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Integral Control for a Class of Planar Systems with Uncertain Measurements under Control Input Saturation

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Abstract— **This paper investigates the problem of global regulation for a class of planar systems with uncertain measurements in the presence of control input saturation. By taking into account the saturation nonlinearity at the outset of the controller design, a saturated integral controller is proposed in a very simple form to regulate the planar system with uncertain measurements. Moreover, the problem of tracking a ramp signal with unknown slope and the extension of the case for measurement function with a generalized unknown form are also presented. A novel Lyapunov based stability proof is provided and the simulation studies demonstrate the effectiveness of the proposed method.**

I. INTRODUCTION

This paper considers the global regulation problem for a class of planar systems under control input saturation. The planar system with uncertain measurements is described as follows.

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= u, \\ y_1 &= sign(x_1)|x_1|^{\theta_1}, \\ y_2 &= x_2 + \theta_2, \end{aligned} \tag{1}$$

where $x = [x_1,\ x_2]^T \in \mathbb{R}^2$ and $u \in \mathbb{R}$ are the system state vector and control input respectively. y_1 is the uncertain measurement with unknown power $\theta_1 \in \mathbb{R}^+$ and y_2 is the uncertain measurement with unknown bias drift $\theta_2 \in \mathbb{R}$. Our objective is to design a controller under control input saturation which globally regulates the planar system (1).

Planar systems are of great importance and widely used to describe dynamics of different physical systems, such as circuit analysis, mechanical systems, and angular motion systems, etc. [1], [2], [3] [4]. In the case where the relationship between the measurement and the state. i.e., $y = h(x_1)$, is explicitly clear, it is very easy to design state feedback controllers to stabilize system (1). In this situation, output feedback controllers can also be easily designed by utilizing different observer/estimator technologies. However, the explicit structures of $h(\cdot)$ are difficult to obtain or the actual values of the output function could deviate from the real values in industrial applications due to the limitations of measurement sensors and noises [5], [6], [7], [8]. To deal with the uncertain measurements, [9] proposed an output feedback design for nonlinear systems with an uncertain output function $y = h(x_1)$ by using the homogeneous domination approach [10]. A critical assumption in [9] is that $h(x_1)$ is differentiable and bounded by two linear functions. The work [11] proposed an output feedback controller for a class of nonlinear systems with uncertain measurement sensitivity (i.e., $y = \theta(t)x_1$, $\theta(t)$ is bounded by two positive constants), where the sensor sensitivity is a bounded unknown continuous function of time, and a dual-domination approach is proposed. By employing the idea of K-filter proposed in [12], the problem of adaptive output feedback control of nonlinear systems with output parametric uncertainty (i.e., $y = \theta x_1$ with an unknown constant θ) is studied in [13]. However, some sensors in the real world might not have the linear relationship between the measurement and the real state. For instance, as shown in [14], the voltage output from an infrared distance sensor is a nonlinear function. A typical infrared sensor for the real distance d will only output d^p where the constant p is around 0.8 but its precise value is varying from product to product. In the situation where the uncertain sensor measurement has a form of unknown power, the aforementioned approaches are not able to handle the problem, even just for the double integrator system. In systems and control theory, the double integrator system is of great importance as it describes the dynamics of many different physical systems. There are countless results for the double integrator system, however, the problem as described in equation (1) is still unsolved yet very interesting. Therefore, it is meaningful to design a saturated controller to regulate the double integrator system subject to uncertain measurements as described in (1).

In control theory, designing a controller normally has no constrains on the value of the controller. However, in practical applications the magnitude of the control signal is always limited by the inherent physical input saturation on the hardware actuator. Saturation from the actuator is a hidden problem which severely limits system performance, increases undesirable inaccuracy and even leads to instability [15]. Saturation nonlinearities are inevitable in engineering systems since all the physical actuators are subject to saturation owing to their maximum and minimum limits. Moreover, sometimes saturation nonlinearities are introduced into engineering systems on purpose such as PWM-based control systems and neural network systems [16]. No matter how saturation arises, the analysis and design of a system that contains saturation nonlinearities is challenging yet of great importance. There are, in general, two main approaches to deal with the actuator saturation. The first strategy is known as anti-windup schemes, which neglecting the saturation in

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the first stage of controller design then adding some schemes to handle the adverse effects caused by saturation. For example, in [17] the authors proposed a saturation controller in the framework of anti-windup compensation for unstable linear time-invariant system. Other results can also be found in [18], [19], [20], [21], [22]. Most of these schemes are able to enhance performance but not good at improving stability. The second strategy takes into account the saturation nonlinearities at the outset of the control design, which analyzes the closed-loop system under actuator saturation systematically. Compared to the first one, the second strategy poses difficulties but improves stability while retaining the performance (see, for example, [23] [24] and the references therein). A saturated linear state feedback controller always works for the double integrator system if the states are known, however, it might fail when the measurements are uncertain as described in (1).

In this note, we will adopt the second strategy of taking saturation into account to design an integral controller for system (1). By proposing a novel Lyapunov function, we will give an rigours stability analysis. Moreover, the problem of tracking a ramp signal with unknown slope and an extension of the case for measurement function with a generalized unknown form will also be studied.

The rest of the paper is organized as follows. In section II, we give three subsections: The first part gives the main theorem and the stability analysis. The second part addresses the problem of tracking a ramp signal with unknown slope. And the last part is dedicated to a planar system with uncertain measurements in a more generalized form. Some examples and related numerical simulations are given to verify the effectiveness of the proposed saturated integral controller. Finally, section III draws the conclusion.

II. MAIN RESULTS

A. Global regulation of system (1) under control input saturation

In this subsection, we propose a saturated integral controller for system (1). The saturation function used in this note is defined as $sat(x) = sign(x)min\{M, |x|\}$, where constant M is the saturation level. We first give the main theorem, then provide the Lyapunov stability analysis.

Theorem 1: The system (1) is globally regulated by the following controller

$$\begin{aligned} \dot{x}_0 &= sat(y_1), \\ u &= -a * sat(x_0 + y_2) - b * sat(y_1), \end{aligned} \tag{2}$$

where a and b are positive constants satisfying $b > 1$.

Proof: Substituting the controller (2) into (1), then we have the closed-loop system

$$\begin{aligned} \dot{x}_0 &= sat(sign(x_1)|x_1|^{\theta_1}), \\ \dot{x}_1 &= x_2, \\ \dot{x}_2 &= -a * sat(x_0 + x_2 + \theta_2) - b * sat(sign(x_1)|x_1|^{\theta_1}). \end{aligned} \tag{3}$$

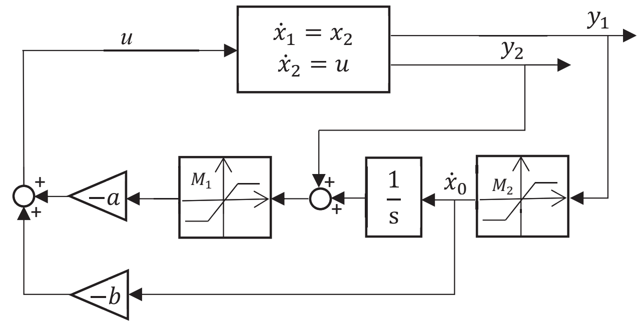

Fig. 1. Block diagram of the closed-loop system.

Fig. 1 shows the block diagram of the closed-loop system. With the following coordinate transformation

$$z_1 = x_0 + \theta_2,\ z_2 = x_1,\ z_3 = x_2,$$

system (3) can be rewritten as

$$\begin{aligned} \dot{z}_1 &= sat(sign(z_2)|z_2|^{\theta_1}), \\ \dot{z}_2 &= z_3, \\ \dot{z}_3 &= -a * sat(z_1 + z_3) - b * sat(sign(z_2)|z_2|^{\theta_1}). \end{aligned} \tag{4}$$

Construct the following Lyapunov function

$$\begin{aligned} V(z_1, z_2, z_3) = b(b-1) \int_0^{z_2} sat(sign(s)|s|^{\theta_1}) ds \\ + \frac{1}{2}(bz_1 + z_3)^2 + \frac{1}{2}(b-1)z_3^2, \end{aligned} \tag{5}$$

which is positive definite and radically unbounded since $b > 1$. The derivative of $V(z_1, z_2, z_3)$ along the closed-loop system (4) can be calculated as follows

$$\begin{aligned} \dot{V}(z_1, z_2, z_3) &= b(b-1)sat(sign(z_2)|z_2|^{\theta_1})\dot{z}_2 \\ &\quad + (bz_1 + z_3)(b\dot{z}_1 + \dot{z}_3) + (b-1)z_3\dot{z}_3 \\ &= -ab(z_1 + z_3)sat(z_1 + z_3), \end{aligned} \tag{6}$$

which is semi-negative definite. Define $S = \{z \in \mathbb{R}^3 | \dot{V}(z_1, z_2, z_3) = 0\}$ as the LaSalle's invariant set. Notice that

$$\dot{V}(z_1, z_2, z_3) = 0 \Rightarrow z_1 + z_3 = 0,$$

which implies $S = \{z \in \mathbb{R}^3 | z_1 = -z_3\}$. In this set we have

$$0 = \dot{z}_1 + \dot{z}_3 = (1-b)sign(z_2)|z_2|^{\theta_1} - a * sat(z_1 + z_3).$$

Thus it can be concluded that $z_2 \equiv 0$ in S. Moreover, by

$$0 = \dot{z}_2 = z_3$$

it can be obtained that $z_3 \equiv 0$ and then $z_1 \equiv 0$ consequently in S. Therefore, the trivial solution $z \equiv 0$ is the only solution in S. By LaSalle's invariance principle, the origin of the closed-loop system (4) is globally asymptotically stable, which implies that $x_1 \equiv 0$ and $x_2 \equiv 0$. Thus, system (1) is globally regulated by the controller (2). This completes the proof. ■

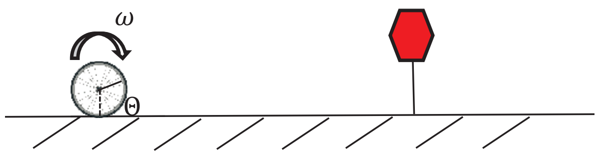

Fig. 2. Rotational motion of a wheel.

Example 1: As Fig. 2 shows, the ideal angular motion of a wheel is based on Newton's second law of motion:

$$T = J\frac{d^2\Theta}{dt^2} = J\frac{d\omega}{dt}, \tag{7}$$

where T is the net torque, J is the moment of inertia, Θ is the angular of rotation and ω is the angular velocity of rotation. Assume the wheel is moving toward a target and needs to stop at some distance before it.

Denote $x_1 = \Theta$ and $x_2 = \omega$, then the mathematical model can be written as

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= u, \end{aligned} \tag{8}$$

where $u = \frac{T}{J}$ is the control input. The horizontal displacement of the wheel can be expressed as rx_1 where r is the radius of the wheel. When using an infrared distance sensor described in [14] to measure the horizontal displacement, and a gyro sensor whose drift model is represented as $\omega_{gyro} = \omega + \delta$ (where ω_{gyro} is the gyro output data from the actual measurements, ω is the real angular velocity and δ is the gyro drift [25]) to measure the angular velocity, the measurements can be expressed as $y_1 = r^p x_1^p$ (note that r is a known positive constant) and $y_2 = x_2 + \delta$, where $p \in \mathbb{R}^+$, $\delta \in \mathbb{R}$ are unknown constants. Based on the Theorem 1, system (8) is globally regulated by the saturated integral controller (2).

For simulation studies of Example 1, the related parameters are selected as $J = 1$, $r = 1$, $p = 13/11$, $\delta = 1/2$, $a = 2$, $b = 3$, and the initial conditions are $[x_0(0),\ x_1(0),\ x_2(0)] = [1,\ 2,\ 3]$. Constants M_1 and M_2 are the saturation levels of $sat(x_0+y_2)$ and $sat(y_1)$ respectively in controller (2). In the simulation, different combinations of M_1 and M_2 are selected to verify the effectiveness of the proposed controller. The simulation results are shown in Fig. 3 - 5. It can be seen that the states x_1 and x_2 converge to the origin for different saturation levels, only with different performances. It's worth mentioning that x_0 converges to $-\delta$ since in this example $z_1 = x_0 + \delta$.

Remark 1: In controller (2), the saturation level of $sat(x_0+y_2)$ and $sat(y_1)$ can be the same or be different. The saturation levels are related to the limitation of the actuator and the control gains $a,\ b$. The proposed controller (2) gives more flexibility to tune the parameters.

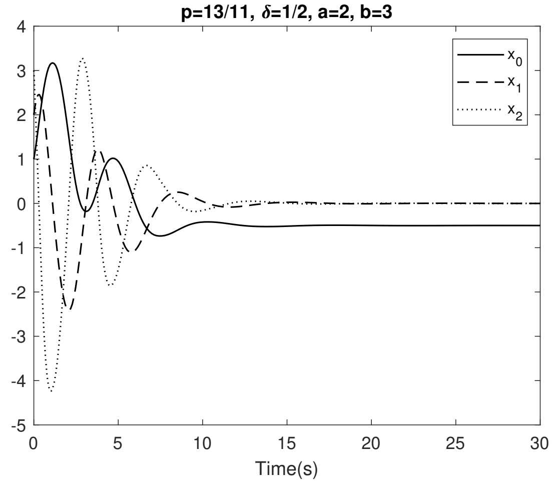

Fig. 3. Trajectories of (8) under controller (2) with saturation level $M_1 = 1$ and $M_2 = 9$.

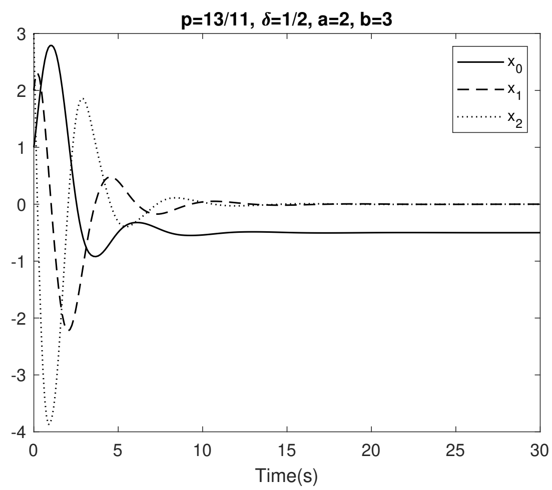

Fig. 4. Trajectories of (8) under controller (2) with saturation level $M_1 = 5$ and $M_2 = 5$.

B. Tracking a ramp signal with unknown slope under control input saturation

In this subsection, we consider the tracking problem under control input saturation for the following system

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= u, \\ y_1 &= sign\left(x_1 - r(t)\right)\left|x_1 - r(t)\right|^{\alpha}, \\ y_2 &= x_2, \end{aligned} \tag{9}$$

where $x = [x_1,\ x_2]^T \in \mathbb{R}^2$ and $u \in \mathbb{R}$ are the system state and control input respectively. The tracking objective $r(t) = \beta t$ is a ramp signal with unknown slope $\beta \in \mathbb{R}$, and the measurement y_1 has an unknown power $\alpha \in \mathbb{R}^+$.

Theorem 2: The system (9) is globally regulated by the saturated integral controller (2).

Proof: Denote the tracking error $e_1 = x_1 - r(t)$, then it is easy to obtain $\dot{e}_1 = x_2 - \beta$. Substituting the controller (2)

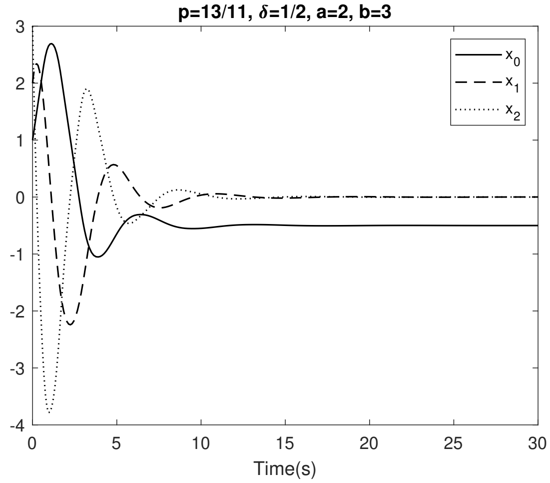

Fig. 5. Trajectories of (8) under controller (2) with saturation level $M_1 = 8$ and $M_2 = 2$.

into (9), and together with the derivative of tracking error $\dot{e}_1$ we have the closed-loop system

$$\begin{aligned} \dot{x}_0 &= sat(sign(e_1)|e_1|^{\alpha}), \\ \dot{e}_1 &= x_2 - \beta, \\ \dot{x}_2 &= -a * sat(z_0 + y_2) - b * sat(y_1). \end{aligned} \tag{10}$$

Define the following coordinate transformation

$$z_1 = e_1, z_2 = x_2 - \beta,$$

then we have the new dynamic system along with the new outputs $\tilde{y}_1, \tilde{y}_2$ as

$$\begin{aligned} \dot{z}_1 &= z_2, \\ \dot{z}_2 &= u, \\ \tilde{y}_1 &= sign(z_1)|z_1|^{\alpha}, \\ \tilde{y}_2 &= z_2 + \beta. \end{aligned} \tag{11}$$

Based on Theorem 1, system (11) is globally regulated by controller (2) with the new outputs $\tilde{y}_1$ and $\tilde{y}_2$. $z_1 = 0$ implies the tracking error $e_1 = 0$, thus x_1 tracks the reference signal $r(t)$. This completes the proof. ∎

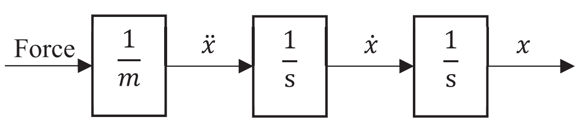

Fig. 6. A rigid body system.

Example 2: Consider a rigid body plant driven by a force actuator on a smooth surface (Fig. 6). Assume the tracking objective $r(t) = \beta t$ and the position sensor gives output $y_1 = sign(x_1 - r(t))|x_1 - r(t)|^{\alpha}$ for unknown constants α and β.

Denote x_1 as the position displacement, $x_2 = \dot{x}_1$ and $u = \frac{Force}{m}$, where m is the mass of the plant. Then the mathematical model can be written as (9). The numerical simulation results for (9) under controller (2) is shown in Figure 7 - 9. In the simulation, system parameters are selected as $m = 1$, $\alpha = \frac{7}{5}$, $\beta = \frac{1}{2}$, $a = 2$, $b = 3$ and initial conditions $[x_0(0),\ x_1(0),\ x_2(0))] = [1,\ 2,\ 3]$. Constants M_1 and M_2 are the saturation levels of $sat(x_0 + y_2)$ and $sat(y_1)$ respectively in controller (2). Here x_1 converges to the reference ramp signal because all the states of system (11) converge to zero, which implies $0 = z_1 = e_1 = x_1 - r(t)$. x_2 converges to the value of slope β since $0 = z_2 = x_2 - \beta$. In the simulation, different combinations of M_1 and M_2 are selected to verify the effectiveness of the proposed controller. Different saturation levels gives different tracking performance, but all of them solved the tracking problem.

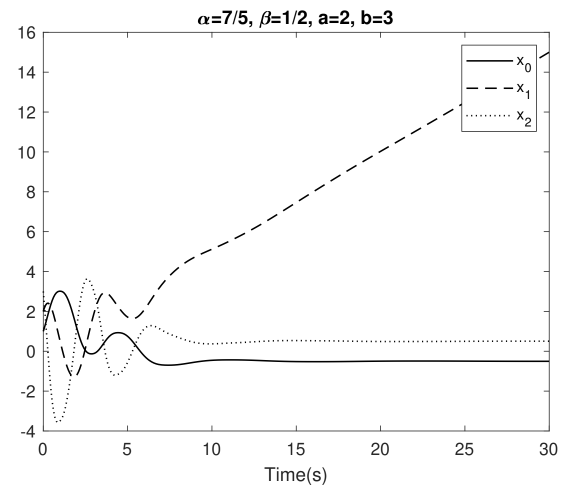

Fig. 7. Trajectories of (9) under controller (2) with saturation level $M_1 = 1$ and $M_2 = 9$.

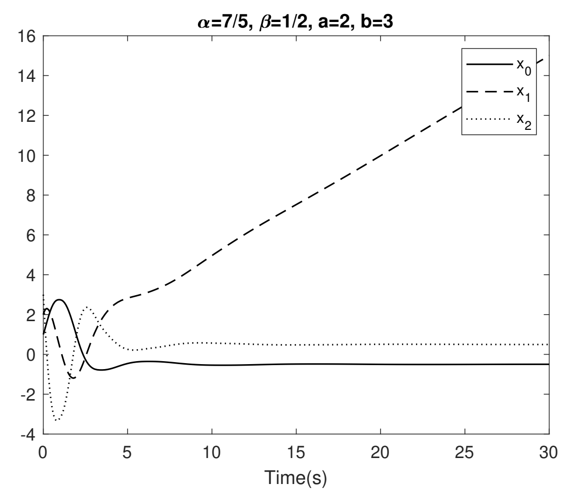

Fig. 8. Trajectories of (9) under controller (2) with saturation level $M_1 = 5$ and $M_2 = 5$.

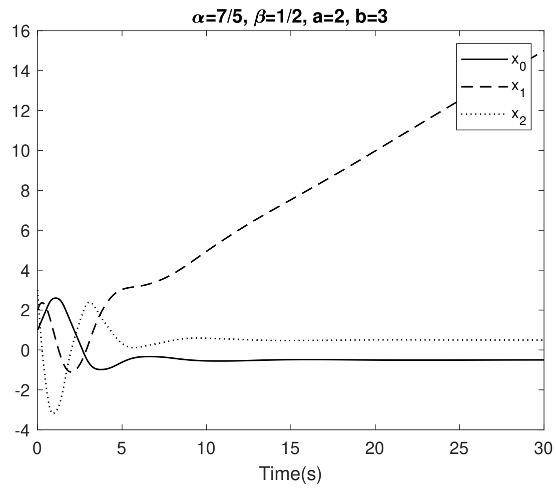

Fig. 9. Trajectories of (9) under controller (2) with saturation level $M_1 = 8$ and $M_2 = 2$.

C. Extension: Global regulation of system (1) with a generalized form of the unknown measurement function

In this subsection, we extend Theorem 1 to the regulation problem of system (1) with uncertain measurement y_1 in a more generalized form

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= u, \\ y_1 &= h(x_1), \\ y_2 &= x_2 + \theta_2, \end{aligned} \tag{12}$$

where θ_2 is an unknown constant and the output function of the measurement $h(s)$ is unknown but satisfies Assumption 1.

Assumption 1: The function $h(s)$ with $h(0) = 0$ satisfies the following

(i) $h(s) \neq 0$ when $s \neq 0$,
(ii) $\int_0^x h(s)ds > 0$ when $x \neq 0$, and
(iii) $\lim_{|x| \to +\infty} \int_0^x h(s)ds = +\infty$.

Corollary 1: Under Assumption 1, system (12) is globally regulated by controller (2).

Proof: Substituting (2) into (12), we have the following closed-loop system

$$\begin{aligned} \dot{x}_0 &= sat(h(x_1)), \\ \dot{x}_1 &= x_2, \\ \dot{x}_2 &= -a * sat(x_0 + x_2 + \theta_2) - b * sat(h(x_1)). \end{aligned} \tag{13}$$

Define the coordinate transformation $z_1 = x_0 + \theta_2,\ z_2 = x_1,\ z_3 = x_2$. Then we can rewrite the closed-loop system (13) as

$$\begin{aligned} \dot{z}_1 &= sat(h(z_2)), \\ \dot{z}_2 &= z_3, \\ \dot{z}_3 &= -a * sat(z_1 + z_3) - b * sat(h(z_2)). \end{aligned} \tag{14}$$

Construct the following Lyapunov function

$$\begin{aligned} V(z_1, z_2, z_3) = b(b-1) \int_0^{z_2} sat(h(s))ds \\ + \frac{1}{2}(bz_1 + z_3)^2 + \frac{1}{2}(b-1)z_3^2, \end{aligned} \tag{15}$$

which is positive definite and radically unbounded under Assumption 1 and together with $b > 1$. Taking the derivative of Lyapunov function (15) along the closed-loop system (14), we have

$$\begin{aligned} \dot{V}(z_1, z_2, z_3) &= b(b-1)sat(h(z_2))\dot{z}_2 \\ &\quad + (bz_1 + z_3)(b\dot{z}_1 + \dot{z}_3) + (b-1)z_3\dot{z}_3 \\ &= -ab(z_1 + z_3)sat(z_1 + z_3). \end{aligned} \tag{16}$$

It is straightforward that $\dot{V}(z_1, z_2, z_3)$ in (16) is semi-negative definite. Similar to the analysis of (6), the origin of the closed-loop system (14) is globally asymptotically stable by LaSalle's invariance principle, which implies that $x_1 \equiv 0$ and $x_2 \equiv 0$. Thus, system (12) is globally regulated by the controller (2). This completes the proof. ■

III. Conclusion

In this paper we proposed a novel integral controller for the double integrator system with uncertain measurements under control input saturation. The saturation nonlinearity was considered at the stage of controller design, which improves the closed-loop stability. For the uncertain measurements, both a special case and the general case are studied. In addition, the problem of tracking a ramp signal with unknown slope is also studied. The proposed method has solved the regulation problem of a class of planar systems with uncertain measurements, however, extending this idea to systems with higher degree is still unsolved and it will be studied in our future work.

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