontinuous nature of the variable structure control which is switching between two distinctively different system structures. Such a system is characterized by an excellent performance, which includes insensitivity to parameter variations and a complete rejection of disturbances. However, since this switching could not be practically implemented with an infinite frequency as required for the ideal sliding mode, the discontinuity generates a chattering in the control, which may unfortunately excite high-frequency dynamics that are neglected in the model and thus might damage the actual physical system.

In view of the above, the SM-VSC was restricted in practical applications until progresses in the electronics area and particularly in the switching devices in the nineteen seventies. Since then, the SM-VSC has reemerged with several advances for alleviating the undesirable chatter phenomenon. Among the main ideas is the approach based on the equivalent control component which is added to the discontinuous component (Utkin, 1992; Hamerlain et al, 1997). In fact, depending on the model parameters, the equivalent control corresponds to the SM existence condition. Second, the approach studied in (Slotine, 1986) consists of the allocation of a boundary layer around the switching hyperplane in which the discontinuous control is replaced by a continuous one. In (Harashima et al, 1986; Belhocine et al, 1998), the gain of the discontinuous component is replaced by a linear function of errors. In (Furuta et al, 1989), the authors propose a technique in which the sliding mode is replaced by a sliding sector.

Most recent approaches consider that the discontinuity occurs at the highest derivatives of the control input rather than the control itself. These techniques can be classified as a higher order sliding mode approaches in which the state equation is differentiated to produce a differential equation with the derivative of the control input (Levant & Alelishvili, 2007; Bartolini et al, 1998). Among them, a particular approach that is introduced in (Fliess, 1990) and investigated in (Sira-Ramirez, 1993; Bouyoucef et al, 2006) uses differential algebraic mathematical tools. Indeed, by using the differential primitive element theorem in case of nonlinear systems and the differential cyclic element theorem in case of linear systems, this technique transforms the system dynamics into a new state space representation where the derivatives of the control inputs are involved in the generalization of the system representation. By invoking successive integrations to recover the actual control the chattering of the so-called Generalized Variable Structure (GVS) control is filtered out.

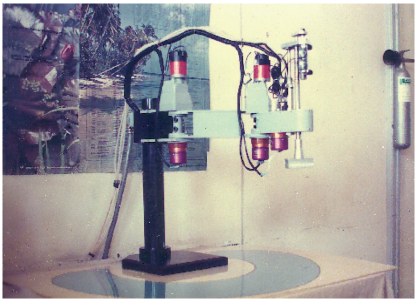
In this paper, we present through extensive simulations and experimentations the results on performance improvements of two GVS algorithms as compared to a classical variable structure (CVS) control approach. Used as a benchmark to the GVS controllers, the CVS is based on the equivalent control method. The CVS design methodology is based on the differential geometry whereas the GVS algorithms are designed using the differential algebraic tools. Once the common state representation of the system with the derivatives of the control input is obtained, the first GVS algorithm is designed by solving the well-known sliding condition equation while the second GVS algorithm is derived on the basis of what is denoted as the hypersurface convergence equation.

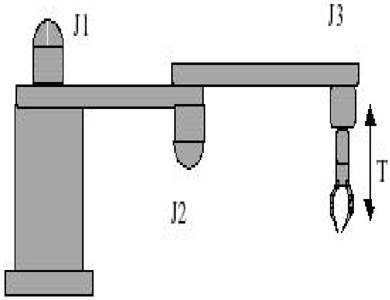
The remainder of this chapter is organized as follows. After identifying experimentally the robot axes in Section 2, the procedure for designing SM-VSC algorithms is studied in Section 3. In order to evaluate the chattering alleviation and performance improvement, simulations and experimentations are performed in Section 4. Finally, conclusions are stated in Section 5.

2. Identification of robot manipulator axes

In this study, Generalized Variable Structure (GVSC) control techniques are implemented on the Robot Manipulator (RP41) as illustrated in Fig. 1-a. From the schematic that is depicted in Fig. 1-b, one can observe that the RP41 is a SCARA robot with four degrees of freedom. The three first joints (J1, J2, and J3) are rotoide while the fourth one (T) is prismatic. To each robot axis, one assigns a controller that uses only a measured angular signal that is generated by a shaft encoder via a 12 bit Analog/Digital converter. As far as control is concerned, it is digitized from 0 to 4096. As illustrated in Table 1, this interval corresponds to an analog input of the converter spanning from – 5 to + 5 Volts. In order to activate the DC drive of each robot joint, these low voltages are amplified by a power board to the range of -24 to +24 Volts.

In virtue of the robustness properties, uncertain linear models of the robot are obtained for the design of the SM-VS controllers. This section briefly presents the experimental identification of the three robot axes resulting in a suitable second order linear model for each manipulator axis.





(a) The SCARA Robot RP41 (b) Schematic of the SCARA RP41 mechanism

Figure 1. The SCARA Robot Manipulator (RP 41), *(Centre de Développement des Technologies Avancées, Algiers)*

Digital controller output	D/A Converter output [volts]	Robot DC motors input [volts]
0	+5	+24
2048	0	0
4096	-5	-24

Table 1. Digital and analog control ranges

For further explanations on the identification of the arm axes, the reader can refer to our previous investigations (Youssef et al, 1998). The complete Lagrange formalism-based dynamic model of the considered SCARA robot has been experimentally studied in (Bouyoucef et al, 1998), in which the model parameters are identified and then validated by using computed torque control algorithm. The well-known motion dynamics of the three joints manipulator is described by equation (1)

$$M(q)\,.\,\ddot{q} + h(q\,,\dot{q}) + g(q) = u \qquad (1)$$

Where $q, \dot{q}, \ddot{q} \in R^3$ are the vectors of angular position, velocity and acceleration, respectively, $M(.) \in R^{3x3}$ is the symmetric positive definite inertia matrix, $h(.) \in R^{3x3}$ is the coefficient matrix of the centripetal and Coriolis torques, $g(.) \in R^3$ is the vector of the gravitational torques, and $u(.) \in R^3$ is the vector of torques applied to the joints of the manipulator.

As developed in (Youssef et al, 1998), considering the diagonal elements preponderance of the non singular matrix $M(q)$, and replacing $h(q,\dot{q})$ and $g(q)$ by $C(q,\dot{q})\dot{q}$ and $G(q)q$, respectively, $M^{-1}(q)\,C(q,\dot{q})$, $M^{-1}(q)\,G(q)$ and $M^{-1}(q)$ by A_1, A_0 and B, respectively, equation (1) can be written as follows:

$$\ddot{q} + A_1\dot{q} + A_0 q = B\,u \qquad (2)$$

where each of the diagonal matrices A_0, A_1 and B contains the dynamic parameters of the three robot axes for the angle, rate and control variables, respectively. On the basis of the plant input/output data, the parametric identification principle consisting of the estimation of the model parameters according to a priori user-chosen structure was performed. Adopting the ARX (Auto regressive with exogenous input) model, and using the Matlab software, the off-line identification generated the robot parameters according to model (2), which are illustrated in Table 1.

$A_0 = diag\,[-5.4 \quad -2.41 \quad -117]$
$A_1 = diag\,[560.7 \quad 200 \quad 413.5]$
$B = diag\,[0.5 \quad 0.65 \quad 7.5]$

Table 1. The identification of the robot parameters corresponding to model (2)

Note that in compliance with model (2), the obtained parameters correspond to the robot model that is used in the CVS control approach, which constitutes in this study as the benchmark to our proposed GVS control approaches. In order to implement GVS approaches, model (2) is not suitable since it doesn't exhibit the derivatives of the control, however, model (3) that contains the zeros dynamics is utilized instead, namely

$$\ddot{q} + A_1\dot{q} + A_0 q = B_1\,\dot{u} + B_0 u \qquad (3)$$

Using the same identification procedure as before, the parameters for model (3) are now given in Table 2.

$A_0 = diag\,[-2.4 \quad -2.965 \quad -13.258]$
$A_1 = diag\,[201 \quad 200.92 \quad 213.92]$
$B_0 = diag\,[0.65 \quad 0.67 \quad 0.61]$
$B_1 = diag\,[0.041 \quad 0.004 \quad 0.006]$

Table 2. The identification of the robot parameters corresponding to model (3)

3. Sliding mode-based variable structure control strategy

The CVS control has been used for a number of years. The switching occurs on the control variable, and this is discussed in the next subsection in the context of differential geometry and constitutes in this study as the benchmark to GVS control approaches. Recently the GVS scheme was introduced in (Fliess, 1990) where the switching occurs on the highest derivative of the control input. The GVS analysis and design are studied in the context of the differential algebra. In subsection 3.2, we design two GVS control approaches, the first GVS approach is designed by solving the well-known sliding condition equation, while the second GVS approach is derived on the basis of what is denoted as the hypersurface convergence equation.

3.1 Classical variable structure control in the differential geometry context

Consider the nonlinear dynamical system in which the time variable is not explicitly indicated, that is

$$\frac{dx}{dt} = f(x) + g(x)U \tag{4}$$

where $x \in X$ is an open set of R^n, $f(x) = [f_1, f_2, \cdots, f_n]^T$ and $g(x) = [g_1, g_2, \cdots, g_n]^T$ are vector fields defined on R^n with $g(x) \neq 0 \ \forall\, x \in X$, and the control is defined so that $U : R^n \to R$.

Assume a hypersurface $S = \{x \in R^n : S(x) = 0\}$ is denoted as the 'sliding surface' on which discontinuous control functions of the type

$$U = \begin{cases} U^+(x) & if \quad S(x) > 0 \\ U^-(x) & if \quad S(x) < 0 \end{cases} \tag{5}$$

make the surface attractive to the representative point of the system such that it slides until the equilibrium point is reached. This behavior occurs whenever the well-known sliding condition $S\dot{S} < 0$ is satisfied (Utkin, 1992).

Using the directional derivative $L_h \sigma$, this condition can be represented as

$$\begin{cases} \lim\limits_{S \to 0^+} L_{f+gU^+} S < 0 \\ \lim\limits_{S \to 0^-} L_{f+gU^-} S > 0 \end{cases} \tag{6}$$

or by using the gradient ∇ of S and the scalar product $< .,. >$ as

$$\begin{cases} \lim\limits_{S \to 0^+} \left\langle \nabla S, f + g \cdot U^+ \right\rangle < 0 \\ \lim\limits_{S \to 0^-} \left\langle \nabla S, f + g \cdot U^- \right\rangle > 0 \end{cases} \tag{7}$$

A geometric illustration of this behavior is shown in Figure 2, in which the switching of the vector fields occurs on the hypersurface $S(x) = 0$.

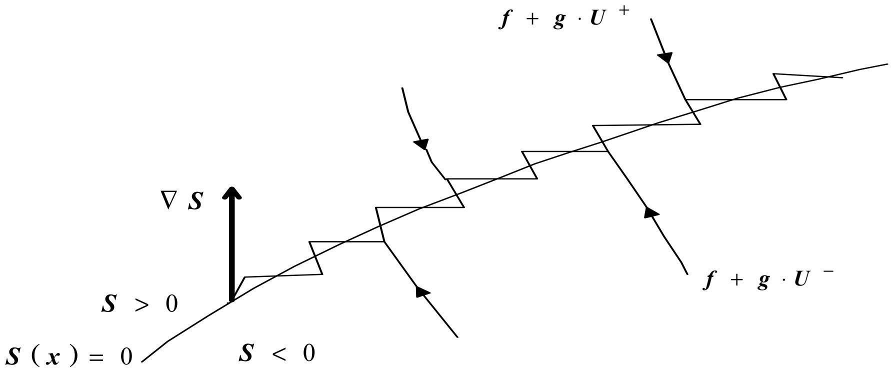


Figure 2. The geometric illustration of the sliding surface and switching of the vector fields on the hypersurface $S(x)=0$

Depending on the system state with respect to the surface, the control is selected such that the vector fields converge to the surface. Specifically, using the equivalent control method, the classical variable structure control law can be finally expressed as a sum of two components as follows,

$$U = U_{eq} + \delta U \tag{8}$$

where the equivalent control component U_{eq} is derived for the ideal sliding mode so that the previously defined hypersurface is a local invariant manifold. Therefore, if $S(x)=0$,

$$L_{f+g\cdot U_{eq}} S = \left\langle \nabla S, f + g \cdot U_{eq} \right\rangle = 0 \text{, then}$$

$$U_{eq} = -\frac{\langle \nabla S, f \rangle}{\langle \nabla S, g \rangle} = -\frac{L_f S}{L_g S} \tag{9}$$

whereas the second component corresponds to the discontinuous control so that $\delta U = -M sign(S)$ where the gain *M* should be chosen to be greater than the perturbation signal amplitude. A typical control U (dotted line), and its components U_{eq} (solid line), and δU (dashed line) are illustrated in Fig. 3. It can be seen that the state of the discontinuous component δU changes from continuous and positive to discontinuous with variable sign. This change coincides to the first crossing of the surface $S(x)=0$. In compliance with the equivalent control component that is always positive, it also switches since it is derived by using the derivative of the surface but with a small amplitude. The switching of the equivalent control component occurs one iteration later than the discontinuous component switching. The control U that is always postive corresponds to the geometric sum of both U_{eq} and δU.

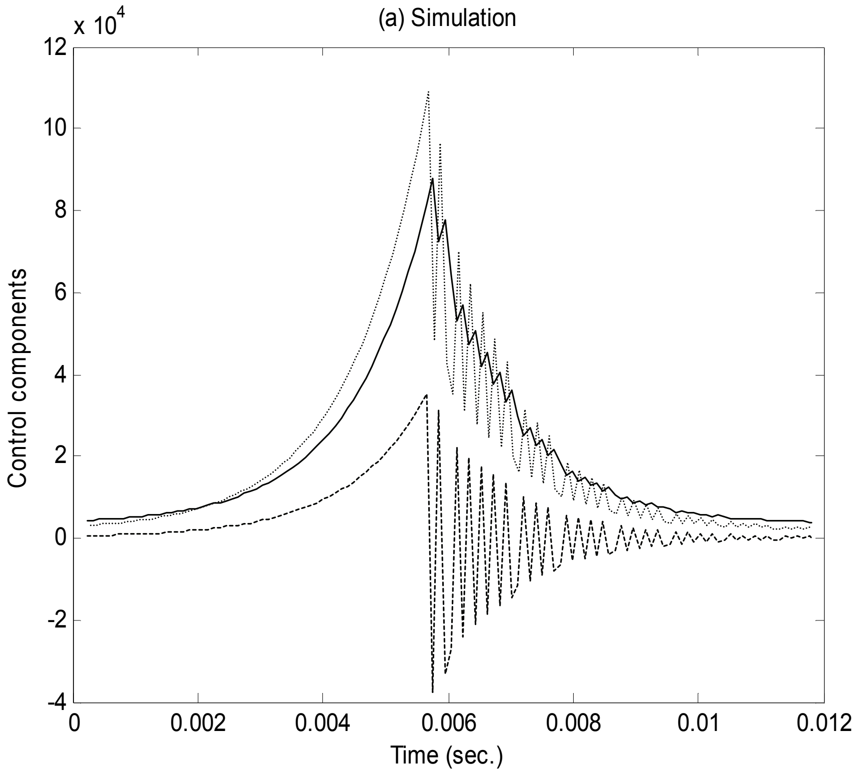


Figure 3. The control and its equivalent and discontinuous components (U dotted line, U_{eq} solid line, and δU dashed line)

3.2 Generalized variable structure control

In the context of differential algebra, and under the existence conditions of the differential primitive element for nonlinear systems, or cyclic element in the case of linear systems, the elimination of the state in the original Kalman state representation leads to the pair Generalized Control Canonical Form (GCCF) and Generalized Observable Canonical Form (GOCF). By associating for example the output equation $y = h(x)$ to the given state equation (4), the elimination of x in both state and output equations leads to the following differential equation:

$$\varsigma(y, \dot{y}, \cdots, y^{(d-1)}, y^{(d)}, u, \dot{u}, \cdots, u^{(\alpha)}) = 0 \tag{10}$$

where $\alpha = d - r$ is a strictly positive integer related to the relative degree r of the output function y with respect to the scalar input u. The integer d is defined such that the rank condition (11) should be satisfied