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Active fault-tolerant control with virtual actuators

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1 Fault-tolerant control

Fault-tolerant control (FTC) aims at increasing the availability of processes subject to faults or failures. The active fault-tolerant control scheme presented in [1] and shown in Fig. 1 adds a supervision level that consists of two components. First the **f**ault **d**iagnosis and **i**dentification (FDI) unit has to detect, isolate and identify the fault f based on the measurement of the control input $\boldsymbol{u}(t)$ and the plant output $\boldsymbol{y}(t)$. Second a reconfiguration unit adapts the controller to the faulty process based on the fault estimate $\hat{f}$.

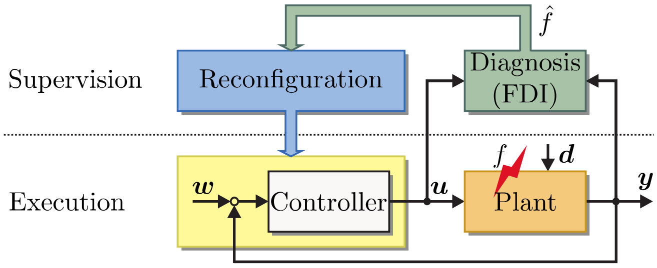

Figure 1: Active fault-tolerant control scheme

2 Project aim

The project aim is to elaborate a complete fault-tolerant control framework as shown in Fig. 1 for systems subject to sensor and actuator failures. These major faults partially break-off the feedback such that parts of the plant are controlled in an open-loop structure.

An adequate solution for the reconfiguration problem after sensor and actuator failures is given by the concepts of the virtual sensor and the virtual actuator presented in [1, 2, 4]. The reconfiguration block is a dynamical system that is placed between the nominal controller and the faulty plant as illustrated in Fig. 3. The reconfiguration block hides the failure from the nominal controller that is kept in operation.

An appropriate method for consistency-based detection and isolation of sensor and actuator failures is the bank of observers presented in [3]. The current project aim is an aggregation of the diagnosis an reconfiguration methods.

In the case of sensor failures, an interesting observation is: The observer that isolates a certain sensor failure is equal to the virtual sensor system that reconfigures the controller in the presence of this failure. It is supposed that the diagnosis and the reconfiguration task can be accomplished by the same dynamical systems also in the case of actuator failures. Therefore, the observers used for actuator failure isolation should by replaced by those virtual actuator systems that reconfigure the corresponding actuator failures. The main question that arises here is: **How can a virtual actuator systems be used for actuator failure detection and isolation?** This aspect is considered in more detail in Sec. 3.

Besides the methodical aggregation of diagnosis and reconfiguration, the resulting framework has to be considered w.r.t. fault-tolerance. The reconfiguration step assumes an accurate diagnosis result which is given sufficiently fast. It is expected that the aggregation of the diagnosis and the reconfiguration methods increases the accuracy of the diagnosis result, but, in general it is not possible to get a unique diagnosis result. Then the question is: **How can the reconfiguration unit handle a set fault candidates?** Here it is supposed that failures that cannot be distinguished by the diagnosis unit have a common solution of the reconfiguration problem. This idea is explained more precisely in Sec. 4.

3 Actuator failure isolation with a bank of virtual actuators

The scheme of consistency-based diagnosis as presented in [1,3] is shown in Fig. 3. The diagnosis unit itself consists again of two components. In the case of observer-based diagnosis the residual generator uses the observer of the nominal plant to generate a detection residual $\boldsymbol{r}_0(t)$. Furthermore it contains an observer of every faulty plant situation to create N_f isolation residuals $\boldsymbol{r}_i(t)$, $i = 1, ..., N_f$, where N_f is the number of different faults that are considered. If a certain observer is consistent with the current process behaviour, the corresponding residual is vanishing, which is tested by the residual evaluation.

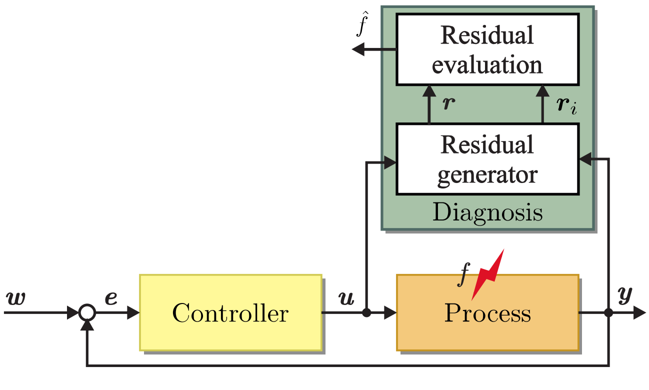

Figure 2: Consistency-based diagnosis scheme

The bank of observers is shown in Fig. 3 (left) for sensor failures. It can be seen that an extension of the isolation observer with the nominal output matrix $\boldsymbol{C}$ reveals the virtual sensor. This means: If a certain isolation residual becomes zero, this virtual sensor has to be activated for reconfiguration.

The case of actuator failures is illustrated by Fig. 3 (right). The virtual actuator is the dual system of the observer and solves the reconfiguration problem after actuator failures. The aim is to find a method for residual generation with the virtual actuator model. The residual, generated by a certain virtual actuator, should vanish if the actuator failure occurs that is reconfigured by this virtual actuator. Then, the methods of model-based diagnosis and model-based control reconfigurations are adequately combined to an overall FTC framework.

4 Simultaneous reconfiguration

In general the diagnosis result is affected by some uncertainties. In general the problems in the diagnosis step derive from model uncertainties, measurement noise, unknown inputs (disturbances) and faults that cannot be isolated. In the case of model-based (observer-based) diagnosis, it is assumed that the model is sufficiently accurate. The observer is also robust against measurement noise. Therefore, the main difficulties in observer-based diagnosis result from unknown inputs (like disturbances $\boldsymbol{d}(t)$ and faults that cannot be isolated. While the unknown disturbance inputs can usually be handled by appropriate extensions of the observer models, the problem of faults that cannot be isolated has not been considered often in literature yet.

This project states the hypothesis that failures that cannot be distinguished by their input-output behaviour in the diagnosis unit, have a common solution of their reconfiguration problems. This seems reasonable since the reconfiguration block reconfigures the controller w.r.t. the input-output behaviour of the faulty plant. The idea is

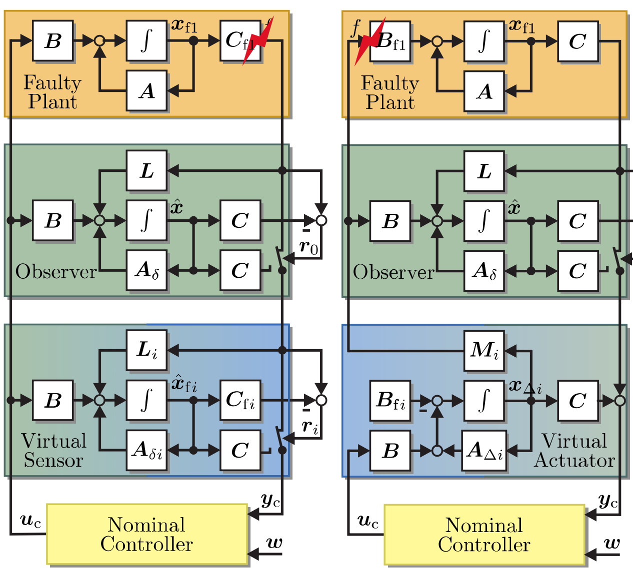

Figure 3: Observer and virtual actuator based diagnosis

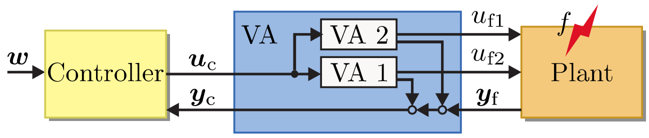

Figure 4: Simultaneous reconfiguration

illustrated by Fig. 4 for a plant with two actuators. It has to be proven that if two residuals vanish the same time, the reconfiguration tasks of the two failures are solvable simultaneously by the same reconfiguration block. This has to be reached without avoiding all actuators that are potentially faulty which would unnecessarily decrease the reconfigurability of the system. Then, it is not necessary to improve the diagnosis result by additional extensions since it does not matter which failure occurred. A further supervision of the reconfigured control-loop might bring up a more precise diagnosis result when it becomes necessary.

5 Application: multirotor UAV

The results of this project are evaluated by the application to different multirotor unmanned aerial vehicles (UAVs). A multirotor UAV is a flying vehicle with several rotors in a symmetric arrangement. Theoretical analysis shows that the quadrotor is not reconfigurable when a rotor is lost. The loss of a rotor of a hexrotor causes an interesting reconfiguration problem where the solvability strongly depends on the rotor arrangement [5]. The diagnosis result is unique. In the case of octorotors there is enough physical redundancy to reconfigure an arbitrary rotor loss, but the diagnosis result is not necessarily unique.

The current aim is the implementation of a complete FTC framework in the experimental environment. Therefore, the diagnosis is first performed by a bank of observers, which is already working in simulations. Later, the methods proposed in Sec. 3 and Sec. 4 have to be applied. The simulations and experiments should verify the analysis results concerning detectability, isolation and reconfigurability.

References

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