Reconfiguration Strategies for Hybrid Systems

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Abstract

In this work we propose several algorithms to solve the reconfiguration problem for linear and hybrid systems. In particular, we consider the decision about the usage of redundant hardware in order to compensate for faults. While this problem can be translated into a constrained model predictive control framework, the computational complexity grows very fast, as the number of possible decisions increases. In this work we propose schemes, that require low computational effort. We discuss the applicability of the methods considering the reconfiguration of the three tank benchmark system.

Keywords: Hybrid Systems, Fault Tolerant Control, Reconfiguration, Model Predictive Control

1 Introduction

Many control systems are subject to faults or malfunctions. The failure of components, like sensors or actuators can partially or fully disable the action of the controller. This results in an unsatisfactory performance of the system, decreased availability, emergency shutdowns or even significant damages to the plant and to its environment. For this reason, several research activities recently focused on the safety aspects of control systems [8, 6]. One way to classify the different approaches is the distinction between passive and active fault accommodation [16]. In passive fault accommodation the closed loop system is designed, such that it is robust, within some performance range, to fault occurrences. On the other hand, active fault accommodation aims at changing the control operation when a fault is detected. These changes can comprise reconfiguration of the controller scheme, modifications of controller parameters or alternative setpoint trajectories. In this work we will focus on active fault accommodation. The key issue we are considering is the usage of redundant hardware for reconfiguration when some faults occur. The term *hardware redundancy* is used for systems where a replication of hardware components is present [16]. In other words, such systems

have components that need not to be used in order to meet nominal control specifications, but can be used in extraordinary situations. The redundancy is often given by subsystems with similar functions, different parameters or alternative locations within the system topology.

The main contribution of this work is to propose several solutions for the *decision problem about the choice of redundant hardware* using mathematical optimization tools. We will refer to this decision simply as *reconfiguration* of the control scheme. To this purpose we are using the modeling formalism of Mixed Logic Dynamical (MLD) systems introduced in [5, 4]. The equations describing an MLD system are

$$x(t+1) = Ax(t) + B_1u(t) + B_2\delta(t) + B_3z(t) + B_6\phi(t) \quad (1a)$$

$$y(t) = Cx(t) + D_1u(t) + D_2\delta(t) + D_3z(t) + D_6\phi(t) \quad (1b)$$

$$E_2\delta(t) + E_3z(t) \leq E_1u(t) + E_4x(t) + E_5 + E_6\phi(t) \quad (1c)$$

where $x \in \mathbb{R}^{n_c} \times \{0,1\}^{n_e}$ are the continuous and binary states, $u \in \mathbb{R}^{m_c} \times \{0,1\}^{m_e}$ are the inputs, $y \in \mathbb{R}^{p_c} \times \{0,1\}^{p_e}$ the outputs, and $\delta \in \{0,1\}^{r_e}$, $z \in \mathbb{R}^{r_c}$ represent auxiliary binary and continuous variables, respectively, $\phi \in \{0,1\}^{f_e}$ denote the occurrence of faults. The auxiliary variables are introduced when translating propositional logic into linear inequalities. For a detailed description of the features and modeling capabilities of MLD systems, we defer to [5, 3]. Constraints on state, input, and auxiliary variables are summarized in the inequality (1c). There are four main reasons for formulating active fault accommodation within the MLD framework. First, the framework allows to consider a large class of systems, including LTI systems, systems with discrete inputs, systems interacting with logic automata and many more. Second, the priorities for the usage of redundant components can be directly included within the MLD model and can therefore be systematically considered during computations. Third, these models are suitable for formulating control or estimation problems as mathematical programs for which solvers are commercially available. Fourth, the decision about redundant hardware is an inherently binary problem, therefore the modeling with binary variables is appropriate. Throughout the paper, the three tank system in Figure 1 will be used to illustrate the proposed ideas. The reconfiguration problem for the three tank system has been defined as a COSY

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benchmark problem [11, 9]. For instance in [1] and [12] schemes that only take into account qualitative information about the state of the plant are considered. In [17] the reconfiguration is formulated as a multi-model switching control task. Approaches using neural networks are reported in [13]. The paper is organized as follows: In Section 2 we summarize the model of the three tank system. In Section 3 the main issues for fault detection and control of MLD systems are presented. In Section 4 we present the ideas for reconfiguration of MLD systems. In Section 5 we apply some of the algorithms to the tank system. The complete version of this paper can be found in [18].

2 The Three Tank System

Figure 1: The COSY Three Tank Benchmark

The three tank system represented in Figure 1 has been adopted recently as a standard benchmark problem for fault detection and reconfigurable control [11]. Three tanks can be filled with two independent pumps acting on the tanks 1 and 2. The tanks are interconnected to each other with switching valves. The nominal outflow Q_{N3} from the tanks is placed at tank 3. In closed loop operation, the controlled variables are the levels in tanks 1 and 3. The level h_1 is controlled by a PI controller manipulating the flow Q_1 , while for the level h_3 , a switching controller manipulating valve V_1 is used. In nominal operation, all other valves are closed, and the flow Q_2 is zero. Therefore the set V_N of *nominal manipulated variables* for this system is given by the valve V_1 and the pump Q_1 , i.e. $V_N = \{V_1, Q_1\}$. All other inputs form the set V_R of *redundant manipulated variables*, i.e. $V_R = \{V_{13}, V_2, V_{23}, Q_2\}$. In [14, 4] it is shown how this system can be modeled in MLD form. The following fault scenarios [11] are considered:

Scenario 1: Valve V_1 is stuck open;

Scenario 2: Valve V_1 is stuck closed;

Scenario 3: Tank 1 has a leak Q_{L1}

For each of these faults, the aim of the reconfiguration scheme is to keep the level h_1 at 0.5 and h_3 at 0.1, by possibly using the redundant manipulated variables V_R . In scenario 3 the additional goal is to have

a minimal water loss from tank 1. There are some aspects that complicate the reconfiguration task for this system:

- There are several possibilities for the choice of the redundant hardware. To check and evaluate all combinations represents a large combinatorial problem.
- The choice of redundant hardware has to be made fulfilling a hierarchy of preferences.
- The plant exhibits typical characteristics of a hybrid system. The dynamics change, if the liquid reaches the height of the upper valves. Moreover, the model has to take into account discrete inputs because of the presence of switching valves.
- The control goal in nominal operation can only be reached by providing a sequence of periodic inputs to the system. For some reference values no constant steady state exists, if the nominal hardware V_N is used.
- The system is subject to constraints on the liquid levels h_i and on the inflows Q_j .

3 Fault Detection and Control

3.1 Problem Formulation for Reconfiguration

The supervision scheme we are considering consists of two stages: In a first stage a fault detection and isolation algorithm is required to monitor the operation of the plant. This part should estimate at each time step which faults occurred or that no fault was detected. We assume that this task is already accomplished, for instance by using the tools described in [4]. The second stage is the actual reconfiguration component. The conceptual scheme is shown in Figure 2. The reconfig-

Figure 2: Reconfiguration Scheme

uration device should decide, which system modification is most suitable to achieve the control goals, or to achieve the best possible performance in terms of some value function. The reconfiguration block takes as inputs the reference r , the control action u , the output signal y and the fault information ϕ . The output is a modification of the controller structure Δs , which can be the inclusion or exclusion of some actuators or the switch to a different controller. The problems of control and fault detection for MLD systems have been considered previously in [5, 4]. The main ideas are summarized next.

3.2 Predictive Control of MLD Systems

There are several ways to systematically find a controller for MLD systems. The approach that we adopt was presented in [5] and uses the ideas of Model Predictive Control (MPC). At each time step the following constrained optimization problem is solved:

$$\min_{\underline{u}, \underline{\delta}, \underline{z}} J = \sum_{k=0}^{T-1} \|u(k+t|t) - u_f\|_{Q_1}^2 + \|\delta(k+t|t) - \delta_f\|_{Q_2}^2 + z(k+t|t) - z_f\|_{Q_3}^2 + \|x(k+t|t) - x_f\|_{Q_4}^2 + \|y(k+t|t) - y_f\|_{Q_5}^2 \quad (2)$$

subject to (1a),(1b),(1c) and

$$x(k+T|t) = x_f \quad (3)$$

where $\|x\|_Q^2 = x'Qx$, $Q_i = Q'_i \geq 0$, $i = 1, \dots, 5$, are given weight matrices, and x_f , u_f , δ_f , z_f , y_f are the target values of the MLD model variables. A steady state target value for an MLD system can be determined by solving the following mixed integer program [2]:

$$\min_{x_f, u_f, \delta_f, z_f} \|y_f - r\| + \|x_f\|_{\rho_4} + \|u_f\|_{\rho_1} + \|z_f\|_{\rho_3} + \|\delta_f\|_{\rho_2} \quad (4)$$

$$\text{s.t. } x_f = Ax_f + B_1u_f + B_2\delta_f + B_3z_f + B_6\phi_f \quad (5)$$

$$E_2\delta_f + E_3z_f \leq E_1u_f + E_4x_f + E_5 + E_6\phi_f \quad (6)$$

Here $\|\cdot\|$ is an arbitrary norm, ρ_i are small, positive definite weights. We recall one property of MLD systems: the phenomenon of *cycling steady states* [18]. For certain systems, the switching components and the MPC controller cause a periodic trajectory of the system around the reference. This gives lower cost in (2) than the stabilization at the constant steady state found with (4)-(6). In other words, the system goes through a cycle of states to stay close to the reference, instead of converging to a constant state. The three tank model presented in Section 2 shows this behaviour for the reference value $r = [0.5, 0.0, 0.1]$ the valve V_1 has to switch repeatedly in order to keep level h_3 close to its reference [18].

3.3 Fault Detection of MLD Systems

The fault detection problem for MLD systems has been considered in [4]. The occurrence of the i -th fault is denoted by $\phi_i = 1$ in (1). The faults can be estimated by using a moving horizon estimation [4, 7] technique. At each time step a least squares problem extending backwards in time over a given horizon is solved. This optimization has the MLD dynamics as constraints. As in controller synthesis, the structure of this mathematical problem is a mixed integer quadratic program (MIQP) [15].

3.4 Objective Prioritization in MLD Systems

We require that the reconfiguration scheme is capable to respect preferences about the use of certain system components. In [10] it was shown, that such objective prioritizations can be directly specified within the MLD framework. The key idea is to formulate the hierarchy of priorities as a set soft constraints in the MPC

optimization (2),(3) yielding:

$$\min_{\theta, \epsilon, \delta} \theta'H\theta + f'\theta + \epsilon'S\epsilon + \rho M_p'\delta$$

$$\text{s.t. } A\theta \leq b + C\epsilon \text{ and } 0 \leq \epsilon \leq M_\epsilon$$

where $\theta = (\underline{u}, \underline{\delta}, \underline{z})$, H and f define the cost function of the MPC optimization, and all constraints are summarized in A and b . ϵ is a vector of slack variables, representing the constraint violations, C is a matrix of appropriate dimension, whose rows are 0 or e'_k depending on whether the k 'th constraint is hard or soft, $S > 0$ is a weighting matrix which determines the trade-off between cost and constraint violation. Additional variables $\delta \in \{0, 1\}^r$ are defined and are associated with constraint violations at r levels of priority. For details we defer to [10]. We just note that the inclusion of these priorities does not alter the optimization problem structure.

4 Reconfiguration of MLD systems

In this section we present various strategies for performing the decision on redundant hardware in case of faults. We characterize the manipulated variables of an MLD system as follows:

- The set V_N (Nominal Inputs)** is the set of all manipulated variables used in nominal operation.
- The set V_R (Redundant Inputs)** is the set of all other manipulated variables, i.e., those inputs that can be used additionally for reconfiguration.
- The sets V_i (Candidate Inputs)** ($i = 1, \dots, n_f$) are the sets of manipulated variables that are proposed to be used by the reconfiguration scheme when fault ϕ_i is detected. n_f is the number of fault scenarios considered.

We assume that all manipulated variables have been partitioned into the sets V_N and V_R , V_R is nonempty, $V_R \cap V_N = \emptyset$ and $V_i \subset (V_R \cup V_N)$ ($i = 1, \dots, n_f$)

4.1 Reconfiguration as a Control Problem

One way to handle the reconfiguration problem is to treat it as a control problem within a receding horizon framework. Once a fault has been detected, we carry on solving the MPC optimization (2),(3) with the corresponding fault information. In faultless mode we impose the usage of the set V_N of manipulated variables by adding prioritizations in the control synthesis optimization, as mentioned in Section 3.4. This idea is summarized in the following reconfiguration algorithm.

Algorithm 1

1. Consider the complete model (1) of the plant, including the complete set of manipulated variables $V_N \cup V_R$.
2. While $\phi = 0$, apply the MPC control algorithm in [5] to the complete model. To avoid the use of the inputs V_R in nominal operation include prioritizations on the inputs V_N .

3. *If a fault ϕ_i occurs, update $\phi(t)$ and use it in the MPC optimization for all future time steps where the fault is active.*

The advantage of this algorithm is that it gives the best possible strategy for reconfiguration, where “best” has to be understood in terms of the cost function (2) for the controller. We can prove stability [18] of this scheme as in [5, Theorem 1]. The drawback is the size of the optimization since the optimization problems for controller synthesis are done at all time instances over the complete model. Therefore the number of variables is large, a problem that is particularly pronounced in the mixed integer optimizations of MLD systems.

4.2 Reconfiguration on Two Decision Levels

In order to avoid the large size of the online optimization problems involved in receding horizon control, we propose three methods how to lower the computational complexity of (2),(3) to the current plant operation. In this context we will measure the complexity of the models by the number of manipulated variables used in (2),(3). We assume that the receding horizon control scheme is operating with the inputs V_N , as long as no fault is detected. If a fault ϕ_i occurs, the first task of the reconfiguration procedure is to decide which inputs V_i have to be used for control. Note that in Section 4.1 this question did not arise, since the choice of manipulated variables was implicitly given by the optimization over all available manipulated variables in $V_N \cup V_R$. The second level consists of *applying the receding horizon control strategy using the manipulated variables V_i determined in the first step.* The three methods described in this section differ from each other in the first decision level, i.e., in the decision about V_i .

4.2.1 Reconfiguration with Reachability

Analysis: In this strategy we propose to determine the manipulated variables V_i offline. A look up table is set up, that denotes the set V_i for each possible fault scenario ϕ_i . The following algorithm describes the procedure:

Algorithm 2

1. *Build up a look up table with the assignment of a set V_i to each possible fault scenario ϕ_i .*
2. *Run the fault detection scheme and the control scheme in parallel.*
3. *For each fault scenario ϕ_i detected, switch the model used in control according to the look up table, i.e., determine the candidate inputs V_i from the look up table.*
4. *Apply the MPC algorithm using the candidate inputs V_i as manipulated variables.*
5. *Repeat step 3. at the next time step using the most recent fault information.*

The choice of manipulated variables V_i can be done via reachability analysis [3]: Those inputs are chosen, that allow the target state to be reachable.

4.2.2 Reconfiguration with Static Steady

State Analysis: We assume that the system does not have cycling steady states (see Section 3.2 and [18]) and that the steady state obtained by (4) to (6) is reachable. If a fault ϕ_i is detected, the candidate inputs V_i are chosen based on the steady state optimization (4)-(6). V_i is chosen as the set of inputs that are different from zero in this optimization. The search for the steady state can be modified to include further constraints or prioritizations, see Section 3.4. This method requires a low computational load, however it lacks guarantees of optimality of V_i . The algorithm can be summarized as follows:

Algorithm 3

1. *Run the fault detection scheme and the control scheme in parallel.*
2. *If a fault ϕ_i occurs, run the steady-state finding procedure (4)-(6) on the model with inputs $V_N \cup V_R$.*
3. *Choose those inputs, which are different from zero in steady state, as candidate inputs V_i .*
4. *Apply the MPC algorithm using the candidate inputs V_i as manipulated variables.*
5. *Repeat step 2. at the next time step using the most recent fault information.*

4.2.3 Reconfiguration with Polytopic

Steady State Analysis: The algorithm presented here is a modification of the method shown in section 4.2.2 that can be applied to systems with cycling steady states. We assume that the cycle consists of reachable states. In case of a fault ϕ_i , the method in Section 4.2.2 extracted the candidate inputs V_i from a single steady state. For systems with cycling steady states we propose to extract V_i from multiple steady states. For a system with n_y outputs we solve $M = 2^{n_y}$ optimizations, given by (4)-(6), subject to exactly one additional constraint:

$$\mu_k y_f \leq \mu_k r \quad (k \in 1 \dots 2^{n_y}) \quad (7)$$

where

$$\mu_k \in \{ \text{diag}(d) \mid d \in \{[\xi_1, \dots, \xi_{n_y}] \mid \xi_i \in \{-1, 1\}\} \} \quad (8)$$

E.g. for a system with $n_y = 2$ outputs the $M = 2^2 = 4$ steady states are found by solving (4)-(6) subject to one of the following four additional constraints, respec-

tively:

$$k = 1 : \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} y_f \leq \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} r \quad (9)$$

$$k = 2 : \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} y_f \leq \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} r \quad (10)$$

$$k = 3 : \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} y_f \leq \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} r \quad (11)$$

$$k = 4 : \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} y_f \leq \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} r \quad (12)$$

Let Y_{iM} be the set of outputs generated by the M steady states computed above. We assume that

$$r \in \text{conv}(Y_{iM}) \quad (13)$$

i.e., the desired reference value is element of the convex hull of the M steady state outputs. If (13) is fulfilled, we define M tentative sets of inputs V_{ik} ($k = 1 \dots M$) as those inputs, that are different from zero at steady state. The candidate set of inputs V_i is then chosen such that $V_{ik} \subset V_i$ ($k = 1 \dots M$). The set of inputs V_i allows to keep the system at each of the M steady state values. Therefore, if r is within the polytope spanned by Y_{iM} , it is reasonable to use these inputs to achieve the actual goal of staying close to the reference r . The graphical representation of the $M = 2^2$ steady states for the previous example is given in Figure 3. The reconfiguration algorithm is summarized next:

Figure 3: Outputs Y_{iM} of steady states: The origin is the desired reference value $r = [r_1 \ r_2]'$, the outputs y_1, y_2, y_3, y_4 result as steady state outputs from the optimization (4)-(6), (7)

Algorithm 4

1. Run the fault detection scheme and the control scheme in parallel.
2. If the fault ϕ_i is detected, find M steady states with property (13). The steady states are found with (4)-(6) on the model with inputs $V_N \cup V_R$. For each steady state define V_{ik} as the set of manipulated variables, that are nonzero in steady state.
3. Find the set of candidate inputs V_i from V_{ik} .
4. Apply the MPC algorithm using the candidate inputs V_i as manipulated variables.
5. Repeat step 2. at the next time step using the most recent fault information.

The obvious solution to find V_i is given by $V_i = \cup_{k=1}^M V_{ik}$. However, in terms of the number of manipulated variables, this can be suboptimal. We defer to [18] for more details.

4.3 Static Fault Compensation

In this approach we set $V_i = V_N \cup V_R$ and we propose a strategy to compute the values of V_i in case of faults, avoiding to run the optimization of Section 4.1 over all manipulated variables. We use the redundant inputs V_R to minimize at each time step the effect of faults. For this purpose the MLD model is rewritten as:

$$x(t+1) = Ax(t) + B_1 u(t) + B_2 \delta(t) + B_3 z(t) + \bar{B}_1 \bar{u}(t) + B_6 \phi(t) \quad (14a)$$

$$y(t) = Cx(t) + D_1 u(t) + D_2 \delta(t) + D_3 z(t) + \bar{D}_1 \bar{u}(t) + D_6 \phi(t) \quad (14b)$$

$$E_2 \delta(t) + E_3 z(t) \leq E_1 u(t) + E_4 x(t) + E_5 + \bar{E}_1 \bar{u}(t) + E_6 \phi(t) \quad (14c)$$

Here we explicitly split up the inputs used in nominal operation and the inputs for reconfiguration purposes as $u \in V_N$ and $\bar{u} \in V_R$, respectively. In nominal operation, we have $\phi = 0$ and $\bar{u} = 0$. Running the MPC optimization we obtain at each time step t a triple $(u_n(t), \delta_n(t), z_n(t))$. The state evolution in nominal operation is then given by

$$x(t+1) = Ax(t) + s_n(t) \quad (15)$$

where $s_n(t)$ is determined online by the MPC controller and

$$s_n(t) = B_1 u_n(t) + B_2 \delta_n(t) + B_3 z_n(t) \quad (16)$$

In the presence of fault ϕ_i , we allow the use of the redundant inputs V_R . The state update is then given by:

$$x(t+1) = Ax(t) + s_e(t) \quad (17)$$

where

$$s_e(t) = B_1 u_e(t) + B_2 \delta_e(t) + B_3 z_e(t) + B_6 \phi(t) + \bar{B}_1 \bar{u}_e(t) \quad (18)$$

The key idea of this method is to make $s_e(t)$ as close to $s_n(t)$ as possible by exploiting the freedom we have to choose the redundant inputs $\bar{u}(t)$. This specification can be translated into the following optimization problem:

$$J_s = \min_{u_e, \bar{u}_e, \delta_e, z_e} \|s_n(t) - s_e(t)\|^2 \quad (19)$$

$$\text{s.t. } E_2 \delta(t) + E_3 z(t) \leq E_1 u(t) + E_4 x(t) + E_5 + \bar{E}_1 \bar{u}(t) + E_6 \phi(t) \quad (20)$$

The algorithm is summarized next. Table 1 summarizes all the algorithms.

Algorithm 5

1. Run the MPC controller and the fault detection scheme in parallel. Compute the MPC control moves with the faultless model, yielding $u_n(t), \delta_n(t), z_n(t)$ and determine $s_n(t)$ from equation (16).
2. If a fault ϕ_i is detected, run the optimization (19), (20) to obtain $u_e(t), \bar{u}_e(t), \delta_e(t), z_e(t)$. If no fault is detected, set $u_e(t) = u_n(t), \bar{u}_e(t) = 0, \delta_e(t) = \delta_n(t), z_e(t) = z_n(t)$.
3. Apply $u_e(t)$ and $\bar{u}_e(t)$ to the system
4. Repeat 1. at the next time step.

5 Reconfiguration of the Tank System

We applied the controller reconfiguration ideas to the three tank benchmark system described in Section 2.

Table 1: Summary of the algorithms

Algorithm	Choice of candidate inputs V_i	Value of candidate inputs V_i given by
1	$V_i = V_N \cup V_R$	MPC over V_i
2	look up table	MPC over V_i
3	static steady state	MPC over V_i
4	polytopic steady state	MPC over V_i
5	$V_i = V_N \cup V_R$	correction (19)-(20)

Due to lack of space we present only an application of Scenario 2. We assume that at time $t = 30$ valve V_1 is stuck closed. When operated with the PI-controller, the tank system reacts to the fault as shown in Figure 4. Figure 5 (left) shows the application of algorithm 5. Tank 2 is starting to be used when the fault is detected. Figure 5 (right) shows the application of algorithm 4. After the failure, the controller switches the manipulated valve from V_1 to V_{13} . In this case the control goal can be achieved without using tank 2, but the behaviour of h_1 is slightly worse than before. See [18] for more simulations and discussions.

Figure 4: Scenario 2, nominal operation

Figure 5: Scenario 2, static fault compensation (left) and polytopic steady state reconfiguration

6 Conclusions

In this paper we have dealt with the problem of choosing redundant manipulated variables for a system, which is subject to faults. This decision problem can be formulated within the framework of mixed logic dynamical models and can be solved with mathematical optimization tools. The methods presented in this work aim at reducing the complexity of the reconfiguration problem, in order to render the problem tractable in an online supervision scheme.

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