Advanced Robust Control Techniques: Comparison and Application to a second order highly nonlinear System

Muhammad Yasir Amir Khan, Vali Uddin Abbas and Umer Amir Khan

***Abstract* – Robust integral of sign of error (RISE) is a relatively new control technique. It has been applied to several nonlinear systems. However its efficacy in comparison to existing robust control techniques is yet to be established. Terminal sliding mode control (TSMC) is a well known robust control technique, which belongs to the family of Sliding Mode Control. This paper deals with the application of RISE and TSMC to control of a well known and highly nonlinear system - the inverted pendulum for comparison of these two techniques. The comparison is made on the basis of time response, control energy and tracking performance. It is reported that TSMC gives faster response with lower control energy and better tracking performance as compared to RISE based control.**

Index Terms – Robust Control, RISE, Terminal Sliding Mode Control, Inverted Pendulum, Control Energy, Tracking Error, Sign of Error.

I. INTRODUCTION

The control of uncertain nonlinear systems has attracted tremendous mainstream research interest over the last few decades ([16],[14],[13],[12],[11],[8]). Robust control methods are among the tools of choice when dealing with unstructured and uncertain nonlinear control systems ([11],[7]). Most of the robust controllers for example variable structure controller *sliding mode control*, are discontinuous by nature due to *signum* function [9], which also leads to an undesirable phenomenon of chartering. Most of the controllers assure error convergence to an ultimate bound. According to [2] a new asymptotically stable continuous robust controller could be traced back to [3] where instead of sign of error, integral of sign of error, was proposed. In literature this methodology is known as Robust Integral of Sign of Error (RISE) ([17],[4],[24],[5]). Patre *et. al.* in [17] showed that combination of an adaptive model based feedforward term with RISE feedback term yields asymptotic tracking result for systems with structured and unstructured uncertainities. In [19], Fischer *et. al.* considered a neural network augmented RISE control structure for second-order affine nonlinear systems with time varying state delays, to achieve semi-global asymptotic tracking in the presence of bounded disturbances, nonlinearly parametrized uncertainity and unknown arbitrarily large unknown time varying delays. Fischer *et. al.* in [18] proposed a saturated controller using a continuous control law with smooth saturation functions, for a class of second order nonlinear uncertain systems including nonlinearly parameterized and time varying functions with bounded disturbances. Here the bounds on the control were apriory known and could be adjusted by altering feedback gains. Based on RISE control technique, the proposed controller had the benifits and merits of high gain control without violating saturation limits. Despite presence of modeling uncertainty and disturbances, the saturated controller could yield asymptotic tracking.

RISE control like most of the other robust control techniques, makes use of constant high gain to compensate for uncertainties in system dynamics. For this knowledge of upper bounds of system trajectories containing uncertainties, is required. However it is not a preferred way to compensate for system uncertainties with a blind application of extra gain without considering these bounds [2]. Recently Bidikli *et. al.* proposed a RISE structure with time varying compensation gain [1] which was later improved to self tuning RISE feedback formulation as proposed in [2] and extended RISE-based control to full state feedback control in [26].

This new control scheme has successfully been applied on many nonlinear systems. Some of the important applications are given here. In [5] RISE was used to develop a tracking conrol for second order motor motion control system. Bennehar *et. al.* in [25] applied RISE-based adaptive controller on a 3DOF parallel kinematic manuplator. In [22], Taktak-Meziou *et. al.* applied RISE to hard disk drives control. Fischer *et. al.* applied this control technique to underwater vehicles [23].

Control of inverted pendulum (IP) is a very interesting problem. An IP is a highly nonlinear system. It has been extensively studied in control theory. Various control strategies have successfully been applied to inverted pendulum system, most important of them are the sliding mode control [20]. The sliding mode control (SMC), integral sliding mode control (ISMC) and the terminal sliding mode control (TSMC) are the robust control techniques of choice for a highly nonlinear system prone to external disturbances. Robust control techniques are quite useful in presence of matched and unmatched uncertainities and in presence of discrepancies between system and its mathematical model. The IP system in its upright position is very vulnerable to disturbances and necessitates the use of robust control methods such as SMC, ISMC, TSMC and RISE.

In this paper the main contribution is comparison of RISE based control with TSMC, cogitating the appication of RISE and TSMC to inverted pedulum system. To the best of our knowledge, RISE based control scheme has not been implemented on one degree of freedom inverted pendulum till to date. TSMC belongs to a family of well known and

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well established robust control techniqies - sliding mode control. The comparison is made on the basis of time response, control energy and tracking performance. Comparison criteria is explained in Section IV a detailed comparison between the two control schemes is made. The results very strongly suggest preeminence of TSMC over RISE based control. The rest of the paper is organized as folows: in Section II the mathematical model of the system and control schemes - RISE and TSMC based control are presented in detail. Section III validates the developments in Section II, by presenting and discussing in detail the experimental results. Finally the last section concludes the paper.

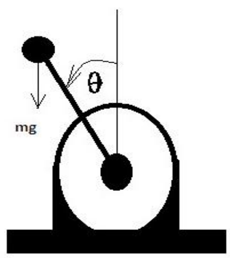

Fig. 1 Simple Inverted Pendulum system.

TABLE I IP PARAMETERS

Parameter	Symbol	Value	Unit
Pendulum Mass	m	0.026	Kg
Pendulum Moment	J	0.000362	$Kg.m^2$
Pendulum half length	l	0.1	m
Gravity	g	9.8	m/sec^2
Friction	B	0.001	$sec^{-}1$

II. SYSTEM MODEL

An IP system as shown in Figure 1, consists of pendulum connected to shaft of dc motor housed in a fixed casing. The pendulum is essentially a swingable arm with a mass connected to its end. The arm of pendulum makes an angle of θ with the vertical axis positive in counter clock-wise direction. The applied torque is in counter clock wise direction. The various paramters and variables of IP system are summarized in Table I and II. By application of Newtons Laws the equations governing the system are:

$$J\ddot{\theta} + B\dot{\theta} + mglsin\theta = \tau \quad (1)$$

A. RISE Control of IP

We will next formulate the problem in the framework of RISE control plroblem. Let us consider the system of form as defined in [3],

$$\mu\theta^{(n)} + f = u \quad (2)$$

TABLE II: IP VARIABLES

Variable	Symbol	Unit
Angular displacement of Pendulum	θ	radians
Applied Torque	τ	Nm

where $\theta^{(i)} \in R\ \forall i = 0,...,n$ represent the system states. The functions $\mu(\theta,\dot{\theta},..,\theta^{(n-1)}) \in R$ and $f(\theta,\dot{\theta},..,\theta^{(n-1)}) \in R$ are uncertain functions, $u(t) \in R$ is the control input, function $\mu(.)$ is positive bounded function,

$$\underline{\mu} \leq \mu(\theta) \leq \bar{\mu}(|\theta|,|\dot{\theta}|,...,|\theta^{(n-1)}|) \quad (3)$$

where $\underline{\mu} \in R_{>0}$ and $\bar{\mu}(.) \in R$ is positive nondecreasing function. The functions $\mu(.),f(.)$ are supposed to be continuously differentiable up to the second derivative. In problem under consideration, based on (1),

$$\mu = J$$
$$f = B\dot{\theta} + mglsin\theta \quad (4)$$

The first and second time derivatives in (4) are:

$$\dot{\mu} = 0$$
$$\ddot{\mu} = 0$$
$$\dot{f} = B\ddot{\theta} - mgl\dot{\theta}\cos\theta$$
$$\ddot{f} = B\theta^{(3)} - mgl[\dot{\theta}\sin\theta + \ddot{\theta}\cos\theta] \quad (5)$$

It can be easily observed that the derivatives of both of above functions are continously differentiable atleast upto the second derivative and μ is a bounded function $\forall\theta \in R$. The tracking error at the output is defined as,

$$e_1(t) = \theta_d(t) - \theta(t) \quad (6)$$

where $\theta_d(t) \in R$ represents the reference trajectory or the desired output and $\theta_d^{(i)}(t) \in L_\infty\ \forall i = 0,1,2..(n+2)$. In (2) the main control objective is to make sure that the error converges to zero asymptotically under full state feedback control, assuming all states are measurable (i.e. $\theta^{(i)}\ \forall i = 0,..,(n-1)$ are measurable).

The following error equation is based on the developments in [3] and [2],

$$e_{i+1} = \dot{e}_i + e_i$$
$$\vdots$$
$$e_n = \dot{e}_{n-1} + e_{n-1} + e_{n-2} \quad (7)$$

The generalized expression for error $e_i(t)$ $i = 2,..n$ is,

$$e_i = \Sigma_{j=0}^{i-1} a_{ij} e_1^{(j)} \quad (8)$$

where $a_{ij} \in R_{>0}$ are constants as defined in [3]. An auxiliary error signal, which would depend upon unmeasurable signal
$\theta^{(n)}$, is defined in [3] as,

$$\gamma = \dot{e}_n + \alpha e_n \quad (9)$$

here $\alpha \in R_{>0}$ is constant control gain. It may be noted that auxiliary signal given above, cannot be used in control design.

Differentiating (9) gives,

$$\dot{\gamma} = \ddot{e}_n + \alpha\dot{e}_n \quad (10)$$

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Now, the second derivative of (8) with $i = n$ is,

$$\ddot{e}_n = \Sigma_{j=0}^{n-1} a_{nj} e_1^{j+2} \quad (11)$$

Multiplying both sides of (10) by $\mu(\theta)$ and using (11),

$$\mu(\theta)\dot{\gamma} = \mu(\theta)\Sigma_{j=0}^{n-1} a_{ij} e^{j+2} + \mu(\theta)\alpha\dot{e}_n \quad (12)$$

Differentiating (2) with respect to time,

$$\mu(\theta)\theta^{n+1} + \dot{\mu}(\theta)\theta^n + \dot{f}(\theta) - \dot{u} = 0 \quad (13)$$

Now the $(n + 1)$ derivative of (7) is,

$$\theta^{(n+1)} = \theta_d^{(n+1)} - e_1^{(n+1)} \quad (14)$$

Using (13) and (14),

$$\mu(\theta)\dot{\gamma}(\theta) = \mu(\theta)[a_{nn-1}e_{n1+1} + \Sigma_{nj=0-2} a_{ij} e_{j+2} + \mu(\theta)\alpha \dot{e}_n] + \mu(\theta)(\theta_{dn+1} - e_{n1+1}) + \dot{\mu}(\theta)\theta_{n+1} + \dot{f}(\theta) - \dot{u} \quad (15)$$

Taking $a_{nn-1} = 1$ and rearranging terms,

$$\mu(\theta)\dot{\gamma}(\theta) = \mu(\theta)[\theta_{dn+1} + \Sigma_{nj=0-2} a_{ij} e_{j+2} + \mu(\theta)\alpha \dot{e}_n] + \dot{\mu}(\theta)\theta^n + \dot{f}(\theta) - \dot{u} \quad (16)$$

As defined in [3] the auxiliary function is, $\Xi(\theta, \dot{\theta}_1, .., \theta^n, t)$ as,

$$\Xi = \mu(\theta)[\theta_d^{n+1} + \Sigma_{j=0}^{n-2} a_{ij} e^{j+2} + \mu(\theta)\alpha\dot{e}_n] + \dot{\mu}(\theta)[\theta + \frac{1}{2}r] + e_n + \dot{f}(\theta) \quad (17)$$

Using (17), (16) becomes,

$$\mu(\theta)\dot{\gamma} = -\frac{1}{2}\dot{\mu}(\theta)\gamma - e_n - \dot{u} + \Xi \quad (18)$$

here n = 2. The function Ξ is further given as,

$$\Xi_d = \Xi_{\theta=\theta_d}$$

$$\Xi = \tilde{\Xi} - \Xi_d \quad (19)$$

The RISE control law based on as defined in [3] is,

$$u(t) = (k_s)e_n(t) - (k_s)e_n(0) + \int_0^t [(k_s)\alpha e_n(\tau) + \beta \; sgn(e_n(\tau))]d\tau \quad (20)$$

In [3] k_s, β were taken constants. In [1] and [2] adaptive tuming of these parameters was proposed. In this paper k_s, β, α are taken as constants.

According to Theorem 1 in [3] for asymptotic convergence of error to zero $\alpha > \frac{1}{2}$. We choose the control gains β, k_s according to (25) and (49) in [3], respectively. The derivative of control in (20) is:

$$\dot{u} = k_s\gamma + \beta sgn(e_n) \quad (21)$$

And the closed loop error system is thus given by next equation based on [1], [2] and [3].

$$\mu\dot{\gamma} = -\frac{1}{2}\dot{\mu}\gamma - e_n - k_s\gamma - \beta \; sgn(e_n) + \Xi \quad (22)$$

B. Terminal Sliding Mode Control of IP

In Terminal Sliding Mode (TSM) unlike sliding mode control a nonlinear term is introduced in the design of sliding surface. When the sliding surface or manifold is reached the trajectories are attracted within the manifold and converge to the origin following. In contrast, in conventional sliding mode asymptotic stability is guaranteed which leads to convergence of state variables to the origin but in infinite time [10]. Let us reconsider the IP system of (1). The sliding variable for the given system in Terminal Sliding Mode Control (TSMC) is [21],

$$s = e_2 + \beta \; e_1^{p/q} \quad (23)$$

where $e_i = x_i - x_d$ and $\theta = x_1, \dot{\theta} = x_2$. The state space model of given system is,

$$\dot{e_1} = e_2$$

$$\dot{e}_2 = -\frac{B}{J}e_2 - \frac{mgl}{J}e_1 + \frac{1}{J}u \quad (24)$$

The TSMC law is given by (25). Equivalent control is obtained by differentiating (23), equating with zero and using (24). In TSMC the control law is given as:

$$u = u_{dis} + u_{eq}$$

$$u_{dis} = -ksgn(s)$$

$$u_{eq} = (B)e_2 + (mgl)sin(e_1) - (\beta/J)(p/q)e_1^{\frac{p}{q}-1}e_2 \quad (25)$$

Here $1 < p/q < 2$ and $\beta > 0$.

III. EXPERIMENTAL RESULTS AND DISCUSSION

To demonstrate the relevance of proposed RISE based control of IP system, we implement control on Inverted Pendulum Trainer. The different parameters of system are summarized in Table I.

A. Description of testbed

The testbed which is used to obtain experimental results is Inverted Pendulum Trainer(IPT) Figure 2. The IPT consist of dc motor housed in a fixed casing. The motor shaft is mounted with a pair of swingable arms both connected to same shaft on opposite ends so that they can be treated as single inverted pendulum. The angular displacement of pendulum is measured by rotary potentiometer. The system is interfaced with PC installed with MATLAB, through PC interface unit. This unit comprises of a dc motor drive, data acquisition module. The drive delivers power to the dc motor connected to the pendulum while the data acquisition module sends the digitized angular displacement to PC through USB interface.

B. Results of RISE based control

The result of application of RISE based control law as given in (20) on IPT for output regulation, is shown in Figure 3. The initial position of pendulum was $\theta = -89.1^{\circ}$. It can be observed that the control brings the pendulum to the deisred position of $\theta = 0^{\circ}$ in 5s. The time response specifications for a constant input to the IP system are summarized in Table V.

The system was also tested for tracking a sinusoidal input of amplitude $\pi/10$ and frequency of πrad/sec. The tracking error is shown in Figure 4. It can be seen that the error reduces to zero after 5s. However there is noise in the signal due to electronics. The RISE controller parameters which were designed on the basis of inequalities (25) and (49) in [3] and set to give very good regulation and tracking, are summarized in Table III.

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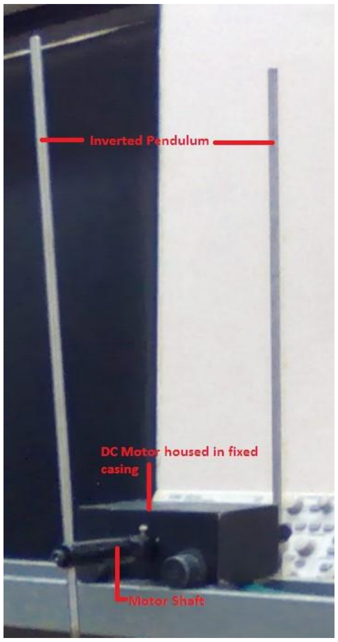

Fig. 2 Inverted Pendulum testbed.

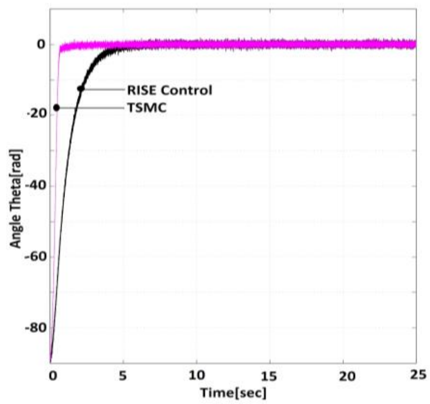

Fig. 3 Regulation of pendulum angle at zero rad.

C. Results of TSMC

The result of application of TSMC law as given in (23) to (25) on IPT for output regulation is shown in Figure 3. The initial position of pendulum was $\theta = -89.1^{\circ}$. It can be observed that the control brings the pendulum to the desired position of $\theta = 0^{\circ}$ in 0.8s. The time response specifications for a constant input to the IP system are summarized in Table V.

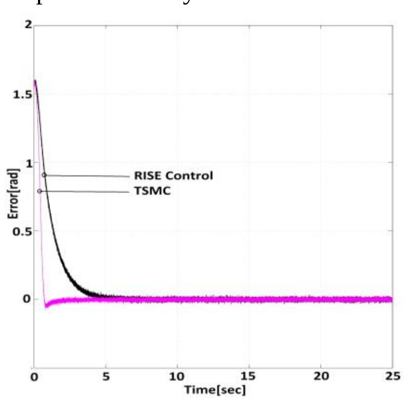

Fig. 4 Tracking error with RISE Control and TSMC.

TABLE III RISE CONTROLLER PARAMETERS

Symbol	Value
β	10
k_s	10
α	2

The system was also tested for tracking of sinusoidal input of amplitude $\pi/10$ and frequency of πrad/sec. The tracking error is shown in Figure 4. It can be seen that the error reduces zero after 1.8s. The noise in the signal is due to electronics. Based on conditions imposed on TSMC controller parameters in (25), we chose the values which gave best regulation and tracking, as summarized in Table IV.

IV. COMPARISON BETWEEN RISE BASED CONTROL AND TSMC

The comparison of results obtained from the two given control methodologies is discussed here. The comparison criteria is first explained as follows:

TABLE IV TSMC CONTROLLER PARAMETERS

Symbol	Value
β	10
k	10
p/q	1.5

TABLE V TIME RESPONSE SPECIFICATIONS

Control	T_r	T_s	Overshoot	E_{ss}
RISE	3s	5s	nil	0
TSMC	0.6	0.8s	nil	0

A. Comparison criteria

The performance of the two control methodologies are compared in this paper, on the basis of:

1. Time Response Specifications of desired response, for output regulation, using the best designs of given control methodologies.
2. Tracking Error of desired input using the best designs of given control methodologies.
3. Control Energy of control signal in given control methodologies with different designs but yielding similar time response specifications.

Time Response Specifications include: *Rise time* T_r is defined in literature as the time required to reach from 10 to 90 percent of steady state value. [6] *Settling time* T_s is the time to reach 98 percent of steady state value.[15]

Steady state error E_{ss}, which is the mean value of difference between desired output and actual output at steady state.[6] Tracking Error: is the instantaneous value of errors for the given control strategies.

Control Energy: We define control energy (E) as an "effort" exerted by the given controller to give the desired results. Ideally the desired output should be achieved by smallest effort possible. Mathematically,

$$E = u^2 \tag{26}$$

B. Comparison

The comparison is based on following, Time Response Specifications: It can be observed that TSMC gives better regulation and tracking performance. It needs to be noted that the design parameters chosen were those which gave the best performance for the given technique. The TSMC has faster transient response and faster convergence to steady state value. While both techniques yield zero steady state error. Tracking Error: The tracking error convergence is also faster in case of TSMC. The root mean squared error (MSE) calculated in the basis of (27), for TSMC and RISE based control is summarized in Table VI.

$$MSE = \sqrt{\frac{1}{N}\sum (e_i)^2} \tag{27}$$

where N is the number of samples of discretized error signals. It can be seen that TSMC has a lower MSE value for tracking error than RISE control.

Control Energy: In order to compare the performance of system under RISE based control and TSMC as a first the TSMC parameters were changed. The new parameters were chosen to yield a response that was similar to the RISE based response. The updated parameters are $k = 2, \beta = 1, p/q = 1.5$. The new system tracking response (to a sinusoidal input used in previous section) is given in Figure 5. The Control Energy for both control techniques is given in Figure 6. In order to

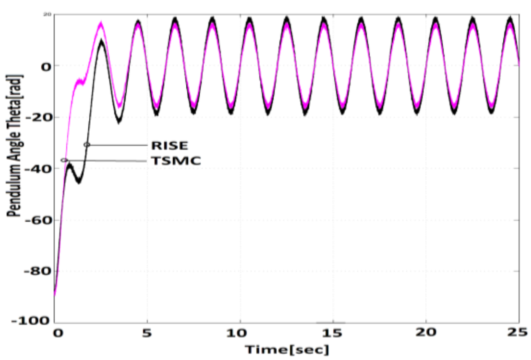

Fig. 5. Tracking response of redesigned system for RISE and TSMC.

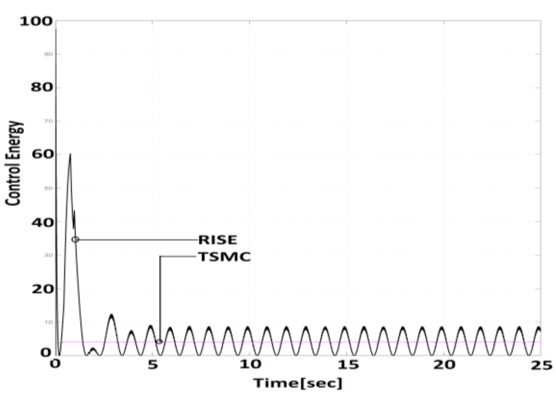

Fig. 6. Control Energy as function of time for RISE and TSMC.

determine which control has lower average value of E, we find A defined by:

$$A = \frac{1}{t_1 - t_o}\int_{t_o}^{t_1} E(t)dt \tag{28}$$

For RISE A = 5.429 while for TSMC A = 3.996. This shows that TSMC is exerting lesser effort in order to yield the same response which is obtained from RISE.

V. CONCLUSION

This paper considered the control of a nonlinear system Inverted Pendulum, using RISE and TSMC. The two control schemes were compared on the basis of time response, control energy and tracking performance. The findings suggest that TSMC exhibits better performance over RISE based control with faster response, lower control energy and smaller tracking error.

TABLE VI: ROOT MEAN SQUARED ERROR

Control	MSE
RISE	12.89
TSMC	5.46

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