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

# What is Reconfigurable Control?

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

## 1 Introduction

The recently increasing complexity of man-made systems increases their vulnerability for faults and malfunctions. At the same time, requirements for system dependability are surging as a consequence of, for example, tightening environmental regulations. Maintaining system dependability at required levels by improving individual components is challenging and expensive. Feedback control is an ideal technology for increasing the system dependability. *Control reconfiguration* denotes a class of solutions to the fault-tolerant control problem, where the closed-loop structure and the controller dynamics are actively adjusted in response to component malfunctions. The goal of the control reconfiguration consists in preventing component-level faults and failures into system-level failures.

## 2 Fault-tolerant control

*Fault-tolerant control (FTC)* describes techniques for adapting control loops to faulty plants by suitable use of the available redundancy [1]. It aims at preventing component faults, component failures or subsystem faults from causing system failures. *Passive FTC*, such as robust control, denotes techniques to let the controller tolerate a set of possible faults. However, the set of faults that can be tolerated without active controller re-adjustment is usually limited.
*Active FTC* denotes techniques to achieve fault tolerance by changing the control loop after fault-time (Figure 1). *Fault diagnosis* (FDI) seeks to find out whether the plant is subjected to a fault and to identify the fault. The fault diagnosis step is followed by a controller adjustment step, called *control reconfiguration*.

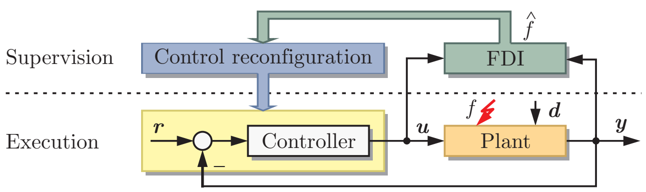


Figure 1: Active fault-tolerant control scheme.

## 3 Reconfigurable control problem

Control reconfiguration changes both the loop structure and the controller dynamics in response to faults. After reconfiguration, the signals measured and manipulated by the controller and the controller dynamics are adjusted to the current fault [2].

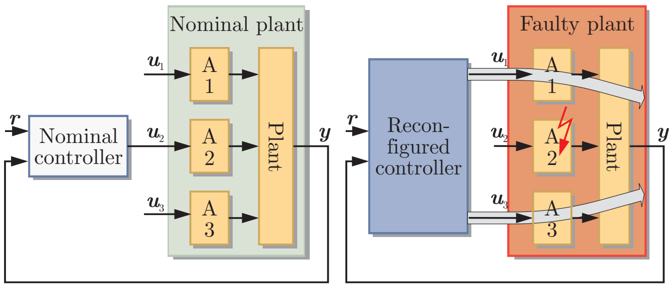


Figure 2: Control reconfiguration restructures the loop.

An important reconfiguration problem arises after actuator failures (Figure 2). Control reconfiguration must orchestrate the functioning actuators in order to replace the effect of faulty or failed actuators.

## 4 Fault-hiding framework

In the fault-hiding approach, the faulty closed-loop system is augmented by placing a reconfiguration block $\Sigma_R$ between faulty plant $\Sigma_{Pf}$ and controller $\Sigma_C$ (Figure 3). The basic approach is valid for actuator as well as sensor faults alike. By adequate choice of the reconfiguration block structure, the reconfigured plant $\Sigma_{Pr} = (\Sigma_{Pf}, \Sigma_R)$ is described by the same I/O model as the nominal plant. This property is called *fault-hiding*. The fault-hiding property permits the nominal controller to be kept in the reconfigured closed-loop system. From an implementation perspective, the interconnection $\Sigma_{Cr} = (\Sigma_R, \Sigma_C)$ is the reconfigured controller. Dual approaches for actuator and sensor faults in linear systems based on fault-hiding were developed in [9].

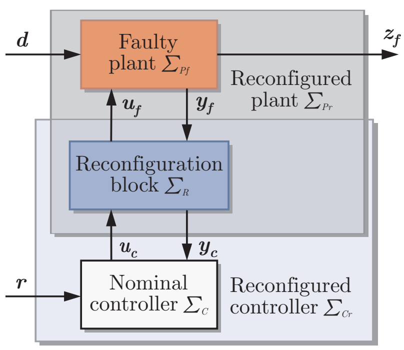


Figure 3: Reconfiguration block hiding faults from controller.

## 5 Results for actuator and sensor faults

The problem that must be solved consists in finding suitable structures for the reconfiguration block, and determining its free parameters. The general structure of the reconfiguration solution is shown in Figure 4. The reconfiguration block $\Sigma_R = (\Sigma_S, \Sigma_A)$ consists of a *virtual sensor* $\Sigma_S$ and a *virtual actuator* $\Sigma_A$.

The virtual sensor $\Sigma_S$ provides an estimate of the faulty plant state, which is used by the virtual actuator. The latter contains a reference model $\Sigma_{\tilde{P}}$ of the nominal plant $\Sigma_P$, and state feedback and control feedforward in order to keep the difference $\boldsymbol{x}_\Delta$ between nominal and faulty plant state small. In the case of linear or Hammerstein systems and pure actuator faults, the structure shown in Figure 4 is simplified by combining the virtual sensor and the virtual actuator dynamics into a single dynamical system.

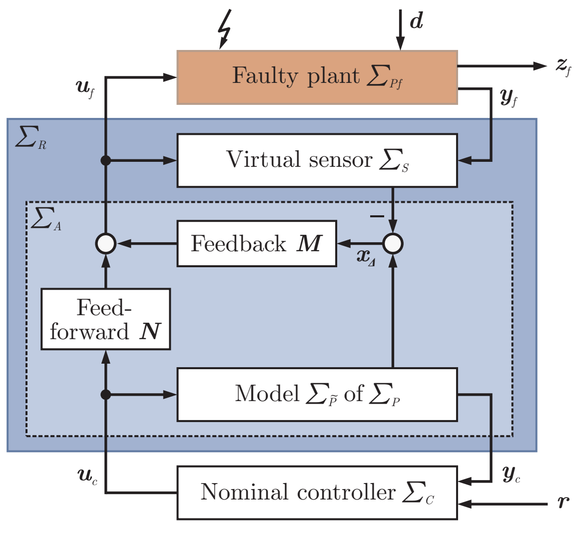


Figure 4: General structure of the reconfiguration block used in the fault-hiding approach.

The design of virtual actuators and virtual sensors has been solved for linear systems and two classes of nonlinear dynamical systems.

- **Linear systems:** Stability, setpoint tracking, optimal performance, and perfect performance recovery [3–5, 8, 9],
- **Hammerstein-Wiener systems:** Stability, setpoint tracking and optimal performance recovery [4],
- **Piecewise affine systems:** Stability and setpoint tracking recovery [4].

The linear virtual actuator has turned out to be a generalisation of the dual observer [6]. All mentioned methods have been successfully implemented and tested using the process described in the following section.

## 6 Experiments

Figure 5 shows the flow diagram of a continuous-flow thermofluid process used for the experimental evaluation of the fault-hiding approach. The process blends salt concentrate with fresh water for controlling conductivity $\nu_{TS}$, temperature $\vartheta_{TS}$, and level $l_{TS}$ in the reactor TS. The fault scenarios are combinations of the failure of the valve $u_{TB}$ ($f_1$), of the heater $u_{TS}$ ($f_2$), and of the pump $u_{PS}$ ($f_3$). All methods developed so far have been successfully applied to this process [7].

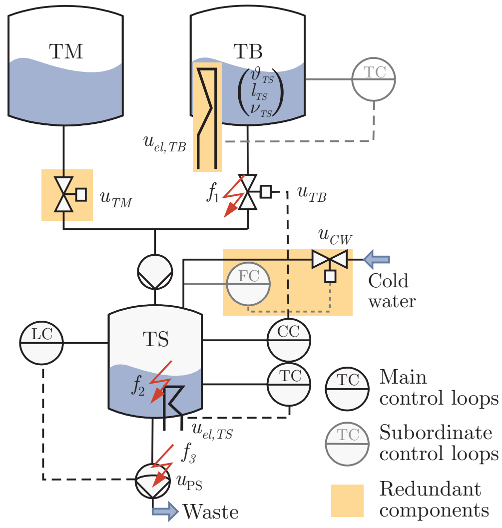


Figure 5: Thermofluid process for experiments.

## 7 Cooperation

This project is done in cooperation with Prof. M. Heemels, Prof. N. van de Wouw, and Prof. S. Weiland from Eindoven University of Technology (TU/e), The Netherlands.

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