CONTROL RECONFIGURATION

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Contents

Summary

This chapter explains methods for the automatic selection of a new control configuration after some fault has changed the dynamical properties of the plant. An automatic control system can use this method after severe faults have been detected in the plant by a monitoring algorithm. It chooses new actuators, new sensors, a new control law and possibly new set-points so as to stabilize the plant in the prescribed operation point under the influence of the fault.

1. Introduction

Controller reconfiguration considers the problem of automatically changing the control structure and the control law after a fault has occurred in the plant. The aim is to satisfy the given requirements on the closed–loop system despite of the faulty plant behavior. These requirements usually comprise

i) the stability,
ii) the set–point following property for predefined classes of command signals w and disturbances d, which includes the tracking of a prespecified trajectory $w(k)$ and
iii) specifications on the dynamical behavior of the closed–loop system.

In the ideal case, the reconfigured controller maintains the performance of the closed-loop system under the influence of the fault. Otherwise, it should gracefully degrade the performance and hold it on an acceptable performance level.
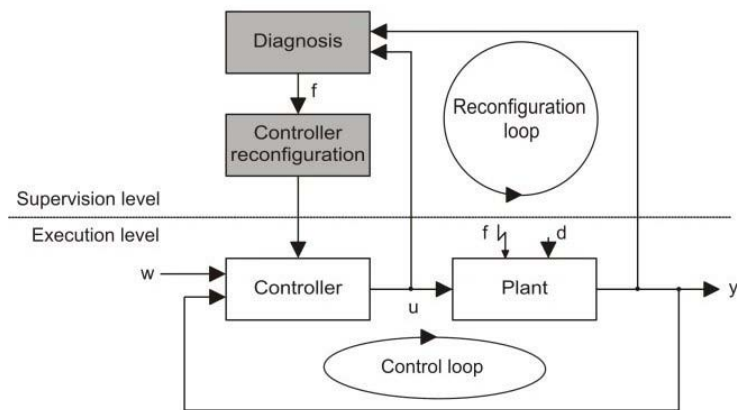
Figure 1: Reconfiguration loop

The basic scheme of controller reconfiguration is depicted in Figure 1. On the execution level, a feedback controller

$$u = k(y, w)$$

is used to attenuate the disturbance d and to ensure command tracking for the command input w. The control law k is designed so that the closed–loop system satisfies the requirements (i) – (iii) for the faultless plant. Before a fault f occurs the supervision level shown in the figure is not active.

The reconfiguration task, which is solved on the supervision level, concerns the situation, in which a fault f changes the availability of the actuators and sensors or changes the plant dynamics severely:

iv) **Sensor faults** break the information link between the plant and the controller. They make the plant partially unobservable. New sensors have to be selected and used in order to solve the control task.

v) **Actuator faults** disturb the possibilities to influence the plant. They make the plant partially uncontrollable. New actuators have to be used.

vi) **Plant faults** change the dynamic behavior of the process. Such changes cannot be tolerated by the control law k. A redesign of the controller is necessary.
The controller has to be "reconfigured" in the sense that the whole process of selecting a suitable control configuration and of choosing appropriate controller parameters has to be repeated after the fault is present. It is not sufficient to change some controller parameters. Instead, the control problem has to be considered "from scratch" by appropriately choosing

vii) the signal vector y to be controlled and the input vector u to be used,

viii)   the control law k including the controller parameters,
ix) the set–point w.

Control reconfiguration can be thought of as an "analytical repair" of the closed–loop system where instead of repairing the plant the controller software is changed in order to exploit the redundant measurement or control signals for satisfying the control specifications for the faulty plant.

Whereas the usual control design task is solved off-line by iteratively searching for an appropriate trade–off between different control specifications (cf. Part C: Analysis and Design Methods for Control Systems), the reconfiguration problem has to be solved on–line by selecting the mentioned items *automatically*. To solve this task, the discrete–time model $\mathcal{M}$

$$x(k+1) = g(x(k), u(k), d(k), f), \quad x(0) = x_0 \tag{1}$$

$$y(k) = h(x(k), u(k), d(k), f). \tag{2}$$

with state $x \in \mathrm{R}^n$, input $u \in \mathrm{R}^m$ and output $y \in \mathrm{R}^r$ is assumed to be available which also describes the dependence of the plant dynamics upon the fault $f \in \mathcal{F}$ where the set $\mathcal{F}$ includes all possible faults.

The reconfiguration loop shown in Figure 1 includes the following steps:

1. **Fault diagnosis:** The fault f affecting the plant has to be found as precisely as possible. It is not only necessary to known *that* a fault has occurred (fault detection), but also *which* fault is present (fault identification). A detailed description of the fault is necessary to assess the effects of the fault on the availability of the actuators and the sensors and the changes of the plant dynamics (cf. fault identification in *Fault Diagnosis of Linear Systems*). The fault has to be found quickly in order to prevent that the plant moves too far from the required operation point.

2. **Evaluation of the faulty system:** The first step of the control reconfiguration concerns the solvability of the control task under the influence of the fault. The system is called *reconfigurable* for the given fault f if there exists a controller that satisfies the control specifications (i) – (iii) for the faulty plant. A prerequisite for reconfigurability is the fact that the plant is controllable and observable through the still available inputs and outputs. It has to be investigated whether the control aim (i) – (iii) can be satisfied by a new controller for the faulty system. If necessary, the automatic reconfiguration logic must find a tolerable but possibly degraded level of performance. This mainly requires the specification (iii) on the dynamic loop behavior.

3. **Control reconfiguration:** The reconfiguration step (in the narrow sense) concerns the appropriate selection of the input vector u, the output vector y, the control law k and the set point w.

As the diagnostic problem can be solved by methods described in *Fault Diagnosis for*

Linear Systems, Fault Diagnosis for Nonlinear Systems, Design Methods for Robust Fault Diagnosis, Qualitative Methods for Fault Diagnosis, and Statistical Methods for Change Detection, this chapter considers the steps 2 and 3 in which the reconfiguration problem is solved. This problem can be summarized as follows:

Reconfiguration problem

Given: Model $\mathcal{M}$ of the continuous-variable system

Nominal controller

Fault f

Control specifications (i) – (iii)

Find: Control configuration and new control law **k**

This problem statement points to some important aspects of control reconfiguration:

(i) The plant is not repaired but a controller is chosen so as to circumvent the effects of the fault. Hence the system remains in operation until a possible repair of the plant is accomplished.

(ii) The reconfiguration task is solved automatically by the automation equipment. Reconfiguration necessitates the implementation of algorithms that use one of the reconfiguration methods that are surveyed in this chapter.

Note that in contrast to the usual controller design problem, in the reconfiguration problem also a nominal controller is given. A part of the reconfiguration methods concentrates on replacing the existing controller by another controller such that the closed-loop system behaves as similar to the nominal closed-loop system as possible.

2. Example

The idea and some practical circumstances of control reconfiguration is illustrated by the following simple control problem. Consider the three coupled tanks depicted in Figure 2. These tanks are connected by pipes which can be controlled by several valves. Water can be filled into the left and right tank using two identical pumps. Measurements available from the process are the continuous water levels h_i and discrete water levels: *low*, *medium* or *high* from two proximity switches attached to each tank. For Tank T_3, these qualitative values are $low = [0, 9]$ cm, $medium = [9, 11]$ cm and $high = [11, 60]$ cm. For the nominal case, only the left (T_1) and the middle tank (T_3) are used, whereas the right tank (T_2) and pump (P_2) act as redundant hardware. The main aim of the two tanks used is to provide a continuous water flow Q_N to a consumer. The water level in Tank T_3 has, therefore, to be maintained at a level $h_3 = medium$. The reservoir-tank T_1 is filled by Pump P_1 up to a nominal water level of h_{1nom} above the two pipes. Water flows between the tanks can be controlled by several valves (V_1, V_{13}, V_2, V_{32}). For the nominal case, Valves V_{13}, V_2, V_{32} are closed and not in use. Valve V_1 is used to control the water level in Tank T_3. Valve V_{1L}, which can be used to simulate a leakage in Tank

T_1, is closed. The connection pipes between the tanks are placed at the bottom of the tanks (pipes with Valves V_{13}, V_{32}) and at a height of 30 cm (pipes with Valves V_1, V_2). To control water levels in the reservoir-tank T_1 and supply-tank T_3, a conventional PI-controller and an discrete (on-off) controller are used (Figure 2). The control specifications include the stability (i) and set-point following requirement (ii) as well as the specification (iii) that the level h_3 has to remain at the *medium* level, i.e. $h_3 \in [9, 11]$ cm.
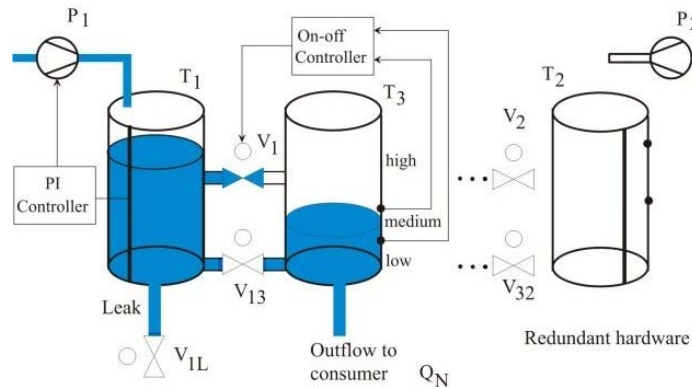

Figure 2: Three-tank system

For the reconfiguration problem, three different fault scenarios are given:

1. Valve V_1 is closed and blocked.
2. Valve V_1 is open and blocked.
3. Valve V_{1L} is open simulating a leak in Tank T_1.

The reconfiguration task is to find automatically a new control configuration of the system such that

(iii) the water level h_3 remains *medium* for all scenarios and, hence, satisfies the specifications (i) – (iii)

(iv) for scenario 3, the loss of water is minimal, which is an additional specification for the faulty situation.

The reconfiguration task consists in finding a new control structure by selecting alternative actuators and sensors, new control laws and new set-points for the control loops such that the control aims given above are satisfied. If needed, the use of redundant hardware components is possible. Obviously, the idea of reconfiguration cannot be satisfied by simply changing the parameters of the given controllers, but only a structural change of the control configuration. For example, if the Valve V_1 is closed and blocked, the control problem can be solved by using the Valve V_{13} instead. The control system should find this solution automatically and adapt the control law to the new actuator.

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Biographical Sketch

Jan Lunze was born in Dresden, Germany. He obtained the diploma in Automatic Control at the Technical University Ilmenau in 1974. From 1974 until 1992 he was research associate and later

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Professor Lunze's research interests are in linear control theory, particularly in the fields of robust control and large–scale systems, in hybrid systems, discrete–event systems and in applications of knowledge processing to dynamical systems. Currently, his research is focused on qualitative modeling, fault diagnosis and process control applications of robust and decentralized control. He is author and co-author of numerous papers and of several books including *Robust Multivariable Feedback Control* (Prentice–Hall 1988), *Feedback Control of Large–Scale Systems* (Prentice–Hall 1992), *Künstliche Intelligenz für Ingenieure* (Oldenbourg 1994) and *Regelungstechnik* (Springer 1996).