

Lecture Notes in Electrical Engineering 415

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Tran Trong Dao

Sang Bong Kim

Nguyen Tan Tien

Ivan Zelinka

Editors

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Theory and Application

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Editors

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Foreword

The Proceedings on AETA 2016, which you are holding in your hands, consist of selected papers from 14 different, but related, areas of modern engineering. Modern world is based on vitally important technologies that merge, e.g. electronics, cybernetics, computer science, telecommunications, and physics, together. Since the beginning of our technologies, we have been confronted with numerous technological challenges such as finding the optimal solution of various problems including controlling technologies, power sources construction, robotics, etc. Technology development of those and related areas has had and continues to have profound impact on our civilization and our future life style.

Therefore, this proceedings book containing articles of international conference AETA 2016, edited by Ivan Zelinka (Czech Republic), Vo Hoang Duy (Vietnam), Tran Trong Dao (Vietnam), Nguyen Tan Tien (Vietnam) and Sang Bong Kim (Korea), is a timely volume to be welcomed by the community focused on telecommunication, control system and optimization as well as computational science community and beyond.

This proceedings book consists of selected papers on 14 topic areas including robotics, control system, telecommunication, mechanical engineering and computer science. Readers can find interesting papers about different topics that reflect on modern approaches to interesting problems. All selected papers represent interesting ideas and the state-of-the-art overview.

Participations were carefully selected and reviewed; hence, this proceedings book certainly is one of the few discussing the benefit from intersection of those modern and fruitful scientific fields of research. We hope that the proceedings book will be an instructional material for senior undergraduate and entry-level graduate. This book will also be a resource and material for practitioners who want to apply discussed topics to solve real-life problems in their challenging applications. The important part of this proceedings book is the participation of two keynote speakers from the Japan and Hong Kong.

The decision to organize AETA conference and to create this proceedings book was based on the fact that above-mentioned technologies, their use and impact on

life is an interesting area, which is under intensive research of many other branches of science today. This book is written to contain simplified versions of experiments with the aim to show how, in principle, problems about power systems can be solved.

It is obvious that this proceedings book does not encompass all aspects of discussed topics due to limited space and time of conference. Only the main ideas and results of selected papers are reported here. The authors and editors hope that the readers will be inspired to do their own experiments and simulations, based on information reported in this proceedings book, thereby moving beyond the scope of it. For these reasons, we believe that this book will be useful for scientists and engineers working in the above-mentioned fields of research and applications.

Finally, we **would like to thank** to Pukyong National University (Korea), Ton Duc Thang University (Ho Chi Minh City, Vietnam), VŠB-Technical University (Ostrava, Czech Republic) for interest and strong support in AETA conference organization. Also **many thanks** belong to Springer publishing company for its highly professional, precise and quick production process. Without all of this, it would be impossible to organize successful conference joining European and Asian participants.

This conference was supported by the Pukyong National University (Busan, Korea) and Ton Duc Thang University (Ho Chi Minh City, Vietnam) and VŠB - Technical University (Ostrava, Czech Republic) and by the research groups NAVY (<http://navy.cs.vsb.cz/>) and MERLIN (<http://merlin.tdt.edu.vn/>) and CIMEC Lab.

December 2016

Vo Hoang Duy
Tran Trong Dao
Sang Bong Kim
Nguyen Tan Tien
Ivan Zelinka

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Keynote

Variable Structure System and Its Applications

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Abstract. This plenary paper presents some aspects of continuous- and discrete-time variable structure control theory and its applications studied by the author and his colleagues. The continuous-time and discrete-time sliding mode control systems are presented briefly and the idea of the sliding mode is extended to the sliding sector which was brought by the study of the discrete-time sliding mode. The idea of the sliding sector can be used for both continuous- and discrete-time variable structure system. Inside the sliding sector, the control input can be kept zero for stabilizing the system. The application to self-tuning controller is also presented in using the idea of discrete-time sliding mode. In the last, the application to the control of Furuta Pendulum is presented.

Keywords: Discrete-time systems · Lyapunov function · Self-tuning control · Sliding mode · Sliding sector · Furuta pendulum

1 Introduction

The Variable Structure Control (VSC) system has been studied by Russian researcher in the form of sliding mode, details of the history can be found in Utkin (1992). Its robustness to the disturbance and the easiness for the implementation, the variable structure control system has been used in many practical systems. When the continuous-time system is realized by digital controllers, the corresponding discrete-time control system may become unstable after discretization as shown in Furuta et al. (1994), which was brought by the fact that sampling of the continuous system yields unstable zeros shown by Atrom et al. (1992). This plenary lecture presents firstly the fundamental idea of the sliding mode control and then the discrete-time sliding mode control given by Furuta (1990) and (1993) is shown. Especially the idea of sliding sector given by Furuta et al. (2000) for both continuous-time and discrete-time system and the self-tuning idea given in Furuta (1993), Patete et al. (2008a), (2008b) and Sugiki et al. (2008) are presented. In the last its use to the control of the Furuta (2002) and (2003) is discussed.

Recent advances of Variable Structure Systems and Sliding Mode can be found in the papers presented at VSS Workshops sponsored by IEEE Technical Committee on Variable Structure Systems and Sliding Mode Control (TCVSSMC) (Chair is Professor Leonid Fridman at UNAM).

2 Sliding Mode Control for Linear System

2.1 Sliding Mode Design for a Linear System

In this section, the fundamental idea of the sliding mode and its design by the Algebraic Riccati Equation for a linear system are discussed. The system considered is

$$\frac{d}{dt}x = Ax + Bu \quad (1)$$

$$y = Cx \quad (2)$$

where $x \in R^n$ is the state, $u \in R$ is the input and $y \in R^p$ is the output. (A, B) is assumed controllable. The sliding mode for the system is given by the subspace

$$\mathcal{S} = \{x | s = F_s x = 0\} \quad (3)$$

on which the system state should be stable. It is not easy to design the sliding mode. In this section, the matrix F_s for the sliding mode is designed by using the following Riccati Equation

$$A^T P_s + P_s A + Q - P_s B B^T P_s = 0 \quad (4)$$

is solved for positive definite constant matrix P_s to the given state x and bounded $V(x) = x^T P_s x / 2$.

Then the following theorem is given.

Theorem 1. The state x restricted on the sliding surface satisfying

$$F_s = B^T P_s \quad (5)$$

shall converge to zero as time goes to infinity, where P_s is the positive definite matrix solution of Eq. (4).

Proof. The stability of the system Eq. (1) on the sliding surface for the zero input shall be proved. By substituting $F_s = B^T P_s$ into Eq. (4), the ARE is rewritten as

$$A^T P_s + P_s A + Q - F_s^T F_s = 0 \quad (6)$$

Let the candidate Liapunov function be $V(x) = x^T P_s x / 2$, where P_s is the positive definite bounded matrix satisfying (4). The derivative of $V(x)$ with respect to the time is given by

$$\frac{d}{dt}V(x) = x^T (A^T P_s + P_s A)x \quad (7)$$

Multiplying x^T from the left and x from the right to Eq. (6), $\dot{V}(x)$ is written on the sliding surface as

$$\begin{aligned} \frac{d}{dt}V(x) &= x^T (A^T P_s + P_s A)x \\ &= -x^T Qx - x^T F_s^T F_s x = -x^T Qx < 0, \forall x \in \mathcal{S} \end{aligned}$$

So the state on the sliding surface given by Eq. (3) is found stable.

2.2 Sliding Mode Control

In this section, the control law to transfer the state onto the sliding sector is considered. In the first, the equivalent control to keep the state on the sliding mode $\{x|F_s x = 0\}$ is given by

$$u_{eq} = -(F_s B)^{-1} F_s A x$$

since

$$F_s \dot{x} = F_s A x + F_s B u_{eq} = 0$$

Theorem 2. Define the sliding mode variable s as

$$s = F_s x \quad (8)$$

where $F_s B$ is nonsingular and the control input u is designed so that the state x is transformed to the sliding surface by the control given by

$$u = -(F_s B)^{-1} (F_s A x + K \text{sign}(s)) \quad (9)$$

transfers the state onto the sliding surface given by Eq. (5).

Proof. Letting

$$\sigma = \frac{1}{2} s^2 \quad (10)$$

then the derivative of σ is

$$\frac{d}{dt} \sigma = s \dot{s} = s (F_s A x + F_s B u) \quad (11)$$

By substituting the control law of Eq. (9) into the above equation, the following equation is derived.

$$\frac{d}{dt} \sigma = s (F_s A x + F_s B u) \quad (12)$$

$$= -K |s| < 0 \quad (13)$$

The control law to transfer the state onto the sliding surface is also designed by optimal control law minimizing the criterion function

$$J = \int_0^{\infty} (x^T F_s^T F_s x + \epsilon u^2) dt \quad (14)$$

The optimal control is given by

$$u = -\epsilon^{-1} B^T P_c x \quad (15)$$

where P_c is the positive definite solution of

$$A^T P_c + P_c A + F_s^T F_s - P_c B^T B P_c / \epsilon = 0 \quad (16)$$

2.3 Discrete-Time Sliding Mode Control

A discrete-time linear system described by the following state equation is considered.

$$x_{k+1} = \Phi x_k + \Gamma u_k \quad (17)$$

where $x_k \in R^n$ and $u_k \in R^1$ are state and input vectors, respectively; Φ and Γ are constant matrices of appropriate dimensions; and the pair (Φ, Γ) is controllable. Similar to the continuous-time sliding mode control, the function s_k is defined as

$$s_k = Gx_k. \quad (18)$$

where G is designed so that the state x_k staying on $\{x|s_k = Gx = 0\}$ for all k is stable. The matrix G for such sliding mode is designed by the solution P_D of Discrete-time Riccati Equation as

$$G = (R_D + \Gamma^T P_D \Gamma)^{-1} \Gamma^T P_D \Phi \quad (19)$$

where P_D is the following solution.

$$P_D = \Phi^T P_D \Phi + Q_D - \Phi^T P_D \Gamma (R_D + \Gamma^T P_D \Gamma)^{-1} \Gamma^T P_D \Phi \quad (20)$$

The state restricted in the sliding mode $\mathcal{S} = \{x|s = Gx = 0\}$, the system is stable with zero input, since the Lyapunov function of the system

$$V(x_k) = \frac{1}{2} x_k^T P_D x_k$$

is written as

$$V(x_{(k+1)}) = \frac{1}{2} x_{k+1}^T P_D x_{k+1} \leq \frac{1}{2} x_k^T P_D x_k \quad (21)$$

on the sliding mode from Eq. (20).

Lemma 1 (Furuta (1990)). The equivalent control law for the system (17) such that the state rests on the hyperplane of $s_k = s_{k+1}$ for all k is given by

$$u_k = F_{eq} x_k \quad (22)$$

where

$$F_{eq} = -(G\Gamma)^{-1} G(\Phi - I). \quad (23)$$

Theorem 3 (Furuta (1990)). The hyperplane, equivalently G , should be determined so that the system

$$\begin{aligned} x_{k+1} &= [\Phi - \Gamma(G\Gamma)^{-1} G(\Phi - I)]x_k, \\ Gx_k &= 0, \end{aligned}$$

is stable. The pole location can be also taken into consideration by using the idea of Furuta and Kim (1987).

As the second step, the control law to transfer the state on the hyperplane should be determined. Let V_k and Δs_k be defined as

$$V_k = \frac{1}{2}s_k^2$$

$$\Delta s_{k+1} = s_{k+1} - s_k$$

Then the control law to decrease V_k is given by the following lemma.

Lemma 2 (Furuta (1990)). If the control satisfies

$$s_k \Delta s_{k+1} < -\frac{1}{2}(\Delta s_{k+1})^2, \quad \text{for } s_k \neq 0 \quad (24)$$

then

$$V_{k+1} < V_k$$

In this section, the following type of control law is considered:

$$u_k = (F_{eq} + F_D)x_k, \quad (25)$$

where F_{eq} is given by (23) and F_D is a discontinuous control law. Then the variable structure control law to make the system stable is given by the following theorem.

Theorem 4 (Furuta (1990)). If the sliding mode satisfies the conditions of Theorem 3, and the control is chosen by (25), where the absolute value of the i -th element of F_D , f_i is constant for all time and the same for all i , i.e.,

$$|f_i^+| = |f_i^-| = f_0, \quad i = 1, 2, \dots, n,$$

then the control law

$$f_i = \begin{cases} f_0 & \text{for } (G\Gamma)s_k x_{ki} < -\delta_i, \\ 0 & \text{for } -\delta_i \leq (G\Gamma)s_k x_{ki} \leq \delta_i, \\ -f_0 & \text{for } (G\Gamma)s_k x_{ki} > \delta_i, \end{cases} \quad (26)$$

makes the system stable, where x_{ki} is the i -th element of x_k and δ_i is defined as

$$\delta_i = \frac{1}{2}(G\Gamma)^2 \sum_{j=1}^n |x_{ki}| |x_{kj}| f_0$$

with the amplitude of f_0 limited by

$$0 < f_0 < \left| \frac{2}{G\Gamma \sum_{j=1}^n |t_{1j}|} \right|,$$

t_{1i} being the i -th element of t_1 satisfying $Gt_1 = 1$, $Gt_i = 0$, $t_i \perp t_j$ ($i \neq j$).

With the consideration of the parameter uncertainty, represent the actual system matrix Φ as

$$\Phi = \Phi_0 + \Delta\Phi$$

where Φ_0 is known and $\Delta\Phi$ is the uncertainty of the system matrix, which is represented by

$$\Delta\Phi = \Gamma D, \quad (27)$$

$$D = [d_1 \ d_2 \ \cdots \ d_n], \quad |d_i| < \bar{d} (i = 1, 2, \dots, n). \quad (28)$$

The known system is represented by

$$x_{k+1} = \Phi_0 x_k + \Gamma u_k \quad (29)$$

It is assumed that both (17) and (29) is stabilized on $\{s_k\} = 0$. Then a robust discrete-time VS controller is designed by the following theorem.

Theorem 5 (Furuta (1990)). If the plant system matrix Φ has the uncertainty $\Delta\Phi$ satisfying (27) and (28), and on $s_k = 0$, the plant is stable with the equivalent control, then the i -th element f_i of the control law F_D satisfying

$$f_i = \begin{cases} f_0 & \text{for } (G\Gamma)s_k x_{ki} < -\delta'_i, \\ 0 & \text{for } -\delta'_i \leq (G\Gamma)s_k x_{ki} \leq \delta'_i, \\ -f_0 & \text{for } (G\Gamma)s_k x_{ki} > \delta'_i, \end{cases} \quad (30)$$

makes the system stable, where

$$\delta'_i = \frac{1}{2}(G\Gamma)^2 \sum_{j=1}^n |x_{ki}| |x_{kj}| (f_0 + \bar{d})$$

with the amplitude of f_0 limited by

$$\bar{d} < f_0 < \left| \frac{2}{G\Gamma \sum_{j=1}^n |t_{1j}|} \right| - \bar{d}.$$

Furuta (1990) proposed another equivalent reaching condition given by

$$s_k(s_{k+1} - s_k) < -\frac{1}{2}(s_{k+1} - s_k)^2$$

and defined a sliding sector as

$$|s_k| \leq h \sum_{i=1}^n |x_i(k)|$$

where h is a positive constant and $x_i(k)$ ($i = 1, 2, \dots, n$) is the i -th element of the state variable x_k . The equivalent control in Furuta (1990) is obtained by setting

$$s_{k+1} = s_k$$

while in the β equivalent control approach, Furuta (1993) defined the equivalent control by

$$s_{k+1} = \beta s_k$$

where $|\beta| < 1$. The state will move into the sliding sector because the proposed discrete-time VS control input satisfies the above reaching condition outside the sliding sector. Inside the sliding sector, the equivalent law ensures the stability of the closed-loop system. With the consideration of parameter uncertainties, a robust discrete-time VS controller was also designed in Furuta (1990) where the sliding sector was modified as

$$|s_k| \leq (h + d) \sum_{i=1}^n |x_i(k)|$$

where the positive constant d is the upper bound of the parameter uncertainty. Furuta (1993) also proposed a discrete-time VS controller with sliding sector for those systems described by transfer function, where the self-tuning control is used to ensure the robust stability.

As an alternate design algorithm of the Variable Structure Control (VSC), a ***PR-sliding sector*** has been proposed in the design of VSC for reducing chattering and for the implementation in discrete-time control systems Furuta (2000). The *PR*-sliding sector is defined as

$$|s_k| < \delta_k = \sqrt{x_k^T Q x_k},$$

which is a subset on the state space where Q is a positive semi-definite matrix. Inside the sector, P -norm of state defined as

$$\|x_k\|_P = \sqrt{x_k^T P x_k}$$

decreases with zero control and satisfies

$$\|x_{k+1}\|_P^2 - \|x_k\|_P^2 < -\|x_k\|_R^2$$

where P and R are positive definite matrices. The *PR*-sliding sector is defined as

$$\mathcal{S}_d = \{x | x^T (\Phi^T P_d \Phi - P_d) x \leq -x^T R_d x, \forall x \in \mathcal{R}^n\} \quad (31)$$

This sector is rewritten as

$$\mathcal{S}_d = \{x | x^T (s_d^2(x) \leq \delta_d^2(x), \forall x \in \mathcal{R}^n\} \quad (32)$$

where

$$s_d^2(x) = x^T P_{d1} x, P_{d1} > 0$$

and

$$\delta_d^2 = x^T P_{d2} x, P_{d2} > 0$$

The corresponding VS controller was designed such that the state move from the outside to the inside of the sector with some VS control law, the control input is zero inside the sector, and some Liapunov function keeps decreasing in the state space with specified negativity of its derivative.

3 Direct Self-tuning Control for SISO System

The input and the output relation of a discrete-time single input and output system is represented by

$$A_s(z^{-1})y_k = z^{-d}B_s(z^{-1})u_k \quad (33)$$

where u_k is the input, y_k is the output, and d is the delay time which is known a priori. The polynomials in the time-shift operator z^{-1} are given by

$$A_s(z^{-1}) = 1 + a_1z^{-1} + \cdots + a_nz^{-n} \quad (34)$$

$$B_s(z^{-1}) = b_0 + b_1z^{-1} + \cdots + b_mz^{-m}, \quad b_0 \neq 0 \quad (35)$$

The control law is derived based on the discrete sliding-mode type variable defined as

$$s_{k+d} = C_s(z^{-1})(y_{k+d} - r_{k+d}) + Q_s(z^{-1})u_k \quad (36)$$

where

$$C_s(z^{-1}) = 1 + c_1z^{-1} + \cdots + c_nz^{-n} \quad (37)$$

$$Q_s(z^{-1}) = q_0 + q_1z^{-1} + \cdots + q_nz^{-l}, \quad q_0 \neq 0 \quad (38)$$

and r_k is the reference and $C_s(z^{-1})$ is designed to be Schur. $C_s(z^{-1})$ and $Q_s(z^{-1})$ are chosen to satisfy that all roots of $A_s(z^{-1})Q_s(z^{-1}) + B_s(z^{-1})C_s(z^{-1})$ are inside of the open unit disk and the polynomials (Q_s, C_s) , (A_s, C_s) and (B_s, Q_s) have no common zero outside of the unit disk. The integrator action is given by choosing

$$Q_s(z^{-1}) = q_0(1 - z^{-1}) \quad (39)$$

and $Q_s(z^{-1})$ can be constant in the case that the desired output is zero.

The control law making s_{k+d} zero is given by

$$u_k = -G_s(z^{-1})^{-1}[F_s(z^{-1})y_k - C_s(z^{-1})r_{k+d}] \quad (40)$$

where $G_s(z^{-1})$ is defined as

$$G_s(z^{-1}) = E_s(z^{-1})B_s(z^{-1}) + Q_s(z^{-1}) \quad (41)$$

$$= g_0 + g_1z^{-1} + \cdots + g_{m+d-1}z^{-(m+d-1)} \quad (42)$$

The $E_s(z^{-1})$ and $F_s(z^{-1})$ are the polynomials satisfying the Diophantine equation

$$C_s(z^{-1}) = A_s(z^{-1})E_s(z^{-1}) + z^{-d}F_s(z^{-1}) \quad (43)$$

where

$$E_s(z^{-1}) = \delta_0 + \delta_1z^{-1} + \cdots + \delta_{d-1}z^{-(d-1)} \quad (44)$$

$$F_s(z^{-1}) = f_0 + f_1z^{-1} + \cdots + f_{n-1}z^{-(n-1)} \quad (45)$$

The control law (40) is easily derived by using the relation

$$s_{k+d} = G_s(z^{-1})u_k + F_s(z^{-1})y_k - C_s(z^{-1})r_{k+d} \quad (46)$$

When the plant is not known, the control (40) should be directly determined by measuring the input and output data, which is said direct self-tuning control or implicit self-tuning control. Such control is given by the following theorem given in Patete et al. (2008a).

Theorem 5. Let

$$\phi_k^T = [y_k, y_{k-1}, \dots, y_{k-(n-1)}, u_k, \dots, u_{k-(m+d-1)}] \quad (47)$$

be the vector of plant data, and

$$\hat{\theta}_k^T = [\hat{f}_0, \hat{f}_1, \dots, \hat{f}_{n-1}, \hat{g}_0, \dots, \hat{g}_{m+d-1}] \quad (48)$$

be the vector of estimated parameters of (45) and (42).

The control (40) with the estimates (48) is given by

$$u_k = -\hat{G}_s(z^{-1})^{-1}[\hat{F}_s(z^{-1})y_k - C_s(z^{-1})r_{k+d}] \quad (49)$$

The parameters are estimated by

$$\begin{aligned} \hat{\theta}_k &= \hat{\theta}_{k-1} + \frac{\Gamma_{k-1}\phi_{k-d}}{1 + \phi_{k-d}^T\Gamma_{k-1}\phi_{k-d}}(s_k + C_s(z^{-1})r_k \\ &\quad - \phi_{k-d}^T\hat{\theta}_{k-1}) \end{aligned} \quad (50)$$

where Γ_k is the positive-definite matrix updated by

$$\Gamma_k = \Gamma_{k-1} - \frac{\Gamma_{k-1}\phi_{k-d}\phi_{k-d}^T\Gamma_{k-1}}{1 + \phi_{k-d}^T\Gamma_{k-1}\phi_{k-d}} \quad (51)$$

The given self-tuning control makes the sliding mode variable $s_k \rightarrow 0$ as $k \rightarrow \infty$, i.e., the output y_k approaches the reference r_k as $k \rightarrow \infty$.

This theorem is correct but the proof in Patete et al. (2008a)a includes some mistakes and this paper corrects the proof as follows:

Proof. At time k ,

$$\begin{aligned} s_{k+d} &= \hat{G}_s(z^{-1})u_k + \hat{F}_s(z^{-1})y_k - C_s(z^{-1})r_{k+d} \\ &\quad + \phi_k^T\tilde{\theta}_k \end{aligned} \quad (52)$$

where $\tilde{\theta}_k = \theta - \hat{\theta}_k$ and \bar{s}_k is defined as

$$\bar{s}_k = s_k + C_s(z^{-1})r_k - \phi_{k-d}^T\hat{\theta}_k = \phi_{k-d}^T\tilde{\theta}_k \quad (53)$$

A Lyapunov function candidate is given by

$$V_k = \frac{1}{2}\bar{s}_k^2 + \frac{1}{2}\tilde{\theta}_k^T \Gamma_k^{-1} \tilde{\theta}_k \quad (54)$$

Its difference is described as

$$\Delta V_k = V_k - V_{k-1} \quad (55)$$

$$\begin{aligned} &= \frac{1}{2}\tilde{\theta}_k^T (\Gamma_k^{-1} - \Gamma_{k-1}^{-1} - \phi_{k-d}\phi_{k-d}^T) \tilde{\theta}_k \\ &+ \tilde{\theta}_k^T \Gamma_{k-1}^{-1} (\tilde{\theta}_k - \tilde{\theta}_{k-1} + \Gamma_{k-1}\phi_{k-d}\phi_{k-d}^T) \tilde{\theta}_k \\ &- \frac{1}{2}\bar{s}_{k-1}^2 - \frac{1}{2}(\tilde{\theta}_k - \tilde{\theta}_{k-1})^T \Gamma_{k-1}^{-1} (\tilde{\theta}_k - \tilde{\theta}_{k-1}) \end{aligned} \quad (56)$$

If

$$\Gamma_k^{-1} - \Gamma_{k-1}^{-1} - \phi_{k-d}\phi_{k-d}^T = 0 \quad (57)$$

and

$$\tilde{\theta}_k - \tilde{\theta}_{k-1} + \Gamma_{k-1}\phi_{k-d}\phi_{k-d}^T \tilde{\theta}_k = 0 \quad (58)$$

are satisfied, we have $\Delta V_k \leq 0$ i.e., $V_k \rightarrow 0$ as $k \rightarrow \infty$. This means that \bar{s}_k converges to zero and $\tilde{\theta}_k$ converges to 0 as $k \rightarrow \infty$. Then s_k approaches zero because of the following relation. Thus, the output y_k approaches the reference r_k as $k \rightarrow \infty$ because $C_s(z^{-1})$ is Schur.

$$\begin{aligned} &|\bar{s}_k - s_k| \\ &= |\phi_{k-d}^T (\tilde{\theta}_k - \tilde{\theta}_{k-d})| \end{aligned} \quad (59)$$

$$\begin{aligned} &\leq |\phi_{k-d}^T (\tilde{\theta}_k - \tilde{\theta}_{k-1})| + |\phi_{k-d}^T (\tilde{\theta}_{k-1} - \tilde{\theta}_{k-2})| \\ &\quad + \cdots + |\phi_{k-d}^T (\tilde{\theta}_{k-(d-1)} - \tilde{\theta}_{k-d})| \end{aligned} \quad (60)$$

$$\leq \|\phi_{k-d}^T\| \sum_{j=0}^{d-1} \|\tilde{\theta}_{k-j} - \tilde{\theta}_{k-j-1}\| \quad (61)$$

Therefore, the stability of both the control and estimation in the considered self-tuner was proved.

From (57), the matrix inversion lemma yields (51). Multiplying ϕ_{k-d}^T to (58),

$$\phi_{k-d}^T \tilde{\theta}_k = \phi_{k-d}^T \tilde{\theta}_{k-1} - \phi_{k-d}^T \Gamma_{k-1} \phi_{k-d} \phi_{k-d}^T \tilde{\theta}_k \quad (62)$$

is obtained. This yields

$$\phi_{k-d}^T \tilde{\theta}_k = [1 + \phi_{k-d}^T \Gamma_{k-1} \phi_{k-d}]^{-1} \phi_{k-d}^T \tilde{\theta}_{k-1} \quad (63)$$

The Substitution of the above equation to (58) and (52) derive (50).

4 Modeling and Swing-Up of Furuta Pendulum

The real pendulum has the additional dynamics about the actuator to move the hinge of the pendulum. There are two ways to move the hinge of the pendulum, one is on the linear rail and the other is by the arm driven by the motor which is called Furuta Pendulum, which is modelled as in Furuta (2002) and (2003). The constraint internal forces inside the mechanical structure have not been paid much attention in the control. This paper studies the control of pendulum taking constraint force into consideration and discusses the following items:

- (1) The modeling of the variable constraint system by the projection method.
- (2) The control of the pendulum by the nonlinear control taking the constraint internal force into consideration.

4.1 Modeling of Furuta Pendulum by Projection

In this paper, projection method by Blajer (1992) is applied to obtain dynamical equations of Furuta Pendulum.

To illustrate the idea of modeling for constrained systems by projection method, let us consider the modeling of Furuta pendulum which is shown in Fig. 1.

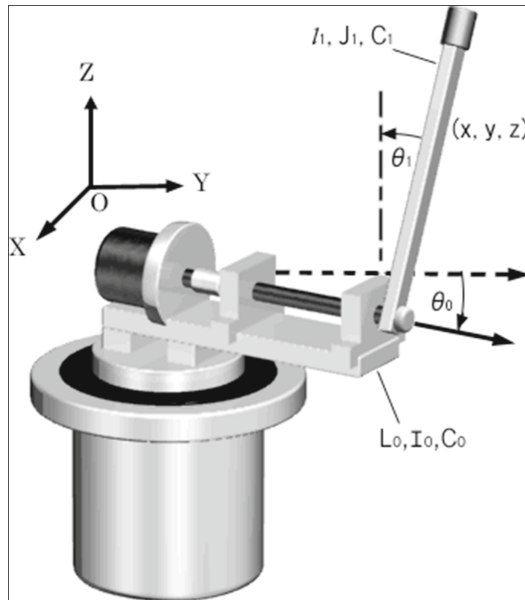


Fig. 1. Illustration of variables (Furuta pendulum)

First, the components of pendulum are assumed to move freely. This means that Furuta pendulum is treated as a unconstrained system. With the help of Euler-Lagrange equation, the differential equation is derived to describe the unconstrained augmented system

$$\dot{q}_a = v \quad (64)$$

$$M_a \dot{v} = h_a \quad (65)$$

where q_a denotes the augmented state

$$q_a = [\theta_0 \ x \ y \ z \ \theta_1]^T$$

$$M_a = \begin{bmatrix} I_0 & 0 & 0 & 0 & 0 \\ 0 & m_1 & 0 & 0 & 0 \\ 0 & 0 & m_1 & 0 & 0 \\ 0 & 0 & 0 & m_1 & 0 \\ 0 & 0 & 0 & 0 & I_1 \end{bmatrix} \quad (66)$$

$$h_a = \begin{bmatrix} \tau_1 - C_0 \dot{\theta}_0 \\ 0 \\ 0 \\ -m_1 g \\ -C_1 \dot{\theta}_1 \end{bmatrix} \quad (67)$$

The parameters of the model are chosen as

- I_0 Inertia of arm around shaft
- I_1 inertia of pendulum
- L_0 arm length
- l_1 length from pendulum-pivot to c.g
- m_1 weight of pendulum
- C_0 friction of arm
- C_1 friction of pendulum
- g acceleration of gravity

Now, consider the pendulum attached to the arm, then not all coordinates are independent, and constraints are expressed as

$$\begin{aligned} x &= L_0 \sin \theta_0 + l_1 \sin \theta_1 \cos \theta_0 \\ y &= L_0 \cos \theta_0 - l_1 \sin \theta_1 \sin \theta_0 \\ z &= l_1 \cos \theta_1 \end{aligned}$$

The derivative of the above equation gives

$$\begin{aligned} \dot{x} &= (L_0 \cos \theta_0 - l_1 \sin \theta_1 \sin \theta_0) \dot{\theta}_0 + l_1 \cos \theta_1 \cos \theta_0 \dot{\theta}_1 \\ \dot{y} &= (-L_0 \sin \theta_0 - l_1 \sin \theta_1 \cos \theta_0) \dot{\theta}_0 - l_1 \cos \theta_1 \sin \theta_0 \dot{\theta}_1 \\ \dot{z} &= -l_1 \sin \theta_1 \dot{\theta}_1 \end{aligned}$$