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• Supplementary File •

Global control for a class of chained nonholonomic systems with input saturations

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Appendix A Proof of Theorem 1

The closed-loop system can be formulated as

$$\dot{x}_0(t) = -\mathrm{sat}_{u_{\max}}\left(\lambda x_0(t) - \beta \mathrm{e}^{-\alpha t}\right). \tag{A1}$$

Let $X = \lambda x_0(t) - \beta \mathrm{e}^{-\alpha t}$. Then the $\dot{X}$ along the trajectory (A1) can be given as

$$\begin{aligned}\dot{X} &= \lambda \dot{x}_0(t) + \alpha\beta \mathrm{e}^{-\alpha t}\\ &= -\lambda \mathrm{sat}_{u_{\max}}(X) + \alpha\beta \mathrm{e}^{-\alpha t}.\end{aligned} \tag{A2}$$

Consider the Lyapunov function

$$V(X) = \frac{1}{2}X^2.$$

Along the trajectory of (A2), the time derivative of $V(X(t))$ is

$$\dot{V}(X) = -\lambda X\, \mathrm{sat}_{u_{\max}}(X) + \alpha\beta\, \mathrm{e}^{-\alpha t} X.$$

Since $\lim_{t\to\infty} \beta \mathrm{e}^{-\alpha t} = 0$, there exists a constant $t_1 > 0$ such that, for $t \geqslant t_1$, $|\alpha\beta|\,\mathrm{e}^{-\alpha t} < \lambda u_{\max}$. Assume that $|X| > u_{\max}$, for $t \geqslant t_1$. Therefore, we have

$$\begin{aligned}\dot{V}(X) &= -\lambda X \mathrm{sign}(X)\left|\mathrm{sat}_{u_{\max}}(X)\right| + \alpha\beta \mathrm{e}^{-\alpha t} X\\ &= -\lambda u_{\max}|X| + \alpha\beta \mathrm{e}^{-\alpha t} X < 0.\end{aligned}$$

Then, according to Lyapunov stability theory, there exists a positive constant $T_0 > t_1$ such that, for $t \geqslant T_0$, $|X| \leqslant u_{\max}$, and thus the controller can be further written as

$$\mathrm{sat}_{u_{\max}}(u_0(t)) = -\lambda x_0(t) + \beta \mathrm{e}^{-\alpha t}. \tag{A3}$$

For $t \geqslant T_0$, (A1) can be described as

$$\dot{x}_0(t) = -\lambda x_0(t) + \beta \mathrm{e}^{-\alpha t},$$

whose solution can be calculated as

$$\begin{aligned}x_0(t) =& \mathrm{e}^{-\lambda t} x_0(T_0) + \beta \int_{T_0}^{t} \mathrm{e}^{-\lambda(t-s)} \mathrm{e}^{-\alpha s} \mathrm{d}s\\ =& \mathrm{e}^{-\lambda t} x_0(T_0) + \beta \mathrm{e}^{-\lambda t} \frac{1}{\lambda-\alpha}\left(\mathrm{e}^{(\lambda-\alpha)t} - \mathrm{e}^{(\lambda-\alpha)T_0}\right)\\ =& \mathrm{e}^{-\alpha t}\left(\mathrm{e}^{-(\lambda-\alpha)t} x_0(T_0) + \beta\frac{1}{\lambda-\alpha}\left(1 - \mathrm{e}^{-(\lambda-\alpha)t}\mathrm{e}^{(\lambda-\alpha)T_0}\right)\right),\end{aligned}$$

substituting which into (A3) yields

$$\begin{aligned}\mathrm{sat}_{u_{\max}}(u_0(t)) =& -\lambda x_0(t) + \beta \mathrm{e}^{-\alpha t}\\ =& \mathrm{e}^{-\alpha t}\left(-\lambda \mathrm{e}^{-(\lambda-\alpha)t} x_0(T_0) - \frac{\lambda\beta}{\lambda-\alpha}\left(1 - \mathrm{e}^{-(\lambda-\alpha)t}\mathrm{e}^{(\lambda-\alpha)T_0}\right) + \beta\right)\end{aligned}$$

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$$
\begin{aligned}
&= \mathrm{e}^{-\alpha t}\left(-\lambda \mathrm{e}^{-(\lambda-\alpha)t}x_0(T_0) + \frac{\lambda\beta}{\lambda-\alpha}\mathrm{e}^{-(\lambda-\alpha)t}\mathrm{e}^{(\lambda-\alpha)T_0} - \frac{\lambda\beta}{\lambda-\alpha} + \beta\right) \\
&= \mathrm{e}^{-\alpha t}\left(\theta(t) + \delta\right),
\end{aligned}
$$

where

$$
\theta(t) = \mathrm{e}^{-(\lambda-\alpha)t}\left(-\lambda x_0(T_0) + \frac{\lambda\beta}{\lambda-\alpha}\mathrm{e}^{(\lambda-\alpha)T_0}\right), \quad \delta = -\frac{\alpha\beta}{\lambda-\alpha},
$$

which proves (3) and $\lim_{t\to\infty}\theta(t) = 0$. The proof is finished.

Appendix B Proof of Theorem 2

For simplicity, we denote

$$
u_1(t) = -\varepsilon_2 \mathrm{sat}\left(\frac{\lambda_2 Y_2(t)}{\varepsilon_2}\right) + u_{1,1}(t), \quad u_{1,1}(t) = -\varepsilon_1 \mathrm{sat}\left(\frac{\lambda_1 Y_1(t)}{\varepsilon_1}\right).
$$

For $t \in [0, T_0)$, the state and controller are bounded. For $t \geqslant T_0$, consider Y_2-subsystem in (8), namely, $\dot{Y}_2(t) = \mathrm{sat}_{u_{\max}}(u_1(t)) = u_1(t)$. Choose the function

$$
W_2(Y_2(t)) = \frac{1}{2}Y_2^2(t),
$$

whose time-derivative along the trajectory of (8) can be calculated as

$$
\begin{aligned}
\dot{W}_2(t) =& Y_2(t)u_1(t) \\
=& -\varepsilon_2 Y_2(t)\mathrm{sat}\left(\frac{\lambda_2 Y_2(t)}{\varepsilon_2}\right) + Y_2(t)u_{1,1}(t) \\
=& -\varepsilon_2 Y_2(t)\mathrm{sign}\left(Y_2(t)\right)\left|\mathrm{sat}\left(\frac{\lambda_2 Y_2(t)}{\varepsilon_2}\right)\right| + Y_2(t)u_{1,1}(t).
\end{aligned}
$$

Assume that $|\lambda_2 Y_2| > \varepsilon_2$. Since $\varepsilon_2 > \varepsilon_1$, we have

$$
\dot{W}_2(t) = -\varepsilon_2|Y_2| + |Y_2|u_{1,1}(t) \leqslant -\varepsilon_2|Y_2| + \varepsilon_1|Y_2| < 0.
$$

Therefore, there exists a positive constant $T_1 > T_0$ such that, for $t \geqslant T_1$, $|\lambda_2 Y_2| \leqslant \varepsilon_2$, and

$$
u_1(t) = -\varepsilon_2 \mathrm{sat}\left(\frac{\lambda_2 Y_2(t)}{\varepsilon_2}\right) + u_{1,1}(t) = -\lambda_2 Y_2(t) + u_{1,1}(t).
$$

Thus (8) can be written as

$$
\begin{aligned}
\begin{bmatrix}\dot{Y}_1\\ \dot{Y}_2\end{bmatrix} &= \begin{bmatrix}0 & \lambda_2\\ 0 & 0\end{bmatrix}\begin{bmatrix}Y_1\\ Y_2\end{bmatrix} + \theta(t)\begin{bmatrix}0 & \frac{\lambda_2}{\delta}\\ 0 & 0\end{bmatrix}\begin{bmatrix}Y_1\\ Y_2\end{bmatrix} + \begin{bmatrix}1\\ 1\end{bmatrix}(-\lambda_2 Y_2 + u_{1,1}(t)) \\
&= \begin{bmatrix}0 & 0\\ 0 & -\lambda_2\end{bmatrix}\begin{bmatrix}Y_1\\ Y_2\end{bmatrix} + \theta(t)\begin{bmatrix}0 & \frac{\lambda_2}{\delta}\\ 0 & 0\end{bmatrix}\begin{bmatrix}Y_1\\ Y_2\end{bmatrix} + \begin{bmatrix}1\\ 1\end{bmatrix}u_{1,1}(t).
\end{aligned} \tag{B1}
$$

Consider Y_1-subsystem in (B1), namely,

$$
\dot{Y}_1 = \frac{\lambda_2}{\delta}\theta(t)Y_2 + u_{1,1}(t). \tag{B2}
$$

Choose the function

$$
W_1(Y_1) = \frac{1}{2}Y_1^2,
$$

whose time-derivative along the trajectory of (B2) can be calculated as

$$
\begin{aligned}
\dot{W}_1(Y_1) &= Y_1\left(\frac{\lambda_2}{\delta}\theta(t)Y_2 + u_{1,1}(t)\right) \\
&= \frac{\lambda_2}{\delta}\theta(t)Y_1Y_2 + Y_1u_{1,1}(t) \\
&= \frac{\lambda_2}{\delta}\theta(t)Y_1Y_2 - \varepsilon_1 Y_1\mathrm{sat}\left(\frac{\lambda_1 Y_1}{\varepsilon_1}\right) \\
&\leqslant \frac{\varepsilon_2}{\delta}|\theta(t)||Y_1| - \varepsilon_1 Y_1\mathrm{sat}\left(\frac{\lambda_1 Y_1}{\varepsilon_1}\right).
\end{aligned}
$$

Since $\lim_{t\to\infty}\theta(t) = 0$, let $T_2 \geqslant T_1$ be a constant such that $\frac{\varepsilon_2}{\delta}|\theta(t)| < \varepsilon_1$, for $t \geqslant T_2$. Assume that $|\lambda_1 Y_1| > \varepsilon_1$, we have

$$
\dot{W}_1(Y_1) \leqslant \frac{\varepsilon_2}{\delta}|\theta(t)||Y_1| - \varepsilon_1 Y_1\mathrm{sat}\left(\frac{\lambda_1 Y_1}{\varepsilon_1}\right)
$$

$$
\begin{aligned}
&= \frac{\varepsilon_2}{\delta}\left|\theta(t)\right|\left|Y_1\right| - \varepsilon_1\left|Y_1\right| \\
&< 0.
\end{aligned}
$$

Therefore, it can be concluded that there exists a positive constant $T_3 > T_2$ such that, for $t \geqslant T_3$, $|\lambda_1 Y_1| \leqslant \varepsilon_1$, and

$$
u_{1,1}(t) = -\varepsilon_1 \mathrm{sat}\left(\frac{\lambda_1 Y_1(t)}{\varepsilon_1}\right) = -\lambda_1 Y_1(t).
$$

Then, for any $t \geqslant T_3$, we can get

$$
\dot{Y} = A_{y,\mathrm{c}} Y + \theta(t) A_2 Y, \tag{B3}
$$

where

$$
A_{y,\mathrm{c}} = \begin{bmatrix} -\lambda_1 & 0 \\ -\lambda_1 & -\lambda_2 \end{bmatrix}, \quad A_2 = \begin{bmatrix} 0 & \frac{\lambda_2}{\delta} \\ 0 & 0 \end{bmatrix}.
$$

Let $P > 0$ be an unique solution to

$$
A_{y,\mathrm{c}} P + P A_{y,\mathrm{c}} = -P.
$$

Choose the Lyapunov function

$$
U(Y) = Y^{\mathrm{T}} P Y,
$$

whose time-derivative along the trajectory of (B3) can be calculated as

$$
\begin{aligned}
\dot{U}(Y) =& - Y^{\mathrm{T}} P Y + 2\theta(t) Y^{\mathrm{T}} P A_2 Y \\
\leqslant& - Y^{\mathrm{T}} P Y + \left|\theta(t)\right| Y^{\mathrm{T}} P Y + \frac{\lambda_{\max}(A_2^{\mathrm{T}} P A_2)}{\lambda_{\min}(P)} \left|\theta(t)\right| Y^{\mathrm{T}} P Y.
\end{aligned}
$$

Since $\lim_{t\to\infty} \theta(t) = 0$, there exists a constant $T_4 \geqslant T_3$ such that, for $t \geqslant T_4$,

$$
\begin{aligned}
\dot{U}(Y) \leqslant& - Y^{\mathrm{T}} P Y + \left|\theta(t)\right| Y^{\mathrm{T}} P Y + \frac{\lambda_{\max}(A_2^{\mathrm{T}} P A_2)}{\lambda_{\min}(P)} \left|\theta(t)\right| Y^{\mathrm{T}} P Y \\
\leqslant& - \varepsilon Y^{\mathrm{T}} P Y,
\end{aligned}
$$

where $\varepsilon > 0$ is a constant. Therefore, according to Lyapunov stability theory, we have $\lim_{t\to\infty} Y(t) = 0$, which, together with (4) and (7), indicates that

$$
\begin{aligned}
&\lim_{t\to\infty} \begin{bmatrix} z_1(t) \\ z_2(t) \end{bmatrix} = \lim_{t\to\infty} \begin{bmatrix} \frac{\lambda_2}{\delta} & 1 \\ 0 & 1 \end{bmatrix}^{-1} Y(t) = \lim_{t\to\infty} \begin{bmatrix} \frac{\delta}{\lambda_2} & -\frac{\delta}{\lambda_2} \\ 0 & 1 \end{bmatrix} Y(t) = 0, \\
&\lim_{t\to\infty} x_1(t) = \lim_{t\to\infty} \mathrm{e}^{-\alpha t} z_1(t) = 0, \\
&\lim_{t\to\infty} x_2(t) = \lim_{t\to\infty} z_2(t) = 0.
\end{aligned}
$$

The proof is finished by noting $\lim_{t\to\infty} u_1(t) = 0$.

Appendix C Extension to Other Nonholonomic Systems

In this section, we extend the methodologies outlined in Theorems 1 and 2 to a chained nonholonomic system comprising an integer subsystem and a bilinear subsystem.

Consider the following chained nonholonomic system

$$
\begin{cases}
\dot{x}_{01}(t) &= x_{02}(t), \\
\dot{x}_{02}(t) &= \mathrm{sat}_{u_{\max}}(u_0(t)), \\
\dot{x}_1(t) &= -\alpha x_1(t) + x_{02}(t) x_2(t), \\
\dot{x}_2(t) &= \mathrm{sat}_{u_{\max}}(u_1(t)),
\end{cases} \tag{C1}
$$

where $\alpha > 0$ is a constant, $x_0(t) = [x_{01}(t), x_{02}(t)]^{\mathrm{T}}$, and $x_1(t), x_2(t)$ are system states. The control inputs $u_0(t), u_1(t) \in \mathbf{R}$ are bounded through the saturation function

$$
\mathrm{sat}_{u_{\max}}(u) = \mathrm{sign}(u) \cdot \min\{|u|, u_{\max}\},
$$

where $u_{\max} > 0$ is a given constant.

Consider the state transformation

$$
y(t) = T_{0,2} x_0(t) \triangleq \begin{bmatrix} \lambda_2 & 1 \\ 0 & 1 \end{bmatrix} x_0(t),
$$

where $y(t) = [y_1(t), y_2(t)]^{\mathrm{T}}$ and $\lambda_2 > 0$. According to [1], the x_0-subsystem in (C1) can be reorganized as

$$\dot{y} = A_{\mathrm{T},2}y + b_{\mathrm{T},2}\mathrm{sat}_{u_{\max}}(u_0), \tag{C2}$$

where

$$A_{\mathrm{T},2} = \begin{bmatrix} 0 & \lambda_2 \\ 0 & 0 \end{bmatrix}, \quad b_{\mathrm{T},2} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}. \tag{C3}$$

With the above preparations, we can now obtain the following result.

Theorem C1. Let $\lambda_i > \alpha > 0$, $\beta \neq 0$, and $\varepsilon_i > 0$, $i = 1, 2$, be constants satisfying

$$\varepsilon_1 + \varepsilon_2 \leqslant u_{\max}, \quad \varepsilon_2 > \varepsilon_1. \tag{C4}$$

Consider the time-varying nonhomogeneous feedback

$$u_0(t) = -\varepsilon_2\mathrm{sat}\left(\frac{\lambda_2 y_2}{\varepsilon_2}\right) - \varepsilon_1\mathrm{sat}\left(\frac{\lambda_1 y_1}{\varepsilon_1} - \frac{\beta\mathrm{e}^{-\alpha t}}{\varepsilon_1}\right), \tag{C5}$$

with $\mathrm{sat}(x) = \mathrm{sat}_1(x)$. Then, the origin point is globally attractive, and the state converges locally to zero exponentially. In particular, there exists a positive constant T_2 such that $x_{02}(t)$ can be expressed as

$$x_{02}(t) = \mathrm{e}^{-\alpha t}\left(\theta_1(t) + \delta_1\right), \quad t \geqslant T_2, \tag{C6}$$

where $\delta_1 = \beta\alpha/\left((\alpha - \lambda_1)(\alpha - \lambda_2)\right)$ is a constant and $\theta_1(t)$ is a time-varying function satisfying $\lim_{t\to\infty}\theta_1(t) = 0$.

Proof. For simplicity, we denote

$$u_0(t) = -\varepsilon_2\mathrm{sat}\left(\frac{\lambda_2 y_2}{\varepsilon_2}\right) + u_{0,1}(t),$$
$$u_{0,1}(t) = -\varepsilon_1\mathrm{sat}\left(\frac{\lambda_1 y_1}{\varepsilon_1} - \frac{\beta\mathrm{e}^{-\alpha t}}{\varepsilon_1}\right).$$

Consider y_2-subsystem in (C2), namely, $\dot{y}_2 = \mathrm{sat}_{u_{\max}}(u_0(t)) = u_0(t)$. Choose the function

$$V_2 = \frac{1}{2}y_2^2,$$

whose time-derivative along the trajectory of (C2) and (C5) can be calculated as

$$\begin{aligned}\dot{V}_2 &= y_2 u_0(t) \\ &= -\varepsilon_2 y_2\mathrm{sat}\left(\frac{\lambda_2 y_2}{\varepsilon_2}\right) + y_2 u_{0,1}(t) \\ &= -\varepsilon_2 y_2\mathrm{sign}\left(y_2\right)\left|\mathrm{sat}\left(\frac{\lambda_2 y_2}{\varepsilon_2}\right)\right| + y_2 u_{0,1}(t).\end{aligned}$$

Assume that $|\lambda_2 y_2| > \varepsilon_2$. Since $\varepsilon_2 > \varepsilon_1$, we have

$$\dot{V}_2 = -\varepsilon_2\left|y_2\right| + \left|y_2\right| u_{0,1}(t) \leqslant -\varepsilon_2\left|y_2\right| + \varepsilon_1\left|y_2\right| < 0.$$

Therefore, there exists a positive constant T_1 such that, for $t \geqslant T_1$, $|\lambda_2 y_2| \leqslant \varepsilon_2$, and

$$u_0(t) = -\varepsilon_2\mathrm{sat}\left(\frac{\lambda_2 y_2}{\varepsilon_2}\right) + u_{0,1}(t) = -\lambda_2 y_2 + u_{0,1}(t).$$

Thus, (C2) can be written as

$$\begin{aligned}\begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \end{bmatrix} &= \begin{bmatrix} 0 & \lambda_2 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \end{bmatrix}\left(-\lambda_2 y_2 + u_{0,1}(t)\right) \\ &= \begin{bmatrix} 0 & 0 \\ 0 & -\lambda_2 \end{bmatrix}\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \end{bmatrix}u_{0,1}(t).\end{aligned}$$

Consider the y_1-subsystem in the above equation, namely, $\dot{y}_1 = u_{0,1}(t)$. According to the proof of Theorem 1, it can be concluded that there exists a positive constant $T_2 \geqslant T_1$ such that, for $t \geqslant T_2$, $\left|-\lambda_1 y_1 + \beta\mathrm{e}^{-\alpha t}\right| \leqslant \varepsilon_1$, and

$$u_{0,1}(t) = -\varepsilon_1\mathrm{sat}\left(\frac{\lambda_1 y_1}{\varepsilon_1} - \frac{\beta\mathrm{e}^{-\alpha t}}{\varepsilon_1}\right) = -\lambda_1 y_1 + \beta\mathrm{e}^{-\alpha t}.$$

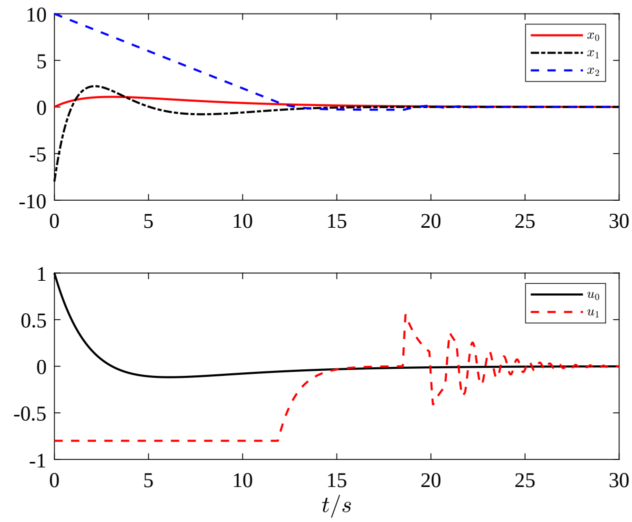

Figure D1 Time evolution of state variables and control inputs for system (1)

Then, for any $t \geqslant T_2$, we can get

$$\dot{y}(t) = A_{y,\mathrm{c}} y(t) + b_{\mathrm{T},2} \beta \mathrm{e}^{-\alpha t}, \tag{C7}$$

where

$$A_{y,\mathrm{c}} = \begin{bmatrix} -\lambda_1 & 0 \\ -\lambda_1 & -\lambda_2 \end{bmatrix}.$$

Choose the function

$$Y(t) = \mathrm{e}^{\alpha t} y(t) + \varepsilon_y,$$

where $Y(t) = [Y_1(t), Y_2(t)]^{\mathrm{T}}$ and $\varepsilon_y = (A_{y,\mathrm{c}} + \alpha I_2)^{-1} b_{\mathrm{T},2} \beta$. Then the time-derivative of $Y(t)$ along the trajectory of (C7) can be calculated as

$$\dot{Y}(t) = \mathrm{e}^{\alpha t} \dot{y}(t) + \alpha \mathrm{e}^{\alpha t} y(t) = (A_{y,\mathrm{c}} + \alpha I_2)\, Y(t) - (A_{y,\mathrm{c}} + \alpha I_2)\, \varepsilon_y + b_{\mathrm{T},2} \beta = (A_{y,\mathrm{c}} + \alpha I_2)\, Y(t),$$

which means that $\lim_{t \to \infty} Y(t) = 0$ since $\lambda_1 > \alpha$ and $\lambda_2 > \alpha$. Hence, $x_0(t)$ can be expressed as

$$\begin{aligned} x_0(t) =& T_{0,2}^{-1} y(t) \\ =& \mathrm{e}^{-\alpha t} \left(T_{0,2}^{-1} Y(t) - T_{0,2}^{-1} (A_{y,\mathrm{c}} + \alpha I_2)^{-1} b_{\mathrm{T},2} \beta \right) \\ =& \mathrm{e}^{-\alpha t} \left(\begin{bmatrix} \frac{1}{\lambda_2} & -\frac{1}{\lambda_2} \\ 0 & 1 \end{bmatrix} Y(t) - \frac{\beta}{(\alpha - \lambda_1)(\alpha - \lambda_2)} \begin{bmatrix} 1 \\ -\alpha \end{bmatrix} \right), \end{aligned}$$

which implies that

$$x_{02}(t) = \mathrm{e}^{-\alpha t} (\theta_1(t) + \delta_1),$$

where

$$\theta_1(t) = Y_2(t), \quad \delta_1 = \frac{\beta \alpha}{(\alpha - \lambda_1)(\alpha - \lambda_2)}.$$

Therefore, (C6) has been proven, and it follows that $\lim_{t \to \infty} \theta_1(t) = 0$. The proof is finished.

For the saturation design of the controller $u_1(t)$ in $[x_1(t), x_2(t)]$-subsystem of (C1), we can follow a similar process as outlined in Section of *Design of control law* $u_1(t)$, which is omitted here for brevity.

Appendix D Numerical Simulation

In this section, we conduct a numerical simulation for system (1) with the controllers $u_0(t)$ and $u_1(t)$ as described in Theorems 1 and 2.

For the simulation, to verify the effectiveness of the proposed method when $x_0(0) = 0$, we set the initial condition as $[x_0(0), x_1(0), x_2(0)] = [0, -8, 10]$. Additionally, the parameters are chosen as $\lambda = 0.5, \beta = 1, \alpha = 0.2, \varepsilon_1 = 0.3, \varepsilon_2 = 0.5, \lambda_1 = 0.2$, and $\lambda_2 = 1$. Figure D1 clearly illustrates that the proposed method successfully drives both the system states and the control inputs to zero in the presence of input saturation.

References

1 Zhou B, Duan G R. Global stabilization of linear systems via bounded controls. Syst Control Lett, 2009, 58(1), 54-61.