Ruhr-Universität Bochum
Institute of Automation and Computer Control
Prof. Dr.-Ing. J. Lunze

Universitätsstrasse 150
D-44805 Bochum, Germany

Phone +49 - (0)234 32 - 28071
Fax +49 - (0)234 32 - 14101

Reconfigurable Control of Hammerstein-Wiener Systems after Actuator and Sensor Faults

Dipl.-Ing. Jan Richter
richter@atp.rub.de

1 Introduction

The autonomous control reconfiguration of automatic control loops after actuator faults is a key problem in fault-tolerant control that addresses component failures [1, 2]. Control reconfiguration must autonomously find a new controller after the occurrence of a fault or failure, such that the reconfigured closed loop approximately satisfies the original set of control specifications. In this project, the fault-hiding approach is generalised from linear systems towards Hammerstein-Wiener (HW) systems for actuator and sensor faults.

2 Reconfigurable control problem and approach

In this project, the control reconfiguration problem is solved for systems with linear dynamics and static input- and output-nonlinearities $\boldsymbol{\varphi}$ and $\boldsymbol{h}$, namely for Hammerstein-Wiener systems

$$\Sigma_P : \begin{cases} \dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{\varphi}(\boldsymbol{u}(t)) + \boldsymbol{B}_{\boldsymbol{d}}\boldsymbol{d}(t), \ \boldsymbol{x}(0) = \boldsymbol{x}_0 \\ \boldsymbol{y}(t) = \boldsymbol{h}(\boldsymbol{C}\boldsymbol{x}(t)). \end{cases} \tag{1}$$

Most technological systems are subjected to actuation range limits modelled as saturations. The input characteristic $\boldsymbol{\varphi}$ represents static nonlinear behaviour, in particular actuator constraints.

The occurrence of actuator or sensor faults changes the nominal Hammerstein-Wiener system to the faulty Hammerstein-Wiener system

$$\Sigma_{Pf} : \begin{cases} \dot{\boldsymbol{x}}_f(t) = \boldsymbol{A}\boldsymbol{x}_f(t) + \boldsymbol{B}_f\boldsymbol{\varphi}_f(\boldsymbol{u}_f(t)) + \boldsymbol{B}_{\boldsymbol{d}}\boldsymbol{d}(t), \ \boldsymbol{x}_f(0) = \boldsymbol{x}_0 \\ \boldsymbol{y}_f(t) = \boldsymbol{h}_f(\boldsymbol{C}_f\boldsymbol{x}_f(t)). \end{cases} \tag{2}$$

By virtue of changed input and output matrices ($\boldsymbol{B}_f$, $\boldsymbol{C}_f$) and characteristics ($\boldsymbol{\varphi}$, $\boldsymbol{h}$), degraded and failed actuators, degraded and failed sensors, and reduced actuation ranges can be represented. The pursued reconfiguration goals are stability recovery, setpoint tracking recovery, and optimal performance recovery.

The reconfiguration block $\Sigma_R = (\Sigma_S, \Sigma_A)$ is realised by means of an interconnection of a HW virtual sensor Σ_S and a HW virtual actuator Σ_A, as shown in Figure 1. Synthesis methods for determining stabilising gains $\boldsymbol{M}$, $\boldsymbol{N}$, and $\boldsymbol{L}$ are provided in [3]. The synthesis procedure is based on absolute stability theory and sector bounds for the input characteristic $\boldsymbol{\varphi}_f$ and the output characteristic $\boldsymbol{h}_f$.

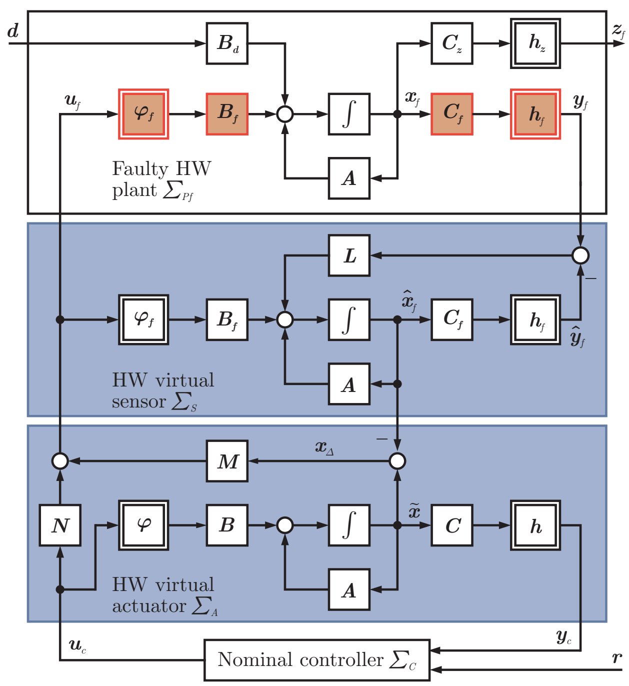

Figure 1: Hammerstein-Wiener virtual sensor and virtual actuator.

3 Actuator faults in Hammerstein systems

The special case of Hammerstein systems ($\boldsymbol{h}(\boldsymbol{x}) = \boldsymbol{x}$) and pure actuator faults ($\boldsymbol{h}_f = \boldsymbol{h}$, $\boldsymbol{C}_f = \boldsymbol{C}$) leads to a simplified reconfiguration block, namely a Hammerstein virtual actuator (Figure 2) that reflects the nonlinear input characteristic of the plant. The reconfigured plant hides the fault from the controller, and the loop stabilisation problem is separated into the independent nominal loop stability problem, and the stabilisation problem of the difference system. For this type of system, the following results have been proven [3–5]:

- stability recovery,
- setpoint tracking recovery (for saturated systems),
- optimal performance recovery (for saturated systems),
- robustness against model uncertainty,
- state-feedback universality.

ciently robust to be applicable to the real process. In summary, the Hammerstein virtual actuator improves considerably upon the results achievable using a linear virtual actuator [3, 6–8].

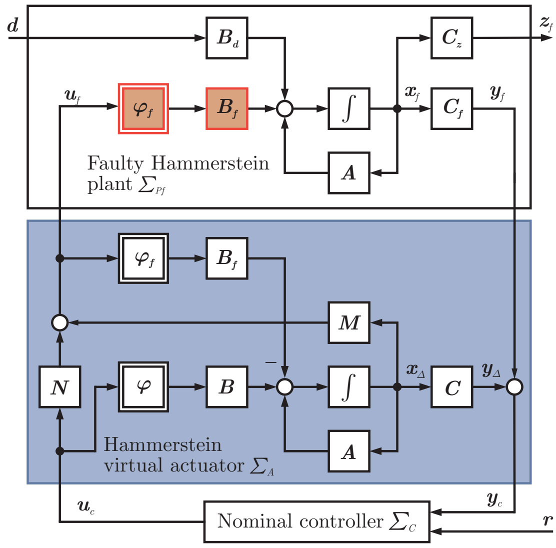

Figure 2: Hammerstein virtual actuator.

4 Sensor faults in Hammerstein-Wiener systems

The special case of Hammerstein-Wiener systems subject to pure sensor faults ($\boldsymbol{\varphi}_f = \boldsymbol{\varphi}$, $\boldsymbol{B}_f = \boldsymbol{B}$) leads to a simplified reconfiguration block, namely a Hammerstein-Wiener virtual sensor (Figure 3) that reflects all nonlinear characteristic of the plant. The following results have been proven [3]:

- stability recovery,
- robustness against model uncertainty,
- output-injection universality.

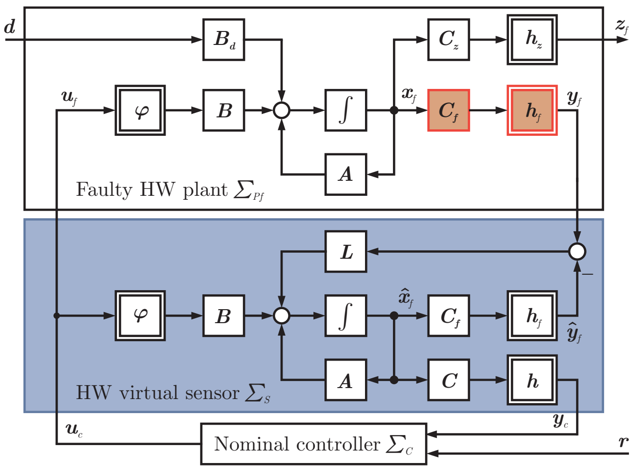

Figure 3: Hammerstein-Wiener virtual sensor.

5 Experiments: thermofluid process

The result of an experimental application of the Hammerstein virtual actuator to the reconfiguration of the thermofluid process subject to valve failure is shown in Figure 4. Clearly, all three output variables (ϑ_{TS}, l_{TS}, and ν_{TS}, shown in solid) attain their setpoints (shown in dashed) with good dynamical transient properties, and without violating physical safety constraints (shown as grey shaded areas). The new methods offers adequately accounts for the actuator saturations, and it is suffi-

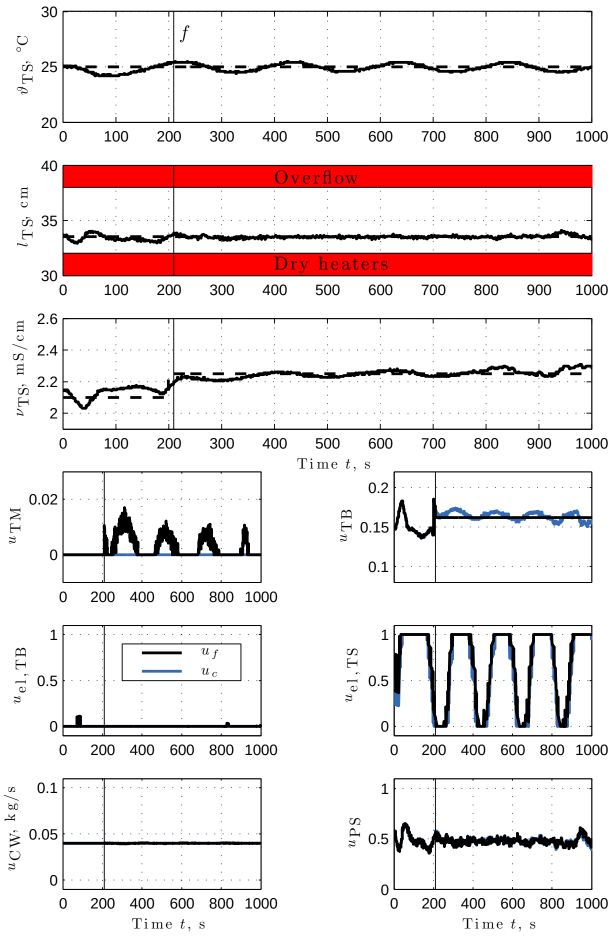

Figure 4: Experimental reconfiguration after valve failure.

References

[1] M. Blanke, M. Kinnaert, J. Lunze, and J. Staroswiecki. *Diagnosis and Fault-Tolerant Control*. Springer Verlag, Heidelberg, 2nd edition, 2006.

[2] J. Lunze and J. H. Richter. Reconfigurable fault-tolerant control: a tutorial introduction. *European J. Control*, 14(5):359–386, 2008.

[3] J. H. Richter. *Reconfigurable Control of Nonlinear Dynamical Systems – a fault-hiding approach*. PhD thesis, Fakultät für Elektrotechnik und Informationstechnik, Ruhr-Universität Bochum, 2009. Submitted.

[4] J. H. Richter and J. Lunze. Reconfigurable control of Hammerstein systems after actuator faults. In *Proc. 17th IFAC World Congress*, pages 3210–15, Seoul, Korea, July 2008.

[5] J. H. Richter and J. Lunze. Reconfigurable control of Hammerstein systems after actuator failures: stability and tracking, 2009. In preparation.

[6] J. H. Richter, T. Schlage, and J. Lunze. Control reconfiguration of a thermofluid process by means of a virtual actuator. *IET Control Theory Appl.*, 1(6):1606–20, November 2007.

[7] C. Ortmann. Anwendung des virtuellen Aktors auf einen nichtlinearen thermofluiden Prozess. Studienarbeit, Lehrstuhl für Automatisierungstechnik und Prozessinformatik, Fakultät für Elektrotechnik und Informationstechnik, Ruhr-Universität Bochum, October 2007. ATP 0046.

[8] D. Meyer. Virtueller Aktor für Hammerstein-Systeme: Sollwertfolge und Übergangsverhalten. Studienarbeit, Lehrstuhl für Automatisierungstechnik und Prozessinformatik, Fakultät für Elektrotechnik und Informationstechnik, Ruhr-Universität Bochum, August 2008. ATP 0056.