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Energy Systems
(LMRES)

Funnel control with internal model and anti-windup for input-saturated mechatronic systems

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13.09.2022 – MTNS 2022, Bayreuth, Germany

Outline

1 Problem statement and motivation

2 Funnel control with internal model

3 Funnel control with internal model and input constraints

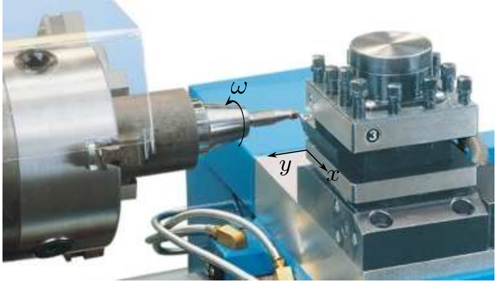
4 Conclusion

Outline

1 Problem statement and motivation

Problem statement and motivation

Reference tracking under load (e.g., CNC turning machine under speed and position control)



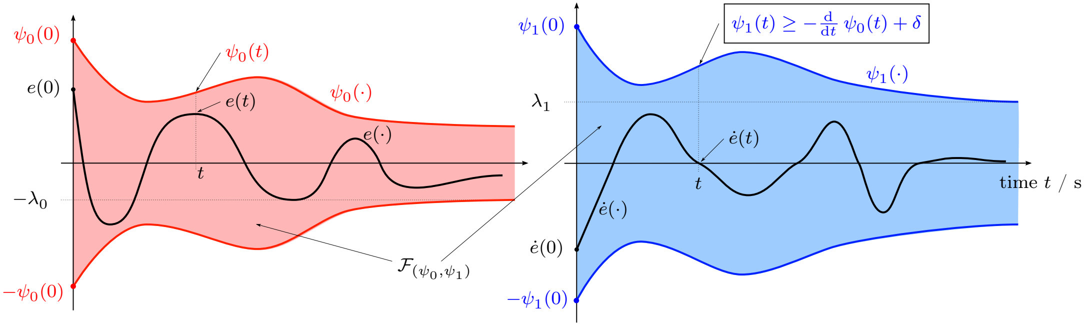
- Problem statement
  - Reference signals $(\omega_{\mathrm{ref}}, x_{\mathrm{ref}}, y_{\mathrm{ref}}) \colon \mathbb{R}_{\geqslant 0} \to \mathbb{R}^3$
  - Precise position and speed control, i.e. for specified $\lambda > 0$

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

- Challenges
  - Nonlinear effects (e.g. actuator saturations, friction)
  - Disturbances and unknown system parameters (or only roughly known)
  - **Noise**, **sampling** and **input-constraints** (as we will see later)!!!

Problem statement and motivation

Reference tracking with prescribed accuracy: Funnel control with derivative feedback ($r = 2$; e.g., position control)



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

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

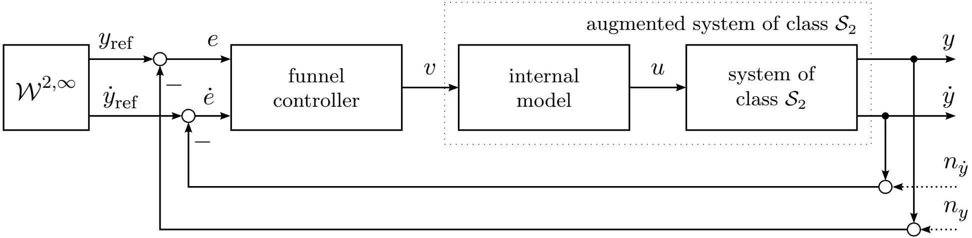
But how to achieve asymptotic accuracy? ... and why is it important?

Outline

2 Funnel control with internal model

Funnel control with internal model

Asymptotic accuracy feasible and very desirable (i.e. $\lim_{t\to\infty} e(t) = 0$ [hard to prove!])



Example (Serial interconnection with internal model feasible (& very simple!))

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

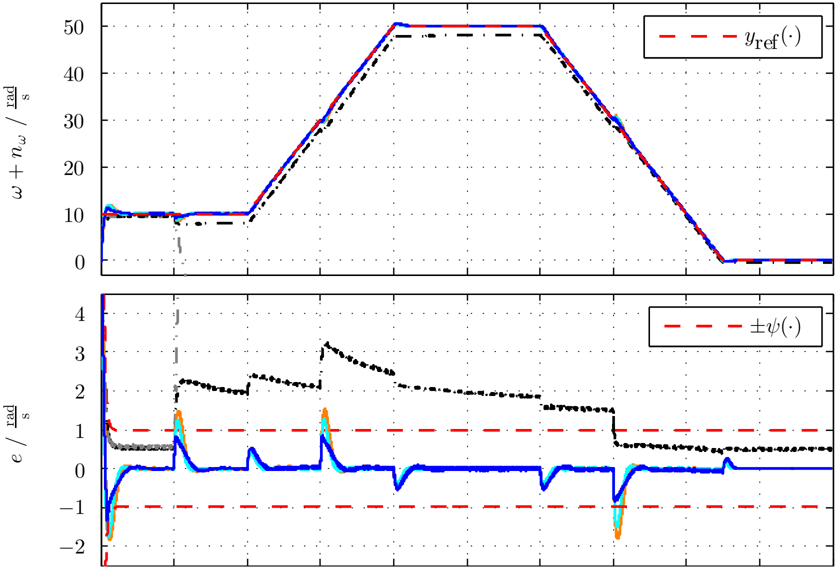
$$F_{IM}(s) = k_P + \frac{k_I}{s} = \frac{k_P\, s + k_I}{s}, \qquad k_P,\, k_I > 0$$

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

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

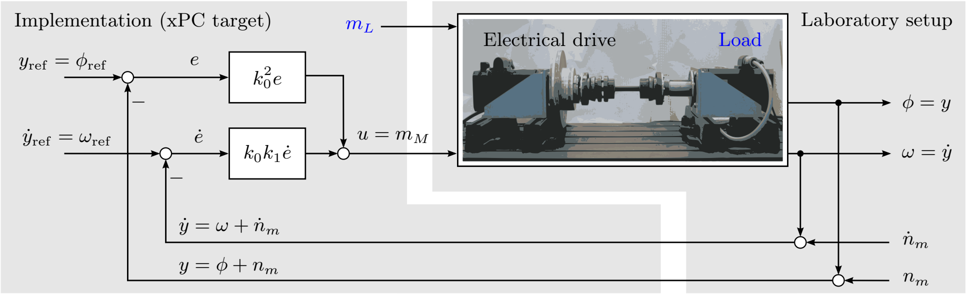
Funnel control with internal model

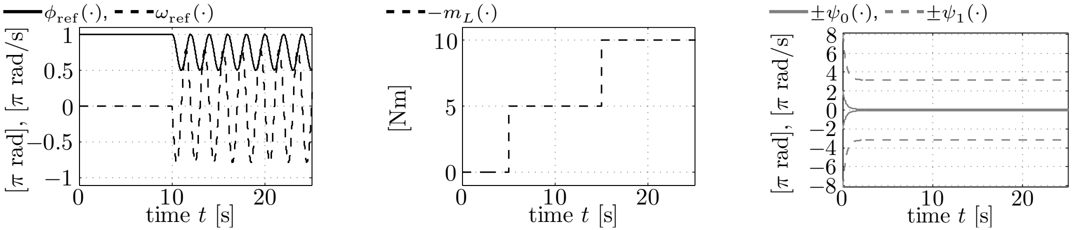
Error might leave funnel **without** internal model due to **noise** and **sampling** (measurements: - - - (FC); ▬▬ (FC)+(IM))



Funnel control with internal model

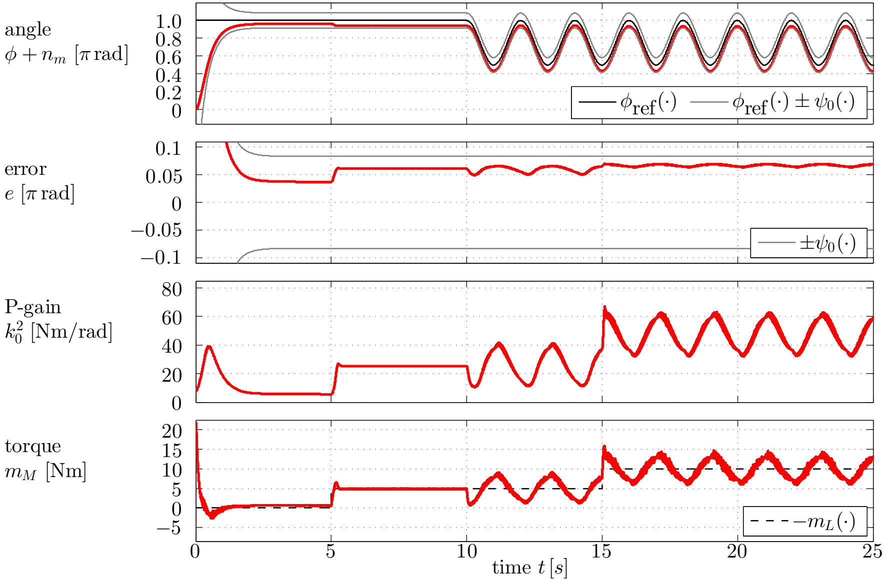
Position funnel control of industrial drives: Implementation [1, 2]





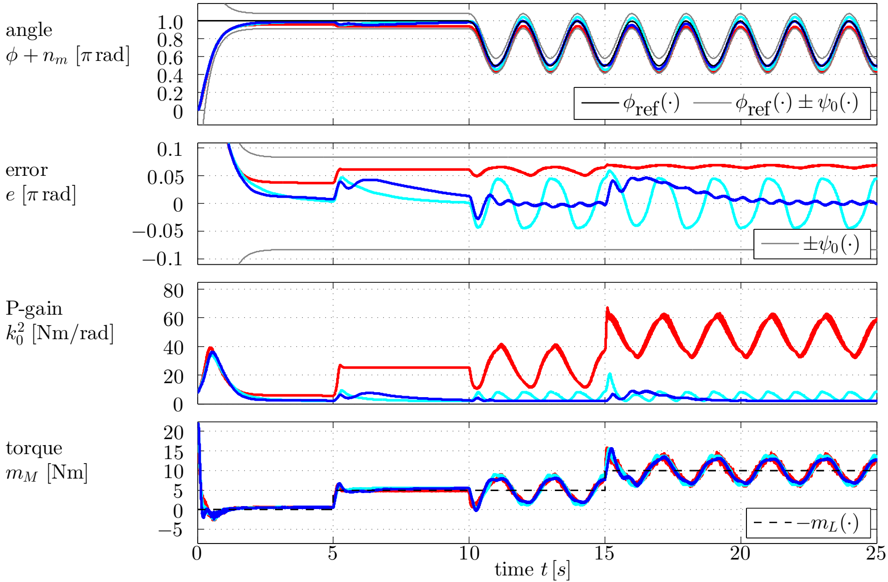
Funnel control with internal model

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 integral and sinusoidal IM]

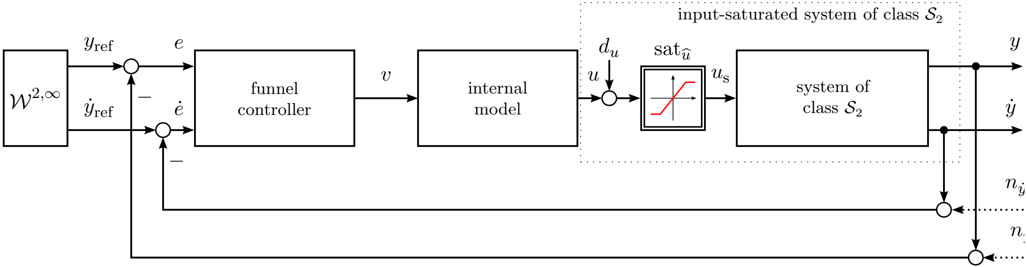


Outline

3 Funnel control with internal model and input constraints

Funnel control with internal model & input constraints

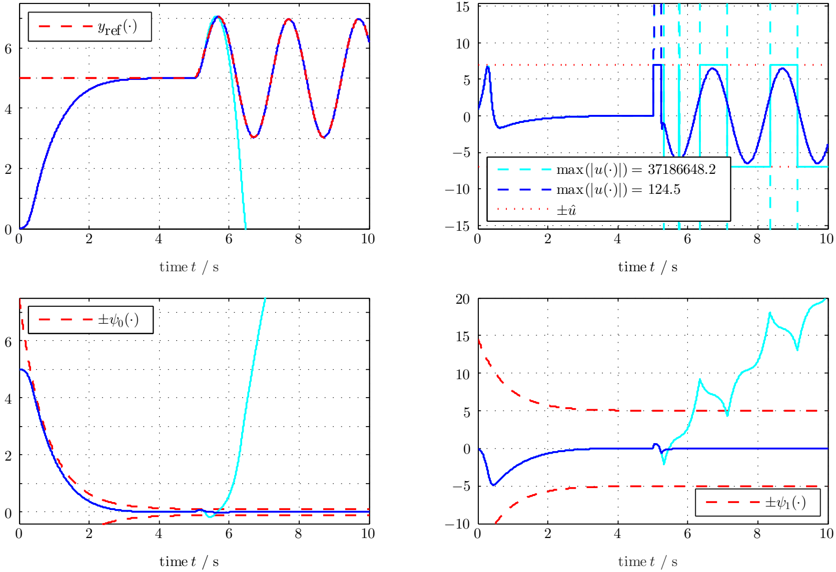
Feasible for **input-saturated systems**?



- Serial interconnection seperated by saturation block
- windup of states of internal model possible (and usually very likely!)
- closed-loop system not necessarily stable (due to unbounded “input perturbation” during windup)

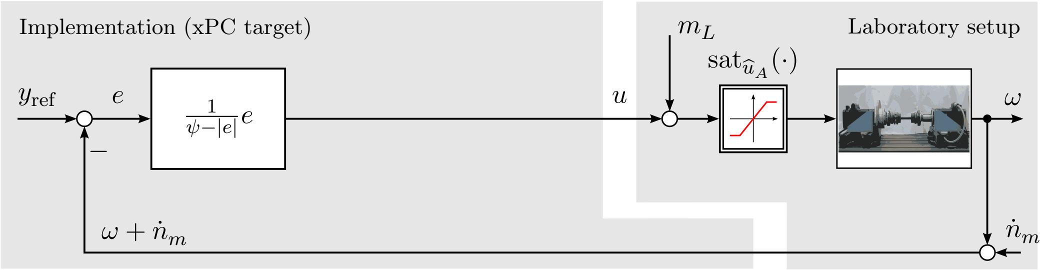
Funnel control with internal model & input constraints

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



Funnel control with internal model & input constraints

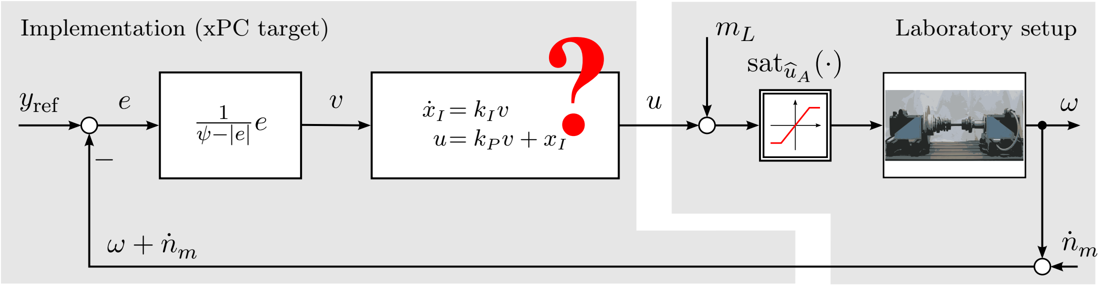
Funnel control in presence of input constraints (e.g., speed control with $r = 1$) [3, 4]



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

Funnel control with internal model & input constraints

PI-Funnel control in presence of input constraints [e.g. speed control ($r = 1$)]

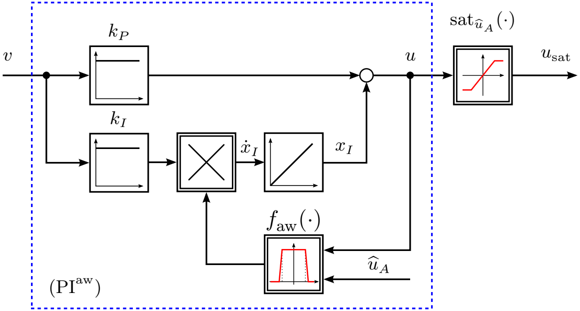


- Reference tracking with prescribed transient accuracy, i.e.

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

Funnel control with internal model & input constraints

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



System theoretic interpretation:

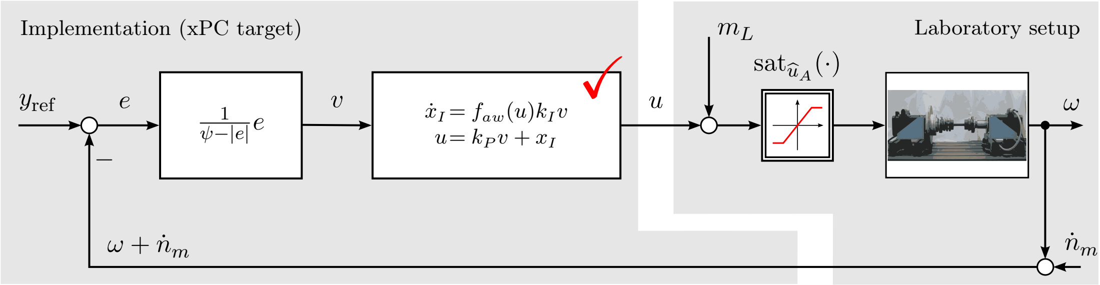
Lemma 1 (see [2, 5])

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

$\Longrightarrow$ Anti-windup: $x_I(\cdot)$ acts like a **bounded “input perturbation”**
($\Longrightarrow$ Similar results for anti-windup of general internal models (see [2, Chap. 10])

Funnel control with internal model & input constraints

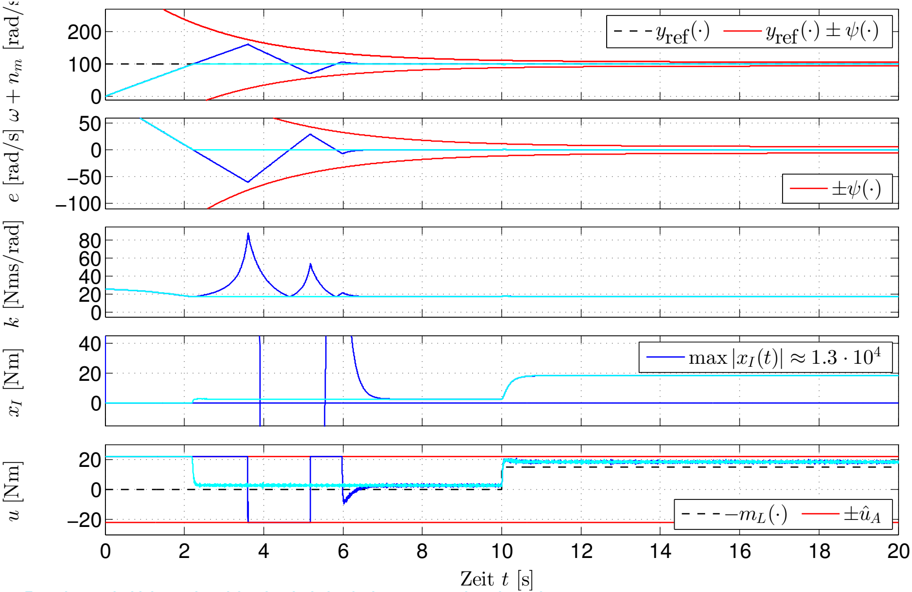
PI-funnel control with saturation



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

Funnel control with internal model & input constraints

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



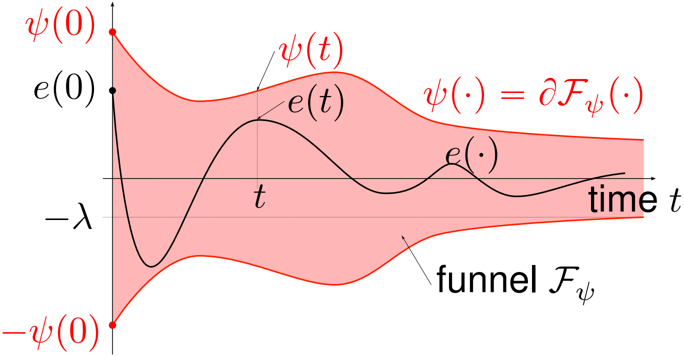
Outline

4 Conclusion

Conclusion

Funnel control: Facts

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

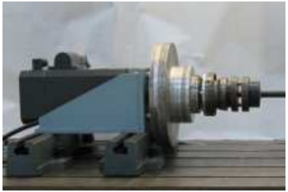


- **Asymptotic tracking** feasible (→ internal models **crucial**, e.g. PI or sinusoidal IM or combinations)
- **Anti-windup** for IM **essential** to guarantee stability for input-saturated systems

Conclusion

Funnel control: Successful real-world implementations (all meaningful **with** IM!) [1, 2, 4–34]

Industrial drives



speed & position control

Industrial robots

position control

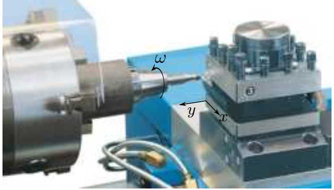
Wind turbine systems

speed control

Elastic drive trains

speed & position control + damping

Machine tools



speed & position control

Electrical machines

current control

References

Monograph [2] (published May 2017; doi: 10.1007/978-3-319-55036-7)

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, oct 2012. Institute of Electrical and Electronics Engineers (IEEE).

[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, sep 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, jan 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, dec 2013. Institute of Electrical and Electronics Engineers (IEEE).

[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 Michael Hackl, Christian Westermaier, and Dierk Schröder. Funnel-control for electrical drives with uncertain parameters. In *Proceedings of the 7th International Power Engineering Conference*, Singapore, 2005.

[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, oct 2006. Institute of Electrical and Electronics Engineers (IEEE).

[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, jun 2006. Institute of Electrical and Electronics Engineers (IEEE).

References II

[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 Michael 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, Paris, France, 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. Institute of Electrical and Electronics Engineers (IEEE).

[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, jun 2007. Institute of Electrical and Electronics Engineers (IEEE).

[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.

[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, jun 2007. Institute of Electrical and Electronics Engineers (IEEE).

[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, jun 2008. Institute of Electrical and Electronics Engineers (IEEE).

References III

[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, jun 2008. Institute of Electrical and Electronics Engineers (IEEE).

[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.

[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, 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, apr 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 & Automation (MED)*, pages 181–188, Corfu Island, Greece, jun 2011. Institute of Electrical and Electronics Engineers (IEEE).

[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, dec 2011. Institute of Electrical and Electronics Engineers (IEEE).

References IV

[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, jul 2012. Institute of Electrical and Electronics Engineers (IEEE).

[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, dec 2013. Institute of Electrical and Electronics Engineers (IEEE).

[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, oct 2014. Institute of Electrical and Electronics Engineers (IEEE).

[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, dec 2015. Institute of Electrical and Electronics Engineers (IEEE).

[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.