HOCHSCHULE
FÜR ANGEWANDTE
WISSENSCHAFTEN
MÜNCHEN

Non-identifier based adaptive control with internal models for mechatronic energy systems

Christoph M. Hackl

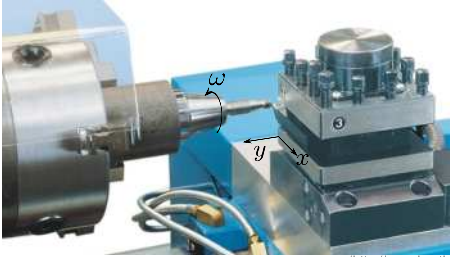
20.03.2018

GAMM 2018, Munich

Outline

Problem statement and motivation

Reference tracking under load (e.g. CNC turning machine)



(http://www.knuth.de)

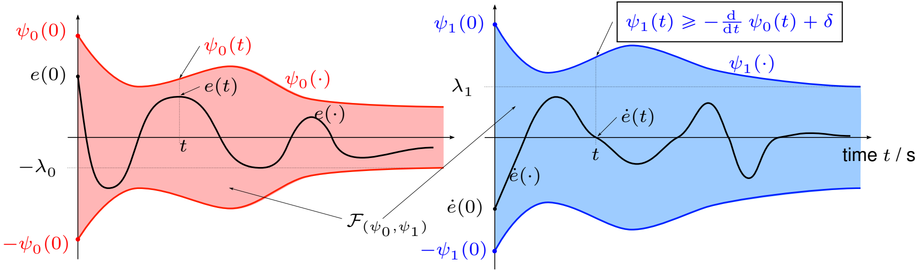
- Problem statement
  - Reference signals $(\omega_{\mathrm{ref}}, x_{\mathrm{ref}}, y_{\mathrm{ref}}) : \mathbb{R}_{>0} \to \mathbb{R}^3$
  - Precise position and speed control, i.e. for specified $\lambda > 0$

$$\boxed{\forall\, t \geqslant t_0 : \qquad |e(t)| = |y_{\mathrm{ref}}(t) - y(t)| \leqslant \lambda \text{ and (if feasible) } \lim_{t\to\infty} e(t) = 0.}$$

- Challenges
  - Nonlineare effects (e.g. actuator saturations, friction)
  - Disturbances and unknown system parameters (or only roughly known)

Problem statement and motivation

Reference tracking with prescribed accuracy: Funnel control with derivative feedback $(r = 2)$



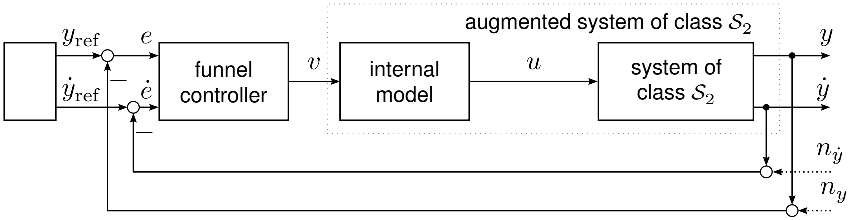
$$u(t) = \operatorname{sign}(\gamma_0)\Big(k_0(t)^2 e(t) + k_0(t)k_1(t)\dot{e}(t)\Big)$$

where $e(t) = y_{\mathrm{ref}}(t) - y(t)$ and $k_i(t) = \dfrac{\varsigma_i(t)}{\psi_i(t) - |e^{(i)}(t)|}, \quad i \in \{0, 1\}$

But how to achieve asymptotic accuracy? ... and why is it important?

Funnel control with internal model

Asymptotic accuracy feasible (i.e. $\lim_{t\to\infty} e(t) = 0$)



Example (Serial interconnection with internal model feasible)

- Constant reference, e.g. $y_{\mathrm{ref}}(t) = c > 0$:

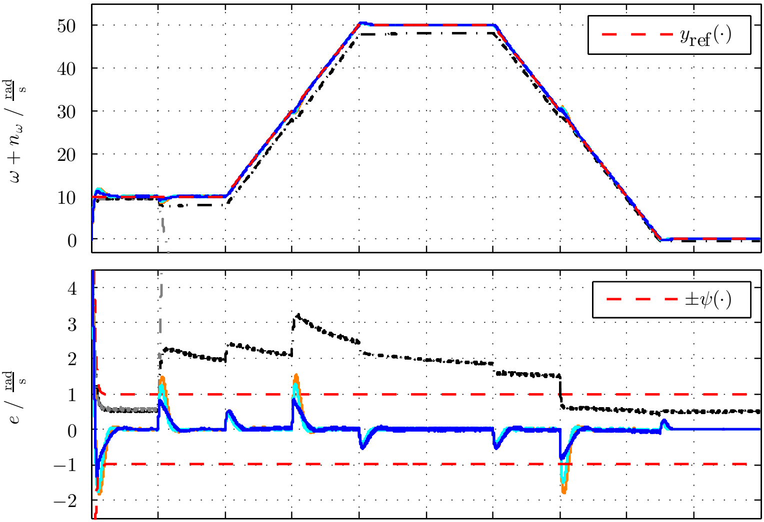
$$F_{IM}(s) = k_P + \frac{k_I}{s} = \frac{k_P\, s + k_I}{s}, \qquad k_P,\, k_I > 0$$

- Sinusoidal reference, e.g. $y_{\mathrm{ref}}(t) = \sin(2\pi f_0 t)$:

$$F_{IM}(s) = \frac{(s+k_C)^2}{s^2 + (2\pi f_0)^2}, \qquad k_C > 0$$

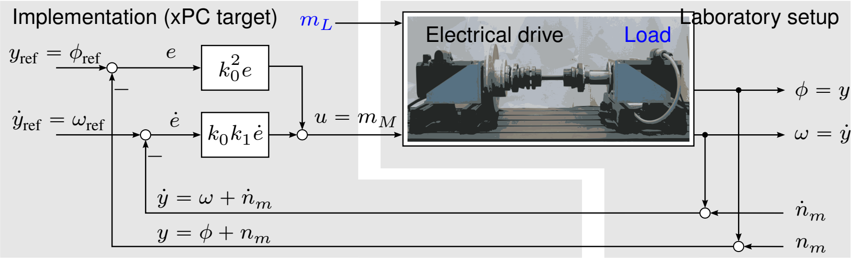
Funnel control with internal model

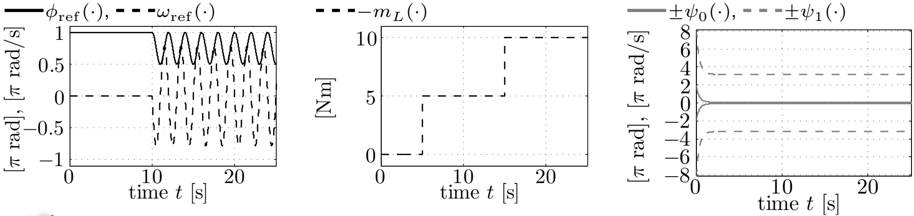
Error might leave funnel **without** internal model (measurements: - - - (FC); ━━ (FC)+(IM))



Funnel control with internal model

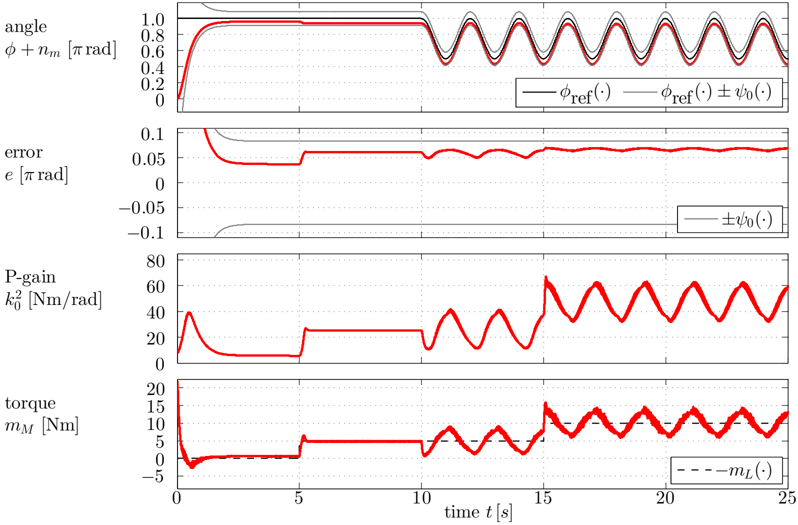
Position funnel control of industrial drives: Implementation [1, 2]





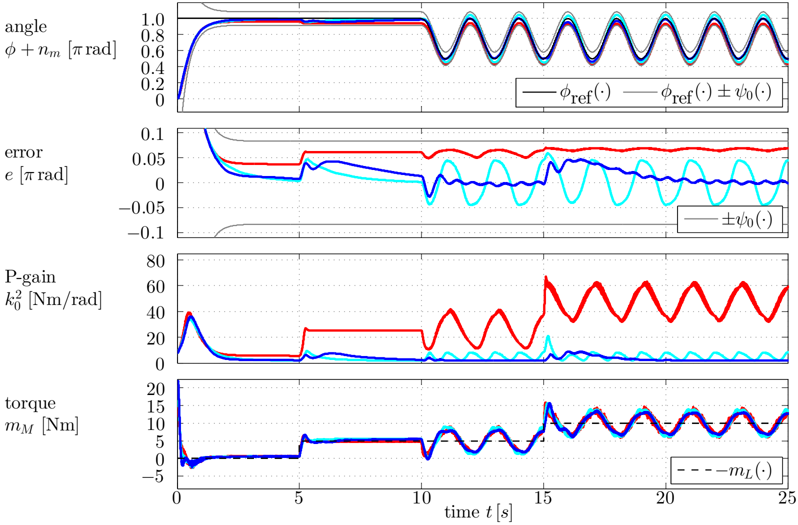
Funnel control with internal model

Measurement results ——(FC$_2$) [w/o internal model (IM)]



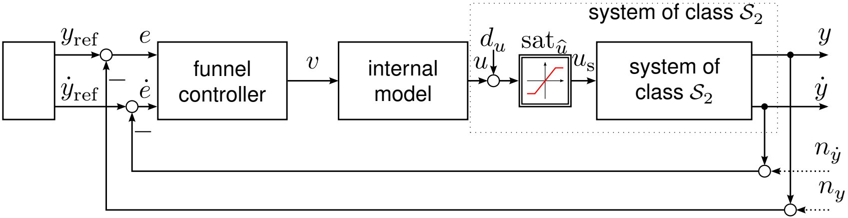
Funnel control with internal model

Measurement results —(FC$_2$), —(FC$_2$)+(PI), —(FC$_2$)+(IM) [with IM]



Funnel control with internal model & input constraints

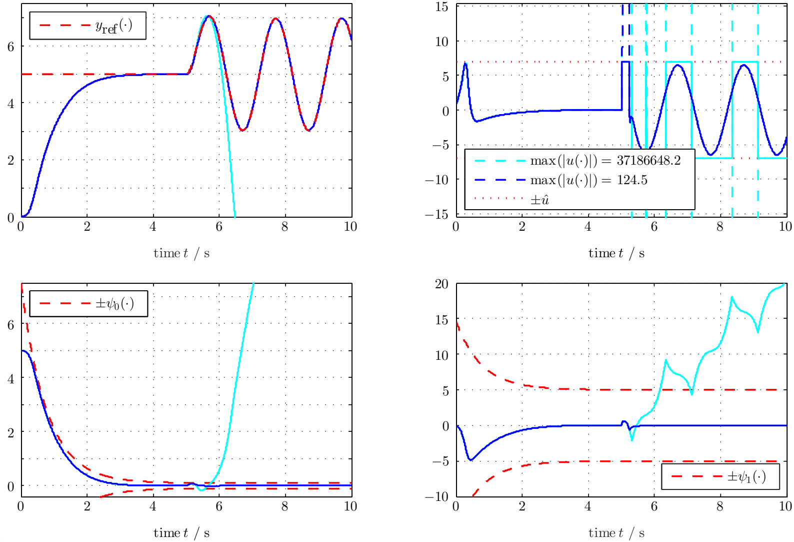
Feasible for **input-saturated systems**?



- Serial interconnection seperated by saturation block
- windup of states of internal model possible
- closed-loop system not necessarily stable (due to unbounded "input perturbation")

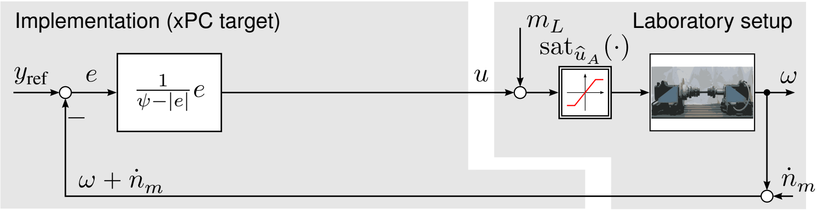
Funnel control with internal model & input constraints

Errors might leave funnel (simulation results (FC)+(IM) and (FC)+(IM)$^{\text{aw}}$)



Funnel control with internal model & input constraints

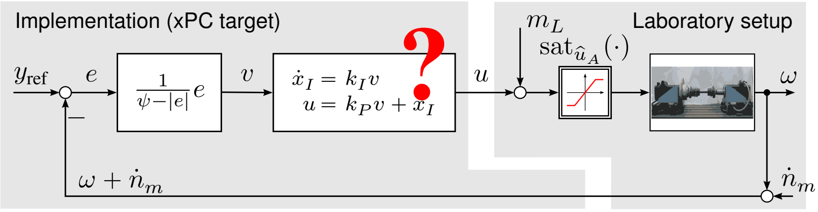
Funnel control in presence of input constraints [3, 4]



- $\widehat{u}_A \geqslant \widehat{u}_{\mathrm{feas}} = \widehat{u}_{\mathrm{feas}}(y_{\mathrm{ref}}, \psi, \text{system}, \dots) \implies \forall\, t \geqslant 0\colon\ \psi(t) - |e(t)| \geqslant \varepsilon$
- $\varepsilon \leqslant \min\left\{\frac{\lambda}{2},\ \psi(0) - |e(0)|,\ \frac{\lambda}{2(\hat{u}_A + \|m_L\|_\infty)}\right\}$
- $\widehat{u}_{\mathrm{feas}}$ conservative! (for laboratory setup $\widehat{u}_{\mathrm{feas}} \approx 63$ [Nm] and $\hat{u}_A = 22$ [Nm])

Funnel control with internal model & input constraints

PI-Funnel control in presence of input constraints

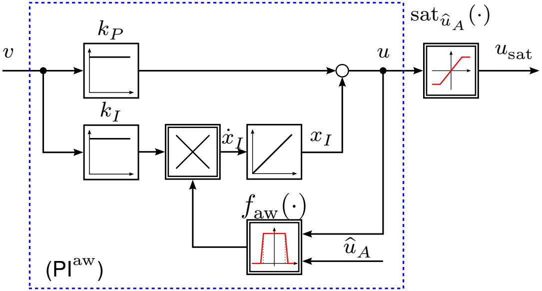


- Reference tracking with prescribed transient accuracy, i.e.

$$\cancel{\forall\, t \geqslant 0: \quad |e(t)| < \psi(t)} \qquad ?$$

Funnel control with internal model & input constraints

PI controller with anti-windup (“conditional integration”)



System theoretic interpretation:

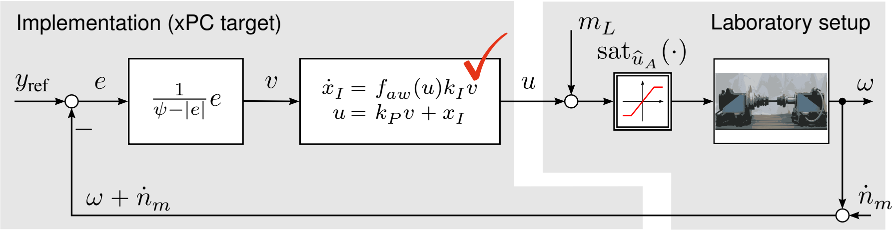
Lemma 1 (see [2, 5])

$$\forall\, v(\cdot) \in \mathcal{C}(\mathbb{R}_{>0};\mathbb{R}) \quad \Longrightarrow \quad \forall\, t \geqslant 0: \quad |x_I(t)| \leqslant \max\{\hat{u}_A,\, x_I(0)\} =: x_I^{\max}$$

$\Longrightarrow$ Anti-windup: $x_I(\cdot)$ acts like a **bounded “input perturbation”**

Funnel control with internal model & input constraints

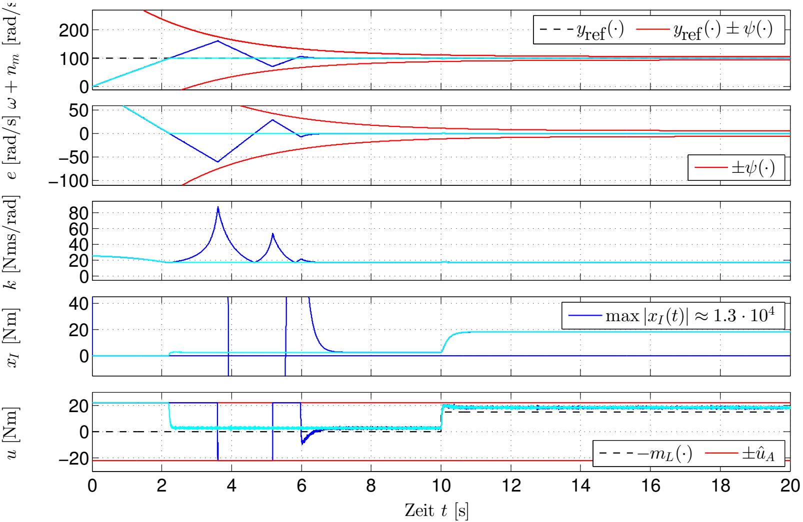
PI-funnel control with saturation



- $\hat{u}_A \geqslant \hat{u}_{\text{feas}} = \hat{u}_{\text{feas}}(y_{\text{ref}}, \psi, \text{system}, \dots) \implies \forall\, t \geqslant 0\colon\ \psi(t) - |e(t)| \geqslant \varepsilon$
- $\varepsilon \leqslant \min\left\{\frac{\lambda}{2},\ \psi(0) - |e(0)|,\ \frac{k_P \lambda}{2(\hat{u}_A + x_I^{\max} + \|m_L\|_\infty)}\right\}$
- $\hat{u}_{\text{feas}} \approx 63\ [\text{Nm}]$

Funnel control with internal model & input constraints

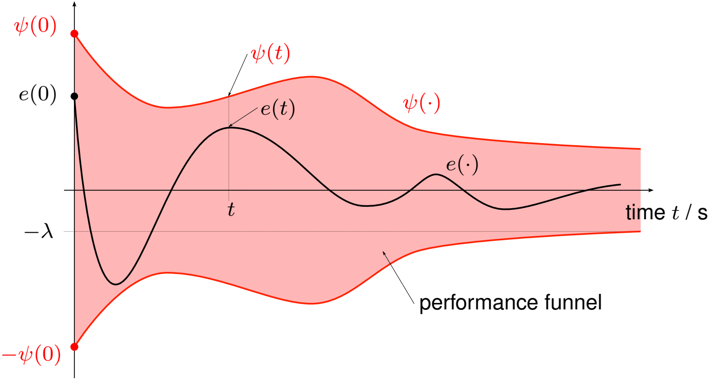
Measurement results: (FC)+(PI), (FC)+(PI$^{\mathrm{aw}}$)



Conclusion

Funnel control: Facts

- **simple** and **robust** controller
- Prescribed **transient accuracy** (→ funnel design)

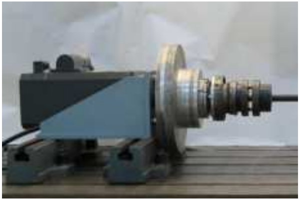


- **Asymptotic tracking** feasible (→ internal models, e.g. PI or sinusoidal IM)
- **Anti-windup** essential to guarantee stability for input-saturated systems

Conclusion

Funnel control: Successful real-world implementations [1, 2, 4–34]

Industrial drives



speed & position control

Industrial robots

position control

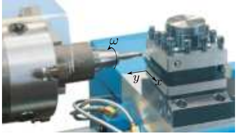
Wind turbine systems

speed control

Elastic drive trains

speed & position control + damping

Machine tools



speed & position control

Electrical machines

current control

References

Monograph published May 2017

References I

[1] Christoph M. Hackl and Ralph M. Kennel. Position funnel control with linear internal model. In *Proceedings of 2012 IEEE International Conference on Control Applications (CCA 2012)*, pages 1334–1339, Dubrovnik, Croatia, 2012.

[2] Christoph M. Hackl. *Non-identifier based adaptive control in mechatronics: Theory and Application*. Number 466 in Lecture Notes in Control and Information Sciences. Springer International Publishing, Berlin, 2017.

[3] Norman Hopfe, Achim Ilchmann, and Eugene P. Ryan. Funnel control with saturation: Nonlinear SISO systems. *IEEE Transactions on Automatic Control*, 55(9):2177–2182, 2010.

[4] Christoph M. Hackl, Norman Hopfe, Achim Ilchmann, Markus Mueller, and Stephan Trenn. Funnel control for systems with relative degree two. *SIAM Journal on Control and Optimization*, 51(2):965–995, 2013.

[5] Christoph M. Hackl. PI-funnel control with Anti-windup and its application for speed control of electrical drives. In *Proceedings of the 52nd IEEE Conference on Decision and Control (CDC)*, pages 6250–6255, Florence, Italy, 2013.

[6] Hans Schuster, Christian Westermaier, and Dierk Schröder. High-gain control of systems with arbitrary relative degree: Speed control for a two mass flexible servo system. In *Proceedings of the 8th IEEE International Conference on Intelligent Engineering Systems*, pages 486–491, Cluj-Napoca, Romania, 2004.

[7] Hans Schuster, Christoph M. Hackl, Christian Westermaier, and Dierk Schröder. Funnel-control for electrical drives with uncertain parameters. In *Proceedings of the 7th International Power Engineering Conference (IPEC)*, pages 15–22, Singapore, 2005.

References II

[8] Hans Schuster, Christian Westermaier, and Dierk Schröder. Non-identifier-based adaptive control for a mechatronic system achieving stability and steady state accuracy. In *Proceedings of the Joint CCA, ISIC and CACSD*, pages 1819–1824, Munich, Germany, 2006.

[9] Hans Schuster, Christian Westermaier, and Dierk Schröder. Non-identifier-based adaptive speed control for a two-mass flexible servo system: Consideration of stability and steady state accuracy. In *Proceedings of the 14th Mediterranean Conference on Control and Automation*, pages 1–6, Ancona, Italy, 2006.

[10] Hans Schuster, Christian Westermaier, and Dierk Schröder. Non-identifier-based adaptive tracking control for a two-mass system. In *Proceedings of the International Conference on Intelligent Engineering Systems (INES)*, pages 190–195, London, United Kingdom, 2006.

[11] Christoph M. Hackl and Dierk Schröder. Funnel-control for nonlinear multi-mass flexible systems. In *Proceedings of the 32nd Annual Conference on IEEE Industrial Electronics*, pages 4707–4712, 2006.

[12] Christoph M. Hackl, Hans Schuster, Christian Westermaier, and Dierk Schröder. Funnel-control with integrating prefilter for nonlinear, time-varying two-mass flexible servo systems. In *Proceedings of the 9th International Workshop on Advanced Motion Control*, pages 456–461, Istanbul, Turkey, 2006.

[13] Christoph M. Hackl, Yang Ji, and Dierk Schröder. Enhanced funnel-control with improved performance. In *Proceedings of the 15th Mediterranean Conference on Control and Automation*, pages Paper T01–016, Athens, Greece, 2007.

[14] Christoph M. Hackl, Yang Ji, and Dierk Schröder. Funnel-control with constrained control input compensation. In *Proceedings of the 9th IASTED International Conference CONTROL AND APPLICATIONS*, pages 147–152, Montreal, Quebec, Canada, 2007.

References III

[15] Christoph M. Hackl and Dierk Schröder. Funnel-control with online foresight. In *Proceedings of the 26th IASTED International Conference MODELLING, IDENTIFICATION AND CONTROL*, pages 171–176, Innsbruck, Austria, 2007.

[16] Christoph M. Hackl, Yang Ji, and Dierk Schröder. Nonidentifier-based adaptive control with saturated control input compensation. In *Proceedings of the 15th Mediterranean Conference on Control and Automation*, pages Paper T01–15, Athens, Greece, 2007.

[17] Christoph M. Hackl, Christian Endisch, and Dierk Schröder. Applicability of funnel-control in robotics. In *Proceedings of the 5th International Conference on Computational Intelligence, Robotics and Autonomous Systems*, pages 65–70, Linz, Austria, 2008.

[18] Christoph M. Hackl, Christian Endisch, and Dierk Schröder. Error reference control of nonlinear two-mass flexible servo systems. In *Proceedings of the 16th Mediterranean Conference on Control and Automation*, pages 1047–1053, Ajaccio, France, 2008.

[19] Christoph M. Hackl, Christian Endisch, and Dierk Schröder. Funnel-control in robotics: An introduction. In *Proceedings of the 16th Mediterranean Conference on Control and Automation*, pages 913–919, Ajaccio, France, 2008.

[20] Christoph M. Hackl, Christian Endisch, and Dierk Schröder. Specially designed funnel-control in mechatronics. In *Proceedings of the 5th International Conference on Computational Intelligence, Robotics and Autonomous Systems*, pages 59–64, 2008.

[21] Christoph M. Hackl and Dierk Schröder. Non-identifier based adaptive control in robotics: An introduction. *International Journal of Factory Automation, Robotics and Soft Computing*, 4:90–99, 2008.

References IV

[22] Christoph M. Hackl, Christian Endisch, and Dierk Schröder. Contributions to non-identifier based adaptive control in mechatronics. *Robotics and Autonomous Systems, Elsevier*, 57(10):996–1005, 2009.

[23] Hans Schuster. *Hochverstärkungsbasierte Regelung nichtlinearer Antriebssysteme*. PhD thesis, Lehrstuhl für Elektrische Antriebssysteme, Technische Universität München (TUM), Germany, 2009.

[24] Christoph M. Hackl and Dierk Schröder. Non-identifier based adaptive control in robotics: An introduction. In Salvatore Pennacchio, editor, *Recent adavances in Control Systems, Robotics and Automation*, volume 1. INTERNATIONALSAR International Society for Advanced Research, Palermo, Italy, third edition, 2009.

[25] Christoph M. Hackl. Funnel Control: Implementierung, Erweiterung und Anwendung. In Dierk Schröder, editor, *Intelligente Verfahren: Systemidentifikation und Regelung nichtlinearer Systeme*, pages 697–760. Springer-Verlag, Berlin, 2010.

[26] Achim Ilchmann and Hans Schuster. PI-funnel control for two mass systems. *IEEE Transactions on Automatic Control*, 54(4):918–923, 2009.

[27] Christoph M. Hackl, Andreas G. Hofmann, Rik W. De Doncker, and Ralph M. Kennel. Funnel control for speed & position control of electrical drives: A survey. In *Proceedings of the 19th Mediterranean Conference on Control and Automation*, pages 181–188, Corfu Island, Greece, 2011.

[28] Christoph M. Hackl, Andreas G. Hofmann, and Ralph M. Kennel. Funnel control in mechatronics: An overview. In *Proceedings of the 50th IEEE Conference on Decision and Control (CDC) and European Control Conference (ECC)*, pages 8000–8007, Orlando, FL, USA, 2011.

References V

[29] Christoph M. Hackl. 'Funnel control' zur Positionsregelung von starren Drehgelenkrobotern mit grob bekannter Trägheitsmatrix. In *Tagungsband des GMA-Fachausschuss 1.40*, pages 302–310, Anif, Austria, 2012.

[30] Christoph M. Hackl and Ralph M. Kennel. Position funnel control for rigid revolute joint robotic manipulators with known inertia matrix. In *Proceedings of the 20th Mediterranean Conference on Control and Automation*, pages 615–620, Barcelona, Spain, 2012.

[31] Christoph M. Hackl. Funnel control with disturbance observer for two-mass systems. In *Proceedings of the 52nd IEEE Conference on Decision and Control (CDC)*, pages 6244–6249, Florence, Italy, 2013.

[32] Christoph M. Hackl. Funnel control for wind turbine systems. In *Proceedings of the 2014 IEEE International Conference on Control Applications (CCA 2014)*, pages 1377–1382, Antibes, France, 2014.

[33] Christoph M. Hackl. Current PI-funnel control with anti-windup for synchronous machines. In *Proceedings of the 54th IEEE Conference on Decision and Control (CDC 2015)*, pages 1997–2004, Osaka, Japan, 2015.

[34] Christoph M. Hackl. Speed funnel control with disturbance observer for wind turbine systems with elastic shaft. In *Proceedings of the 54th IEEE Conference on Decision and Control (CDC 2015)*, pages 2005–2012, Osaka, Japan, 2015.