On-line monitoring and diagnosis based on hybrid component models

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Abstract:

Up to now model-based monitoring and diagnosis is rarely applied in process and chemical industries. The main reason is the huge effort necessary to develop a model comprehensive enough to describe a technical system under various circumstances. However the growing complexity of plants and facilities requires increasingly the use of formal methods to analyze and monitor system behavior. Nevertheless the cost-benefit relation has to be analyzed.

In this paper a monitoring and fault diagnosis method based on hybrid models is proposed. The method is component oriented. A basic feature of the concept is its ability to automatically build clusters of qualitative and dynamical components which can be reused as single components. As an application, the realization of a small system shows that hybrid models are capable to solve monitoring and diagnosis problems.

Key-words:

model-based analysis, qualitative reasoning, dynamical systems, monitoring, diagnosis, hybrid modeling, complex systems, one-tank-system

1 Introduction

For the automation of technical processes the on-line monitoring of normal operating mode is as important as the realization of open and closed loop control functions. It is the task of monitoring to prevent human beings and environment from danger and to avoid damages as far as possible. The engineers very often use model based solutions for process monitoring and diagnosis intending to get a detailed description of the technical process. Within this model the temporal changes of dynamical systems are described exactly. To develop mathematical (e.g. differential equation systems) models for monitoring is very complicated, particularly for complex dynamical systems. If on the one hand not all of the model parameters are known then the analytical methods have to work with state predictions. If any a mathematical model can be built, then the resources on the other hand may not be sufficient to use the model for an on-line simulation. Because of these difficulties it is useful to develop qualitative models in addition to the mathematical description. The advantage of the SQMD-concept is that the internal physical relations have not to be represented exactly. That is to say qualitative models contain only situations in which something ”happens” [1][2]. These models should to be able to distinguish between such situations.

Within the scope of the research field ”Qualitative modeling of complex dynamical systems” the use of already existing mathematical models in combination with qualitative models is examined for process monitoring and diagnosis of technical dynamical systems [3]. In this context the hybrid modeling method SQMD (Situation based Qualitative Monitoring and Diagnosis) has been developed.

2 On-line Monitoring and Diagnosis

Figure 1 shows the procedure for the model based on-line monitoring and diagnosis. The starting point is a process model of the normal and the faulty operation mode. The process model runs parallel to the technical process (on-line). The task of the evaluation is to compare the currently measured process states with the model states. If the model of the normal operation mode contains the measured process states, then the technical process is in a fault-free operation mode. If the measured states are not in the normal but in the faulty mode then it has to be assumed that the technical process is in a faulty mode.

The next step in the procedure consists in locating the fault, this is the task of diagnosis. According to the type of fault it is either sufficient to warn the operator or it is necessary to stop the system.

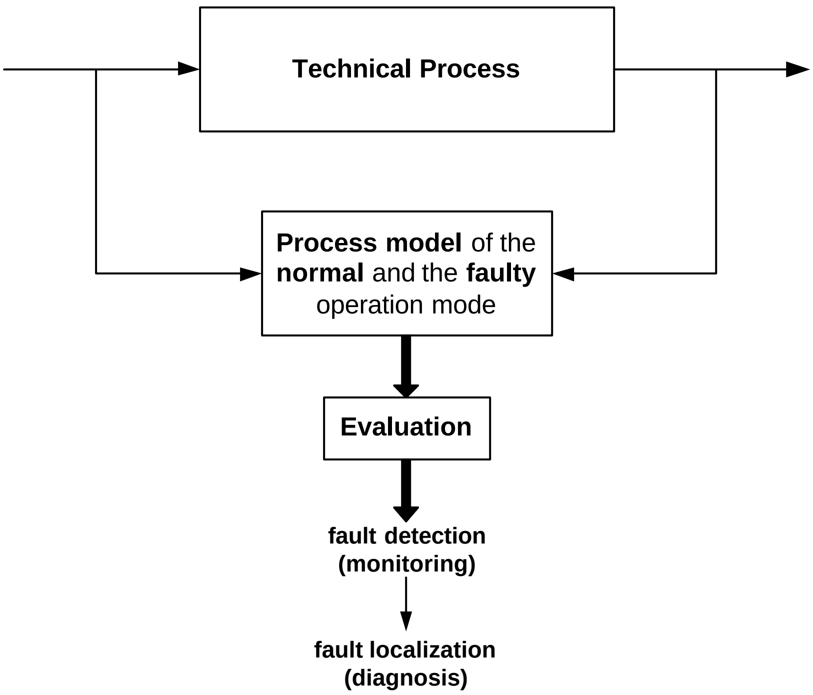

Figure 1: On-line Monitoring and Diagnosis

Depending on the type of the technical process various models are used for process monitoring. For dynamical systems quantitative dynamical models like differential equation systems are commonly used. In these models the dynamical process is described exactly, so that a deterministic behavior is guaranteed. The disadvantage however lies in the complexity of these models. The more components the system contains, the greater complexity the model gains. For complex models the calculations last too long to be used in on-line monitoring systems.

To monitor complex systems nevertheless, it is possible to use qualitative models. These models are normally quite simple and fast built, because of the simplified description of the technical process. But unfortunately the qualitative models describe only the static behavior of a system and can therefore not be used for dynamical systems. A further disadvantage is the non-deterministic behavior of the models because of the fuzzy description of the process.

On the base of these two modeling methods the SQMD (Situation based Qualitative Monitoring and Diagnosis) concept has been developed. SQMD uses hybrid models for on-line monitoring and diagnosis. Hybrid models contain qualitative and dynamical components and combine the advantages of both methods. So it becomes possible to realize on-line monitoring and diagnosis for the detection and localization of faults and failure in complex and dynamical systems.

3 SQMD Modeling concept and application

Figure 2 shows the modeling concept of SQMD, which includes the three steps "Model Building", "State Space Reduction" and "Analysis and Evaluation". Layouts or specifications of the technical process like Piping- and Instrumentation-diagrams are the starting point for modeling. The dependency on time can only be included in dynamical models containing differential equations.

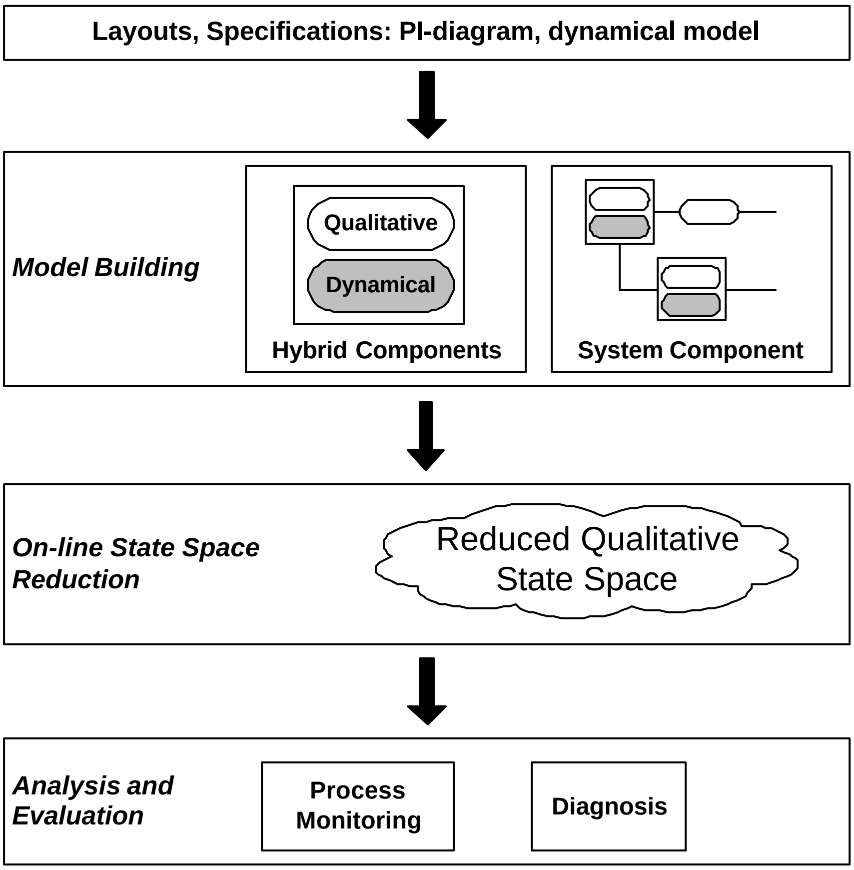

Figure 2: SQMD Modeling Concept

Model Building

One feature of the method is the easy to handle, strict component oriented modeling. The first step consists of the "model building" of the hybrid, i.e. qualitative and dynamical, components. The dynamical models include the mathematical description of the components. The qualitative models is carried out on the base of interval arithmetic, i.e. the engineer assigns to every physical quantity of the component different intervals which describe qualitatively the normal and faulty behavior of this component. All physically possible interval combinations of all quantities concerned are described as situations and stored, the so called situation table.

The model building for the example "tank" is shown in Figure 3. The situation table at the right hand side contains all possible situations of the tank, e.g. the tank can be empty or full. It is also possible to consider faulty situations like an overflow of the tank. The differential equation at the left hand side describes the dynamic behavior of the tank.

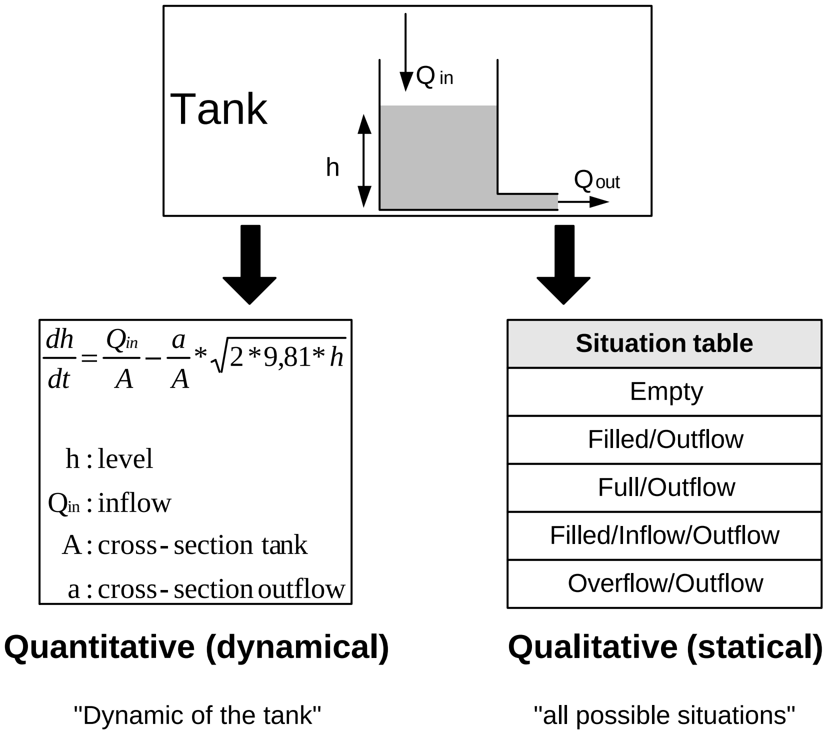

Figure 3 : Model building for the example tank

All components of a technical system are modeled within this method independent of their use in the system. The system model consists of a description of the external system connectors and the information about the hybrid components and the connections among them. The connection information is based on the first and second law of Kirchhoff, applying general laws of conversation of energy. Based on the system model in the second and third step all components are connected on-line to each other and analyzed and evaluated in predefined temporal distances.

On-line State Space Reduction

The second step consists of the "on-line state space reduction" and is shown in Figure 4. The appropriate analysis is carried through on the base of hybrid components, the system model, and sensors and actuators data of the technical process. With this input the computer in the beginning calculates periodically all possible trajectories for a defined time slot and then the computer reduces the state space. The reduced qualitative state space contains all states and transitions of the system for the predefined time slot and can be examined for possible process deviations and process faults.

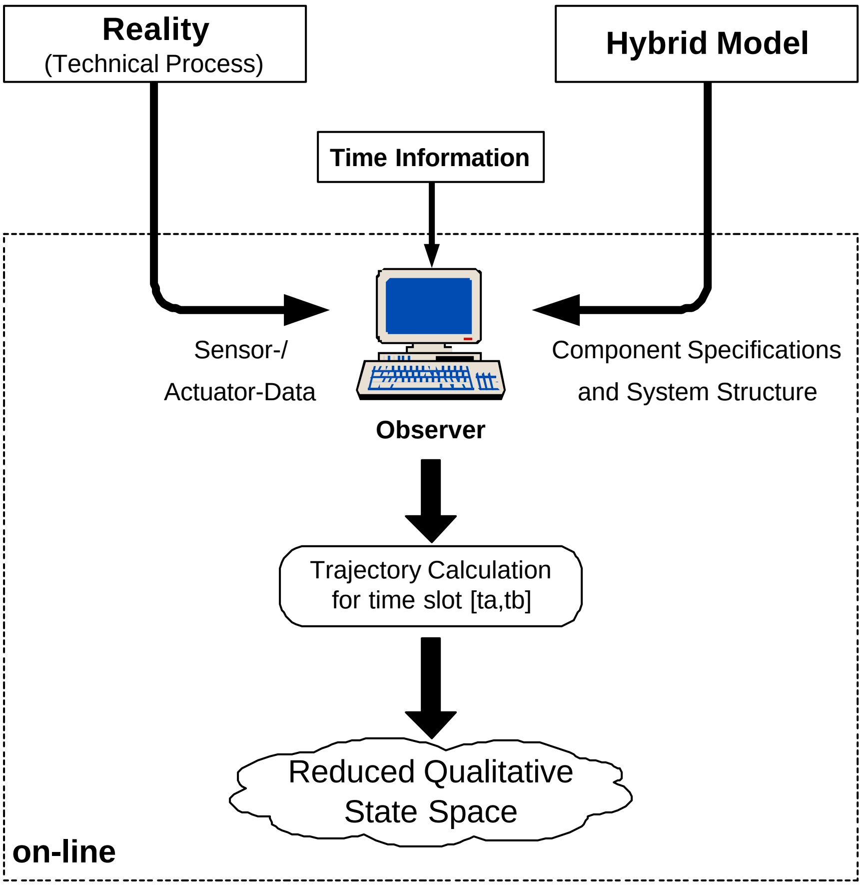

Figure 4: State Space Reduction

The principle of the state space reduction is shown in Figure 5 for the example of the component tank. The input for calculation is on the left side the on-line information of the technical process, that are the sensor- and actuator-data for a given time slot. On the right side the observer obtains as input information the hybrid model of the tank, this is the situation table and the differential equation.

The on-line calculation starts at t = 0 sec with the tank filled (h = 60 cm) and without inflow (Q_{in} = 0 cm^3/sec). Then the observer calculates all possible trajectories for the predefined time slot of 20 sec as a prediction for all possible states. The calculation of the trajectories is performed within the dynamical model of the tank. The result shows, that the level of the tank ranges between h = 60 cm and h = 40 cm. With this information all impossible situations are excluded from the situation table and the result is a reduced qualitative state space for the given time slot.

The calculation shown in Figure 5 is performed periodically for every given time slot and yields different parts of the reduced qualitative state space. The third step consists of the analysis and evaluation of the reduced qualitative state space in order to find faulty or dangerous states.

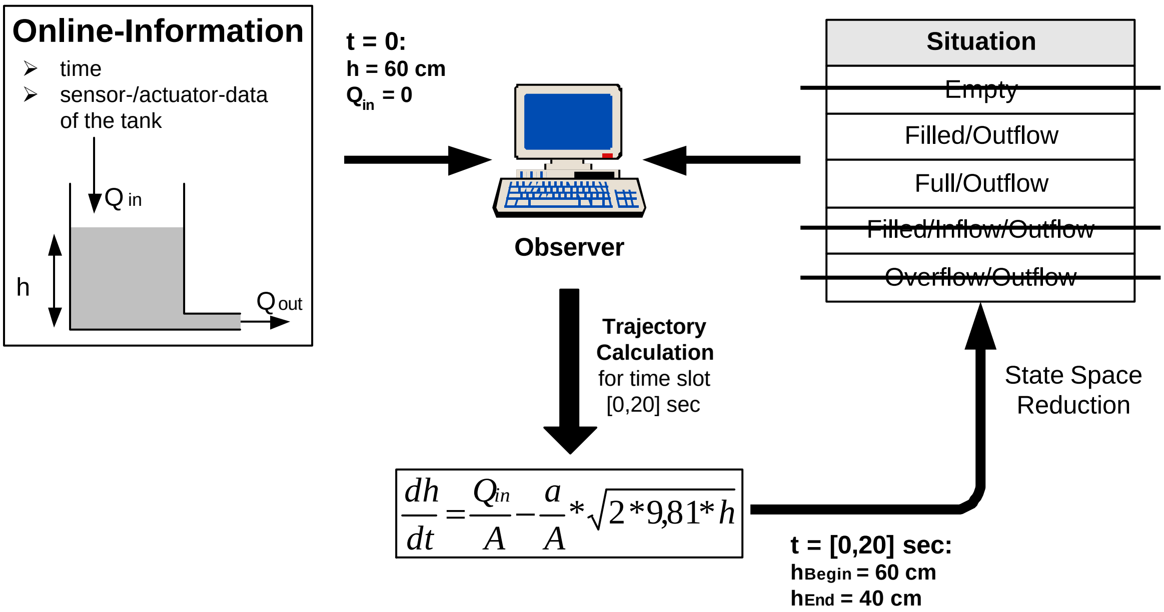

Figure 5: State Space Reduction for the tank

Analysis and Evaluation

In the third step the reduced qualitative state space is analyzed and evaluated according to the application. The SQMD model can also be used in designing software for control systems. The starting point of design is the safety analysis of the technical system by the SQMD-method. Within the safety analysis it is possible to analyse the technical system for all faulty cases. The causes and effects of all known faults in the system can be analyzed, so that the faults or respectively not desired behavior of the system can be detected and taken into account in the early control software design. The aim is to increase the reliability and safety of automation solutions. The models made for the safety analysis can be used without modification for the on-line monitoring of the complete automation system. In this case the observer recognizes whether the technical process is in a faulty or in a dangerous state. It is necessary for the observer to differentiate between these states so that the following steps (like warnings) can be performed.

Because of the on-line state space reduction and the following analysis and evaluation only monitoring in the time range of seconds is possible. For such systems danger and damage can be minimized.

Furthermore it is desirable to identify the localization of the detected faults. The localization is not as time critical as the on-line monitoring and can also be performed in offline-mode. The task of the diagnosis is to localize the faults and to take measures to bring the process into a safety mode. The diagnosis is realized by exchanging the SQMD model in the normal operation mode to the model in the faulty mode. In the faulty mode model all known faults and dangers are considered. Another part of the model, the transition graph of the system, permits the backward tracing of states.

4 On-line Monitoring and Diagnosis of an One-Tank-System

Figure 6 shows a small system of one tank coupled with a pump and a valve. This system consists of three components: tank, pipe with a valve, and pump. The pump fills the tank with a liquid. The pipe has a limited flow rate. The task of the valve is to stop the outflow at a defined time to simulate a total occlusion. At every time the inflow and outflow of the tank are measurable.

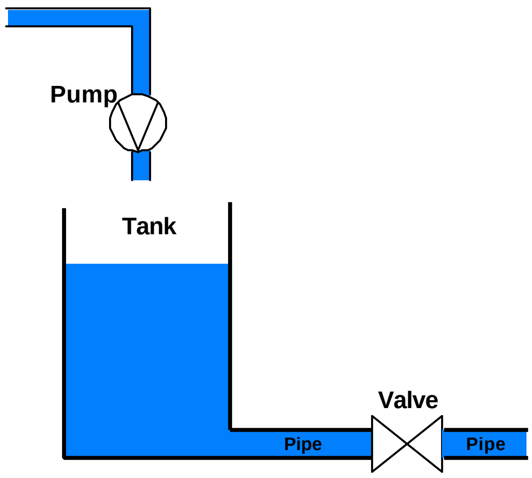

Figure 6: One-tank-system

For the small system shown in Figure 6 the results of the on-line monitoring and diagnosis shall be discussed. The following initial and boundary conditions are presumed for the simulation:

- At the beginning (t = 0 sec) the tank is half full (level = 30 cm)
- The inflow is controlled by a rectangular pulse (as shown in Figure 7)
- The valve is opened up to t = 100 sec, later on it will be closed

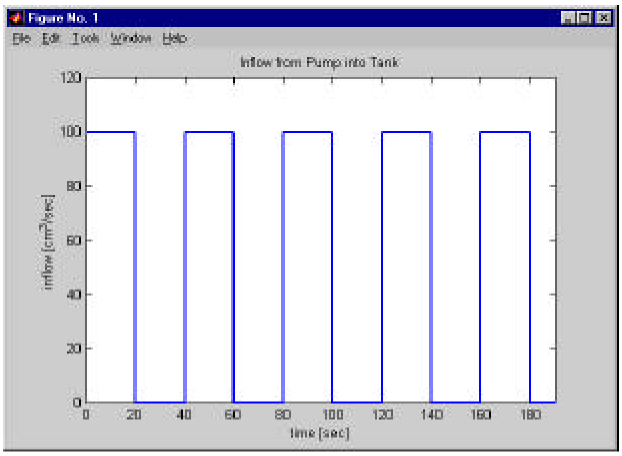

Figure 7: Inflow from Pump into Tank

Figure 8 presents the result of the on-line monitoring for the given initial and boundary conditions. In this figure the qualitative and quantitative trajectories are shown. The quantitative trajectory describes the continuous-value and continuous-time level of the tank depended on time. This solution was obtained with the commercial simulation tool Matlab/Simulink. In Figure 8 it should be noticed, that the valve closes at t > 100 sec, so the tank level cannot sink any lower.

It is the aim of the on-line monitoring using the SQMD model to recognize the overflow of the tank in time as good as the solution of the differential equation. In that case the warning limit at the tank level of 50 cm and the stopping limit at the tank level of 60 cm have to be considered.

The qualitative trajectory is a discrete-value and discrete-time representation of the tank level. This is demonstrated in Figure 8 by rectangles, which symbolize the prediction of the tank level in time intervals of 15 sec. So the tank level ranges, for example, at the time t = 0 sec between 20 and 40 cm or at the time t = 210 sec between 20 and 60 cm. Beginning at the time t = 220 sec the mean value of the prediction reaches the warning limit. In that case it is necessary to warn the operator of the system.

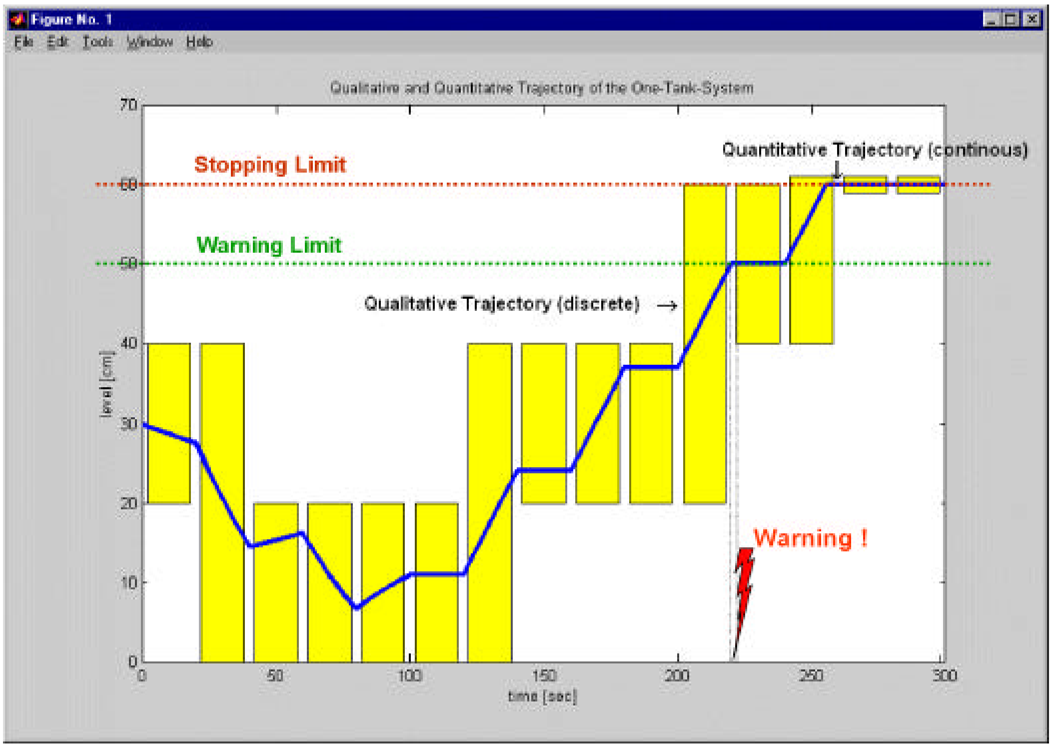

Figure 8: Trajectories of the example one-tank-system

The diagnosis is performed by the backward tracing of the states on the basis of the transition graph. In the given example the fault, which causes the overflow, is recognized as the closed valve at the time t = 100 sec.

5 Outlook

One advantage of the hybrid modeling method is the ease of performance of complex dynamical systems. In this field two aspects play an important role. On the one hand already existing mathematical models are combined with qualitative models so that complex systems can be modeled and simulated. On the other hand a part of the state space is analyzed, so that the states concerned can be evaluated on-line with low computation power.

For the future the model building, analysis and the evaluation should be done in a special SQMD toolbox for Matlab/Simulink. So the model expert can be supported in a comfortable way and the main part of the tasks can be performed automatically.

6 References

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