# Data analysis for the evaluation and design of a model-based fault detection based on an independent metering system for mobile hydraulic drives.

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This paper deals with model-based fault detection based on parity equations for a mobile hydraulic system with independent metering. Considering the associated limitations of mobile systems, different operating points, and a variety of fault scenarios, a set of parity equations is created and investigated by simulation. By analyzing the data generated from the simulation study, the suitability of the parity equation set can be evaluated and thresholds for robust fault detection are determined. The features derived from the equation sets are relevant in the localization of the faulty component.

**Keywords:** model-based fault detection, independent metering
**Target audience:** Mobile Hydraulics, Safety and Reliability

## 1 Introduction

Systems with independent metering (IM systems) have many well-known advantages, such as reduced energy losses and increased structural flexibility. The implementation of these systems requires the consistent implementation of electrohydraulic drive systems and an expanded use of sensors. Due to the progressing digitalization and automation of machines, mechatronic drives are finding their way into machines anyway.

Nevertheless, there are only a few market-ready implementations of IM systems to date, e.g. [1], [2]. The increased system complexity in combination with extensive control algorithms, software architectures and safety aspects may be the reasons for this. Previous work shows that IM systems are able to meet high security requirements if the necessary diagnostic coverage is ensured [3]. To achieve the required diagnostic coverage, model-based fault detection methods are a promising approach for monitoring hydraulic drive systems in general [4] and also mobile hydraulic drives in particular [5]. Especially for mobile hydraulic applications and the associated limitations, a simple and robust method is advantageous. Parity equations fulfill these conditions and have already proven their potential [6]. The use of different parity equations with different balance limits makes it possible to determine the location of the occurring fault in addition to pure fault detection. This leads to a better and quicker maintainability.

Mobile machines are mostly operator-controlled systems whose operating cycles are highly variable. In addition, IM systems have more potential failure sources than a conventional hydraulic system due to the larger number of used components. This results in a large number of system states that must be considered when implementing and designing a fault detection system. A simulation-based variant analysis takes this large number into account and makes it possible to consider this multitude of influences. Features derived from the residuals of the parity equations provide information about the possibilities of error detection as well as for the selection of suitable limit values.

## 2 Subject of investigation

Basis of the design of the fault detection is the excavator test rig at the research centre. The system consists of the working equipment and its electro-hydraulic actuation. An IM system with two pilot-operated 2/2 proportional valves (see **Figure 1**, $V_{prop,A}$, $V_{prop,B}$) and four 2/2 switching valves ($V_{sv,AP}$, $V_{sv,AT}$, $V_{sv,BP}$, $V_{sv,BT}$) each controls the boom and the stick cylinder. The proportional valves control the flow rate or the pressure; the switching valves define the operating mode of the IM structure. The underlying control algorithms follow the approach published in [7]. By means of static decoupling, the cross influences in the MIMO-system are reduced and the IM system can be controlled more easily. An electronically controlled variable displacement pump, operated in closed-loop control, supplies the system. The test stand has extensive sensory equipment. In addition to the pressures before and after the proportional and switching valves, the velocities of the cylinders and the positions of the proportional valves are also measured. This makes it possible to create a set of different parity equations and to evaluate the achievable diagnostic coverage depending on the sensors used.

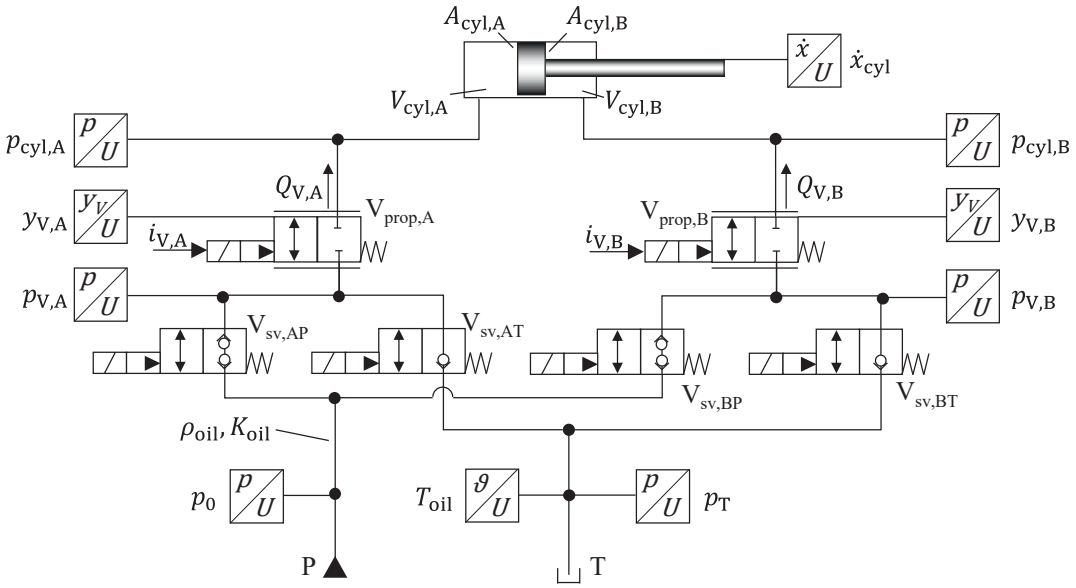



*Figure 1: Design of the investigated independent metering system.*

A validated simulation model of the demonstrator, implemented in SimulationX, exists at the research centre. [8]. This model is part of a Software-in-the-loop environment and provides the basis for the simulation-based variant analysis.

## 3 Model-based fault detection based on parity equations

A detailed description of the parity equations can be found in [6]. Therefore, only the basic aspects as well as the extended considerations of these basics shall be dealt with here. The goal of parity equations is to generate residuals by comparing measured and calculated output variables. The outputs considered here are the cylinder speeds and the positions of the proportional valves.

Considering a cylinder chamber, the volume flow through the proportional valve $Q_V$ leads both to a pressure build-up $\dot{p}_{cyl}$ in the associated volume $V_{cyl}$ and to a movement of the cylinder. As seen in Equation (1), this volume flow balance can be resolved according to the cylinder velocity $\dot{x}_{cyl}$ .

$$\dot{x}_{cyl}(T_{oil}, i_V, p_{cyl}, p_V, x_{cyl}, t) = \frac{1}{A_{cyl}} \cdot \left( Q_V(t, T_{oil}, i_V, p_{cyl}, p_V) - Q_{dp}(t, T_{oil}, p_{cyl}, x_{cyl}) \right)$$
$$= \frac{1}{A_{cyl}} \cdot \left( Q_V(t, T_{oil}, i_V, p_{cyl}, p_V) - \dot{p}_{cyl}(t) \cdot \frac{V_{cyl}(x_{cyl})}{K'_{oil}(T_{oil}, p_{cyl})} \right) \quad (1)$$

The volume flow through the proportional valve $Q_\mathrm{V}$ is approximated by a fourth degree polynomial (Equation (2)). Existing measured values for the flow characteristics and the valve dynamics are the basis of the parameterization.

$$Q_\mathrm{V}(T_\mathrm{oil}, y_\mathrm{V}, p_\mathrm{cyl}, p_\mathrm{V}, x_\mathrm{cyl}, t) = sign(p_\mathrm{V} - p_\mathrm{cyl}) \cdot \sqrt{|p_\mathrm{V} - p_\mathrm{cyl}|} \cdot \sum_{\mathrm{k}=1}^{4} a_\mathrm{k} \cdot \mathrm{y}_\mathrm{V}^{k}(t) \tag{2}$$

The evaluation of measurement results also suggests the assumption of a PT2Tt transfer behavior for the valve dynamics (Equation (3)).

$$\ddot{y}_\mathrm{V}(t) + 2D_\mathrm{V}\omega_\mathrm{V}\dot{y}_\mathrm{V}(t) + \omega_\mathrm{V}^2 y_\mathrm{V}(t) = \omega_\mathrm{V}^2 \cdot K_\mathrm{V} \cdot i(t - T_\mathrm{t}) \tag{3}$$

Another essential model aspect is the hydraulic fluid. The description of the oil behavior is often accompanied by the greatest uncertainties. According to Kim [9] and Karjalainen [10], the temperature as well as the pressure dependency of the fluid bulk modulus can be described as a proportional relationship. Deviations in the range of low pressures are accepted here. By measuring the speed of sound $c_\mathrm{oil}$ and the density of the fluid $\rho_\mathrm{oil}$ and their relation to the adiabatic compression modulus $K_\mathrm{oil}$ (4) the model parameters are determined.

$$c_\mathrm{oil}(T_\mathrm{oil}, p_\mathrm{oil}) = \sqrt{\frac{K_\mathrm{oil}(T_\mathrm{oil}, p_\mathrm{oil})}{\rho_\mathrm{oil}(T_\mathrm{oil}, p_\mathrm{oil})}} \tag{4}$$

An existing test rig allows the measurement of sound velocity as a function of pressure and temperature. The density was determined as a function of temperature and extended with an empirical pressure-dependent approach [11]. An equivalent bulk modulus $K'_\mathrm{oil}$ can be estimated from the bulk modulus of the oil $K_\mathrm{oil}$, taking into account cylinder and line elasticities [11]. For the simulative variant study, these housing elasticities are initially not considered due to insufficient parameterization basis. This will be adjusted during the practical tests.

In order to solve the resulting differential equation system on a mobile controller, a time discrete solver is required. The forward Euler method, as an explicit one-step method, is particularly suitable. For this purpose, the introduced differential equations are transformed into a system of first order differential equations (5). For simplification, the functional dependency of parameters will not be shown in the following.

$$y_\mathrm{Pari_4}: \quad \frac{d}{dt} \cdot \begin{pmatrix} y_\mathrm{V} \\ \dot{y}_\mathrm{V} \\ x_\mathrm{cyl} \end{pmatrix} = \begin{pmatrix} \dot{y}_\mathrm{V} \\ \omega_\mathrm{V}^2 \cdot \left( K_\mathrm{V} \cdot i(t - T_\mathrm{t}) - 2 \cdot \frac{D_\mathrm{V}}{\omega_\mathrm{V}} \cdot \dot{y}_\mathrm{V} - y_\mathrm{V} \right) \\ \left( \frac{1}{A_\mathrm{cyl}} \cdot \left( sign(p_\mathrm{V} - p_\mathrm{cyl}) \cdot \sqrt{|p_\mathrm{V} - p_\mathrm{cyl}|} \cdot \sum_{\mathrm{k}=1}^{4} \left( a_\mathrm{k} \cdot \mathrm{y}_\mathrm{V}^{k} \right) - \dot{p}_\mathrm{cyl} \cdot \frac{V_\mathrm{cyl}}{K'_\mathrm{oil}} \right) \right) \end{pmatrix} \tag{5}$$

This system of equations calculates the cylinder velocity $\dot{x}_\mathrm{cyl}$ based on the measured pressures $p_\mathrm{V}$ and $p_\mathrm{cyl}$ and the input signal $i$ (valve current). Minor modifications to Equation (5) allow the derivation of additional parity equations. If, for example, a position-monitored proportional valve is used, two additional parity equations can be generated in which valve dynamic and flow behavior are no longer coupled, but are each considered as independent parity equations with their own residuals:

$$y_\mathrm{Pari_2}: \quad \frac{d}{dt} \cdot \begin{pmatrix} y_\mathrm{V} \\ \dot{y}_\mathrm{V} \end{pmatrix} = \begin{pmatrix} \dot{y}_\mathrm{V} \\ \omega_\mathrm{V}^2 \cdot \left( K_\mathrm{V} \cdot i(t - T_\mathrm{t}) - 2 \cdot \frac{D_\mathrm{V}}{\omega_\mathrm{V}} \cdot \dot{y}_\mathrm{V} - y_\mathrm{V} \right) \end{pmatrix} \tag{6}$$

$$y_\mathrm{Pari_3}: \quad \dot{x}_\mathrm{cyl} = \left( \frac{1}{A_\mathrm{cyl}} \cdot \left( sign(p_\mathrm{V} - p_\mathrm{cyl}) \cdot \sqrt{|p_\mathrm{V} - p_\mathrm{cyl}|} \cdot \sum_{\mathrm{k}=1}^{4} \left( a_\mathrm{k} \cdot \mathrm{y}_\mathrm{V}^{k} \right) - \dot{p}_\mathrm{cyl} \cdot \frac{V_\mathrm{cyl}}{K'_\mathrm{oil}} \right) \right) \tag{7}$$

If the system pressures $p_0$ or $p_\mathrm{T}$ are used instead of the pressure $p_\mathrm{V}$ between the switching and proportional valve, a further equation is also obtained. For this, a known pressure loss behavior $\Delta p_\mathrm{sv}$ of the switching valve is assumed.

$$y_{\text{Pari_1}}: \quad \frac{d}{dt}\cdot\begin{pmatrix} y_\text{V} \\ \dot{y}_\text{V} \\ x_\text{cyl} \end{pmatrix} = \begin{pmatrix} \dot{y}_\text{V} \\ \omega_\text{V}^2 \cdot \left(K_\text{V} \cdot i(t-T_\text{t}) - 2\cdot\frac{D_\text{V}}{\omega_\text{V}}\cdot\dot{y}_\text{V} - y_\text{V}\right) \\ \dfrac{\left(sign(p_\text{S}-p_\text{cyl})\cdot\sqrt{|p_\text{S}-p_\text{cyl}|-\Delta p_\text{sv}}\cdot\sum_{\text{k=1}}^{4}(a_\text{k}\cdot y_\text{V}^k) - \dot{p}_\text{cyl}\cdot\frac{V_\text{cyl}}{K'_\text{oil}}\right)}{A_\text{cyl}} \end{pmatrix} \tag{8}$$

$$\text{with: } p_\text{S} = \begin{cases} p_0, & \text{for } \dot{x}_\text{cyl} > 0 \text{ (without regeneration modes)} \\ p_\text{T}, & \text{for } \dot{x}_\text{cyl} < 0 \text{ (without regeneration modes)} \end{cases}$$

In the controller of the demonstrator application, the operator request is converted into a set point value of the valve volume flow, taking into account the performance limits of the machine. If the calculated volume flow is replaced with this setpoint, another evaluable relationship is obtained (Equation (9)).

$$y_{\text{Pari_5}}: \quad \dot{x}_\text{cyl} = \left(\frac{1}{A_\text{cyl}}\cdot\left(Q_\text{V,set} - \dot{p}_\text{cyl}\cdot\frac{V_\text{cyl}}{K'_\text{oil}}\right)\right) \tag{9}$$

If one carries out this consideration for each cylinder side separately, ten available parity equations result. Even if there is a high dependency between the parity equations (5), (7) and (8), these equations increase the diagnostic possibilities. Another equation at the overall system level completes the set of parity equations. Based on the measured consumer movements in connection with the circuit configuration of the IM system, a comparison with the supplied pump volume flow $Q_\text{P}$ is possible. Equation (10) describes this relationship, where l stands for all volumes and j represents all consumers whose cylinder chambers are connected to the pump.

$$y_{\text{Pari_S1}}: \quad Q_\text{P} = \left(\sum_{\text{j=1}}^{\text{n}}\left(\frac{1}{A_\text{cyl,n}}\cdot\dot{x}_\text{cyl,n}\right) + \sum_{\text{l=1}}^{\text{m}}\left(\dot{p}_\text{l}\cdot\frac{V_\text{l}}{K'_\text{oil,l}}\right)\right) \tag{10}$$

**Table 1** summarizes the signals needed to generate residuals for each parity equation. The naming of the parity equations results from the balanced cylinder side. Therefore, parity equation A1 indicates equation $y_{\text{Pari_1}}$ for the piston side. The difference between the calculated $y_{\text{Pari_i}}$ and measured value $y_{\text{Pari_i,meas}}$ is the residual $r_{\text{Pari_i}}$ and is equal to zero in the fault-free ideal system.

$$r_{\text{Pari_i}} = y_{\text{Pari_i}} - y_{\text{Pari_i,meas}} \tag{11}$$

| Parity equation | | Input signals for parity equation | | | | | | | | Measured values for comparison | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Name | Eq. | $i$ | $y_\text{V}$ | $p_\text{V}$ | $p_\text{cyl}$ | $p_0, p_\text{T}$ | $Q_\text{V,set}$ | $\dot{x}_\text{cyl}$ | | $\dot{x}_\text{cyl}$ | $y_\text{V}$ | $\alpha_\text{P}$ | $n_\text{P}$ |
| A1, B1 | $y_{\text{Pari_1}}$ | x | | | x | x | | | | x | | | |
| A2, B2 | $y_{\text{Pari_2}}$ | x | | | | | | | | | x | | |
| A3, B3 | $y_{\text{Pari_3}}$ | | x | x | x | | | | | x | | | |
| A4, B4 | $y_{\text{Pari_4}}$ | x | | x | x | | | | | x | | | |
| A5, B5 | $y_{\text{Pari_5}}$ | | | | x | | x | | | x | | | |
| S1 | $y_{\text{Pari_S1}}$ | | | x | x | x | | x | | | | x | x |

*Table 1: Required measured signals for generating residuals based on the parity equations.*

## 4 Simulation-based variant study

For a working error detection, it is necessary for each individual parity equation to have a significant residual only when an error has an effect within the balance limits of that equation. Otherwise, false alarms can be expected during operation. In order to evaluate the suitability of the parity equations for fault detection, it is mandatory to consider different operation and load conditions as well as various fault scenarios. The resulting multitude of system states can only be handled with the help of a simulation-based variant study. Initially, only a single consumer movement of the boom is considered.

The fault scenarios investigated include all electrical and electrohydraulic components. Every proportional and switching valve as well as every sensor is regarded as potentially faulty. Inserting synthetic faults into the components results in different fault conditions. The synthetic errors cause a modified component behavior, e.g. by a value offset, a changed signal amplification or switching to the operating limits of the component. The technical-physical cause of the error is not relevant. Only the effect of a faulty state on the system behavior is important. By varying the error intensity, we try to evaluate the sensitivity of the parity equations. This results in a total of approximately 540 different single fault scenarios, which are examined at each operation point. The influence of different operation points is taken into account by varying the time of failure within a reference cycle. In this way, the failures are inserted during standstill, extension and retraction of the boom at constant speed, as well as during acceleration and deceleration phases. For reasons of consistency, all results are presented only at one fault time ($t_F$ = 7.2 s) . In this operation point the cylinder is actively retracted against the external load and raises the boom.

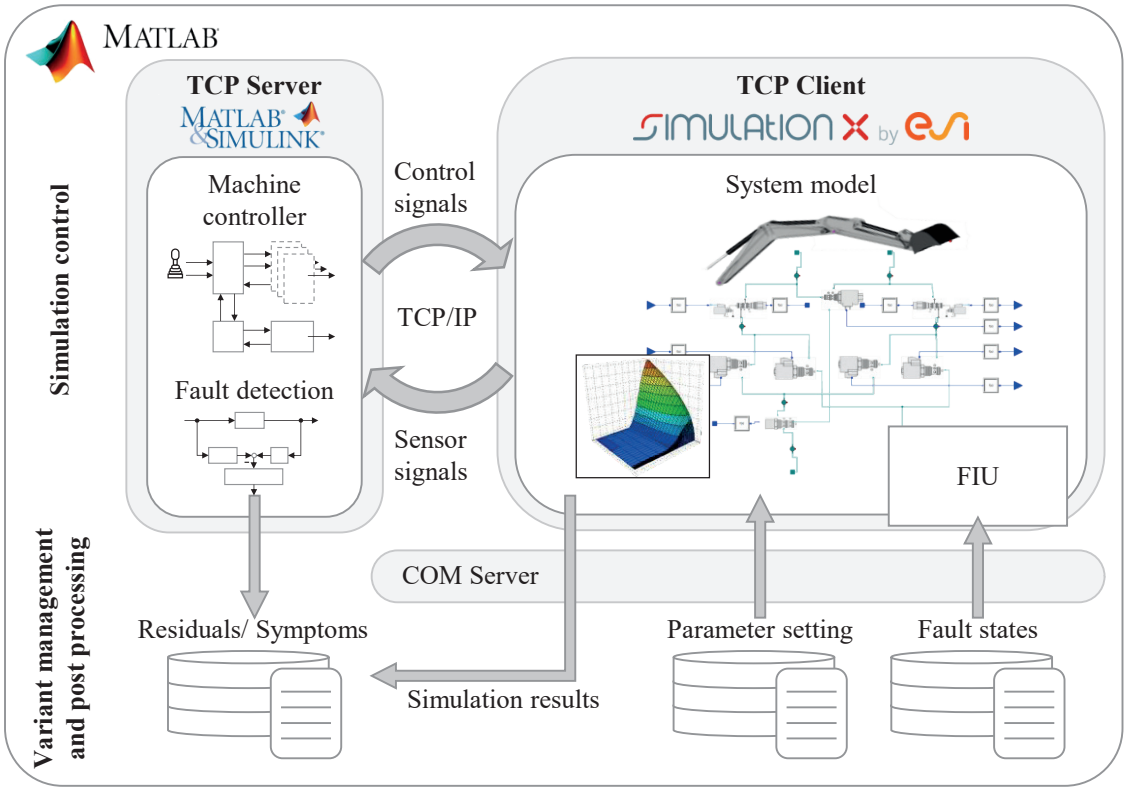



*Figure 2: Structure of the variant simulation*

The basis of the variant study is a simulation model of the demonstrator in SimulationX and a Simulink model, which provides the required algorithms and state machines for valve and pump control (see **Figure 2**). Model-based fault detection in the form of discrete parity equations is also implemented. The exchange of control and sensor signals takes place via the TCP/IP network protocol. This co-simulation can be considered as validated. A freely configurable fault insertion unit (FIU) extends the existing demonstrator model and realizes the implementation of the synthetic faults. The superordinate simulation control and residual evaluation was realized

in MATLAB. Via MATLAB and a COM (Component Object Model) server, specific model parameters can be changed and the resulting signals can be accessed.

Starting point of the further consideration is the assumption that different parity equations react differently to faulty states and therefore the time as well as the location of a fault can be detected. A preliminary study with the created test environment shows the potential of the designed model-based fault detection. Assuming a known fault time, the responses of the implemented parity equations are determined, normalized to the error-free case and plotted in a parallel coordinate system. **Figure 3** shows for the known fault time $t_F$ = 7.2 s the determined residuals $\Delta r_{norm}$ of the different parity equations (A1 to S1) for all imprinted fault states, grouped by the location of the occurring fault. For better clarity, a distinction is made here only between faults (valve and sensor faults) on the piston and rod side of the cylinder and non-assignable sensor faults on system level. The representation proves the selective behavior of the parity equations, and the generation of significant residuals in the error case. For example, imprinted errors on the rod side of the cylinder are only visible in the associated parity equations on the rod side. Faults at the whole system level (e.g. the velocity sensor $\dot{x}_{cyl}$) change the residuals in both the rod and piston side parity equations.

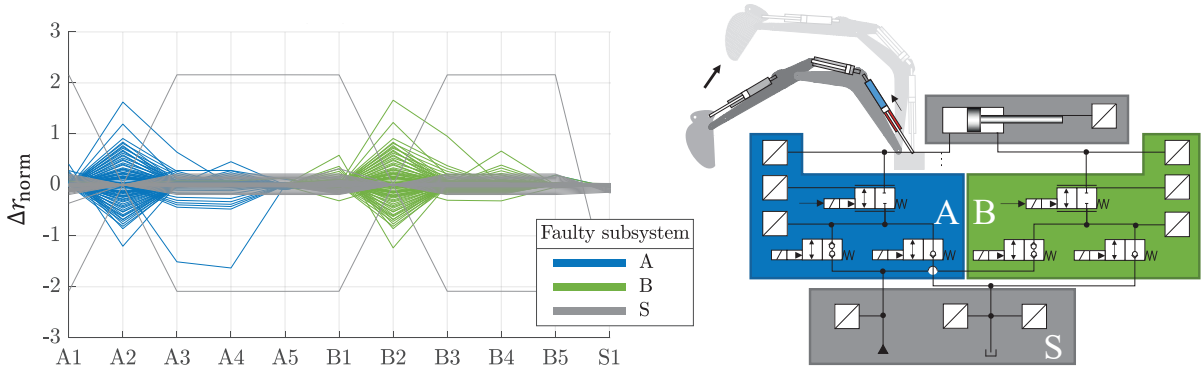



*Figure 3: Sensitivities of the parity equations to faulty states in the subsystems of the valve-controlled actuator in parallel coordinate representation.*

## 5 Determination of robust limit values

Obviously the primary goal of fault detection is the safe detection of dangerous failures. However, for practicable and economic use, it is just as important to exclude false alarms as far as possible. This contradictory demand for sensitivity and robustness is expressed in the search for suitable limit values for permitted residuals of the parity equations. If the residuals exceed the limits, features (symptoms) are generated that indicate the occurrence of an error.

A pragmatic approach to this optimization problem is to determine the limit values under the condition of the highest possible robustness, namely the avoidance of false alarms. Subsequently, the quality of the achievable error detection must be determined.

The simulatively generated database is basis for determining the limit values. Causes for deviations between the calculated and measured variables are model inaccuracies (e.g. fluid model, valve map) and the limitations of the hardware-related implementation (e.g. cyclic program processing, resolution of the variables). In the error-free case, but also in the case of faulty states outside the balance limits of the respective parity equation, these deviations must not lead to exceeding the threshold values. Only then, false alarms and detections are excluded. Dynamic processes and states may cause temporary exceeding of threshold values. These must also not lead to a fault symptom. The determination of the thresholds therefore takes into account that exceedances of thresholds must persist for a minimum period of time, the observation time $t_O$. This time dimension as well as the necessary signal filtering of the measured values reduces the influence of dynamic model inaccuracies in the threshold choice. Static model deviations, such as deviations in the flow rate description of the valve, become the determining factor. These

deviations are dependent on the operation point, but cannot be described by a simple functional relationship. Furthermore, an operating point-dependent determination of the static deviations is costly to realize in practice. For this reason, adaptive thresholds are not used and only one global threshold is determined for each parity equation. These are much easier to determine in practice.

## 6 Evaluation of the effectiveness of fault detection

A second variant study, with implemented thresholds, forms the basis for the evaluation of the error detection potential. This involves a permanent check of whether the residuals of the parity equations exceed the specified threshold values and whether this exceedance is maintained for a minimum period. Symptom generators fulfil this task. They generate evaluable features from the residuals.

The evaluation of the symptoms provides information about detected faults and which parity equations actually generate a symptom as a result of an imposed fault. A faulty condition is considered to be detected if at least one symptom is generated.

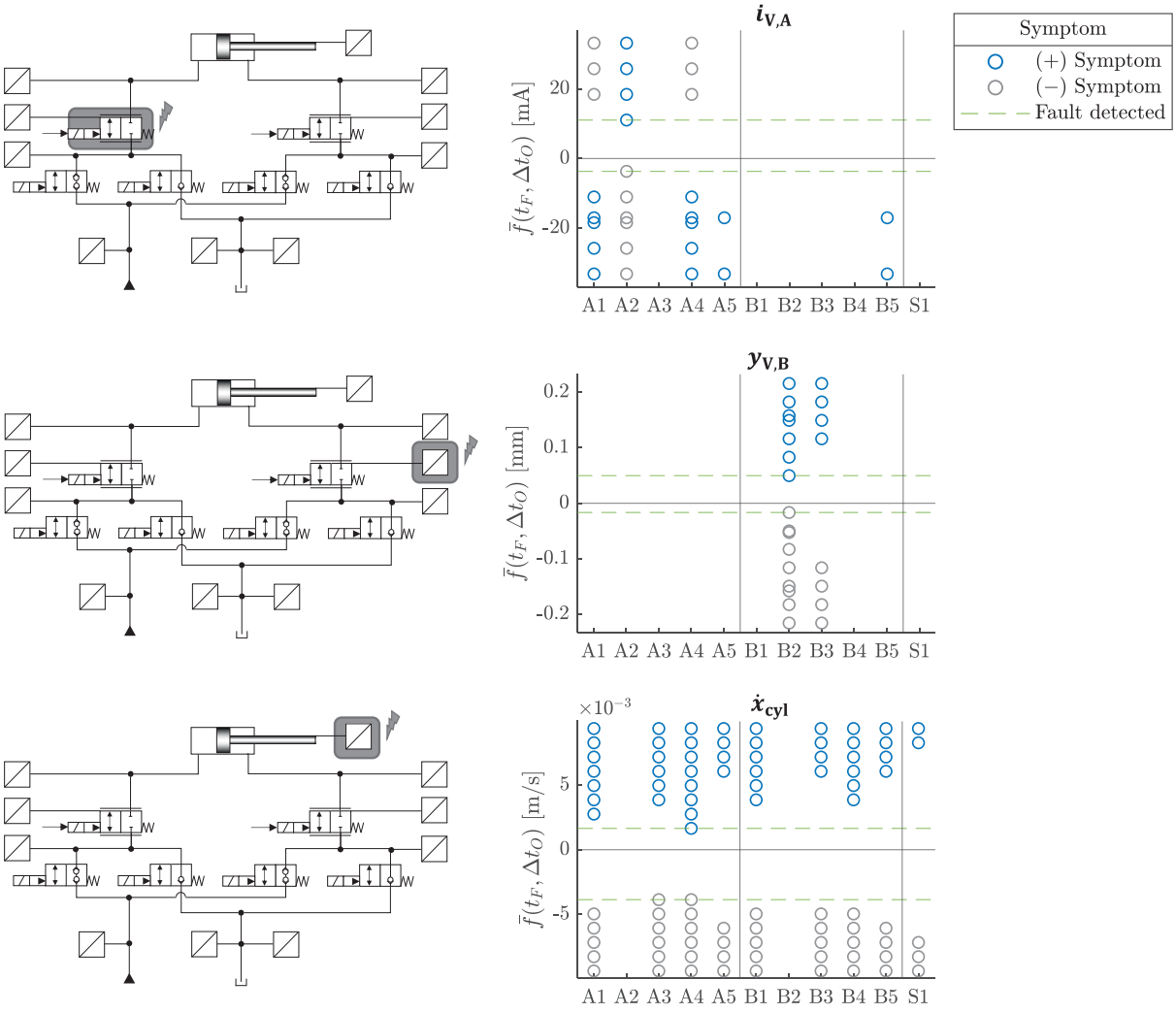



*Figure 4: Generated residuals at different fault states.*

**Figure 4** shows the result of the variant study, exemplified by the generated symptoms of selected fault cases in the considered operation point. The diagram shows the measured variables and control variables that are influenced by the FIU. Manipulation of the valve current $i_{V,A}$ emulates a faulty opening position or a stuck valve spool. Damaged sensors or faulty signal transmission lead to incorrect signals of valve position $y_{V,B}$ and cylinder velocity $\dot{x}_{cyl}$. Each diagram represents different fault states and intensities of one faulty component. Since different

temporal fault characteristics occur depending on the fault state (offset fault, amplification fault, etc.), the fault intensity averaged over time $\bar{f}$ is plotted on the ordinate. If a symptom occurs in one of the parity equations plotted on the abscissa at this averaged error intensity, this is marked according to the legend. Exceeding the upper threshold leads to a positive symptom (+), falling below the lower threshold produces a negative symptom (-). For example, the middle symptom plot shows generated symptoms in case of faulty sensor information of the valve spool position $y_{\mathrm{V,B}}$. According to the expectation, only parity equations B2 and B3 generate a symptom. Equation B2 is more sensitive to the error and detects lower error intensities. Equation B3 requires larger error intensities to provide a symptom. The intensities of detected faults are asymmetrical to the axis origin. Model assumptions within the parity equations lead to a residual $r_{\mathrm{Pari_i}} \neq 0$ even in the error-free case. Depending on the error expression, the amount of the residual is amplified or initially even reduced. This effect and the strongly nonlinear system behavior lead to the asymmetric detection behavior.

Only symptoms that are generated immediately after the fault has occurred (maximum 2 seconds after fault occurrence) are evaluated. Since in many cases a quick detection of faults is necessary to avoid hazardous situations, symptoms that occur later are not considered in the potential evaluation of the fault detection. Faulty states for which no valid symptom is generated within 2 seconds are therefore treated as undetected faults.

The selected thresholds prevent the spurious development of symptoms. However, the sensitivity of the parity equations to the relevant error cases remains. Thus, many fault cases lead to the generation of symptoms. As expected, sufficiently different characteristics are formed that suggest the possibility of localizing the faulty component.

If one takes a holistic view of the investigated operation point, the model-based fault detection generates at least one symptom in 70% of the imprinted fault cases (see **Figure 5**). Accordingly, 30% of the faults remain undetected. In order to be able to evaluate the quality of the fault detection, it is necessary to assess the detected or undetected faults with regard to their potential hazardousness. The faulty movement of the cylinder in relation to the fault-free case is the criteria for this. The greater the position difference in the error case, the more the cylinder movement deviates from the operator's expectation. The histograms shown in the figure provide information about the frequency of position deviations. If faults are detected, the position deviation up to the point of detection is 3 cm at the most. If no reaction measure is initiated, the position deviation increases sharply within 2 seconds for the majority of the errors and in some cases leads to movement into the end position of the cylinder ($\Delta x_{\mathrm{cyl}}$ = 44 cm). These errors are potentially dangerous. In the case of undetected errors, the position deviation on the cylinder is 3 cm at most after 2 seconds. The undetected faults therefore do not lead to a hazardous situation at considered operation point.

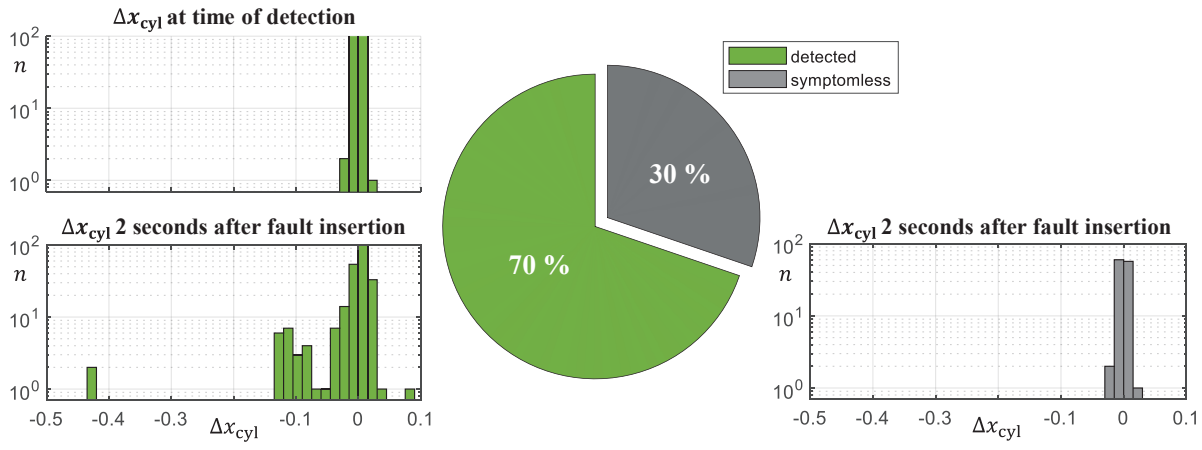



*Figure 5: Amount of detected errors and their impact on the cylinder position.*

This observation was repeated in different operation situations. The resulting detection rates vary widely in some cases. For example, during standstill of the demonstrator, only about 25% of the imprinted faults can be detected. However, all dangerous faults are detected for all points investigated.

The analysis can also be used to identify the most critical error cases. For example, an incorrectly opened drain valve $V_{sv,BT}$ short-circuits the pressure connection of the pump against the reservoir. The resulting system pressure is not sufficient to move the equipment and the boom lowers due to gravity (see **Figure 6**). However, less obvious faults also cause a potentially dangerous malfunction. For example, errors at the pressure sensors $p_0$, $p_{cyl,A}$ and $p_{V,B}$ also cause larger position deviations of up to 12 cm. The strategy for controlling the IM system is based not only on the desired target velocity but also on the various pressure signals. Incorrect sensor information may therefore also be a potential hazard.

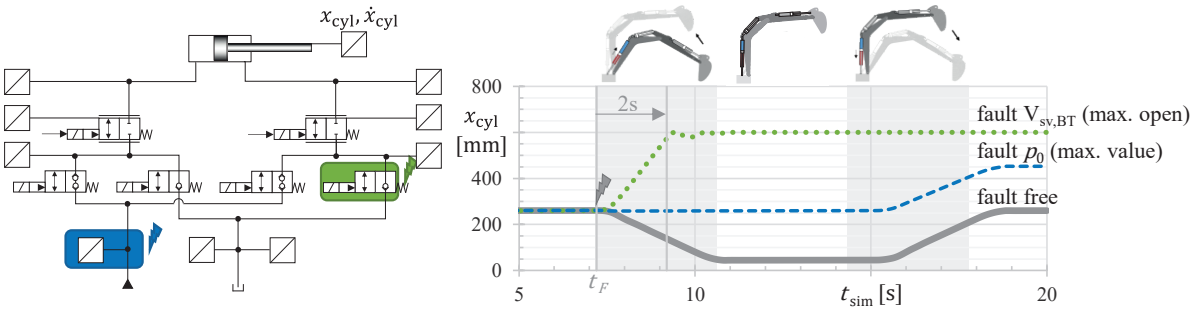



*Figure 6: Examples of identified critical failure cases.*

## 7 Potential for error identification

The parity equations (5) to (8) have very close and clear balance limits. Equations (9) and (10) use setpoints from the machine controller to calculate the residuals. Since various system information are taken into account of this setpoint calculation, the balance limits cannot be trivially specified here. For this reason, the fault state $i_{V,A}$ in Figure 4 also causes symptoms of parity equation B5. Nevertheless, an expectation exists for the created parity equation set due to the used measured values (see Table 1) and the corresponding balance limits, which equation should theoretically generate a symptom in case of a certain error. When comparing the real occurring symptom pattern with the expectation, the fault location can be concluded [12]. With a few exceptions, the expected patterns are characteristic of individual faulty components. Figure 4, however, illustrates the existing challenge. Different symptoms occur depending on the fault cause, but fully developed symptom patterns are not always present. Moreover, symptoms do not occur synchronously.

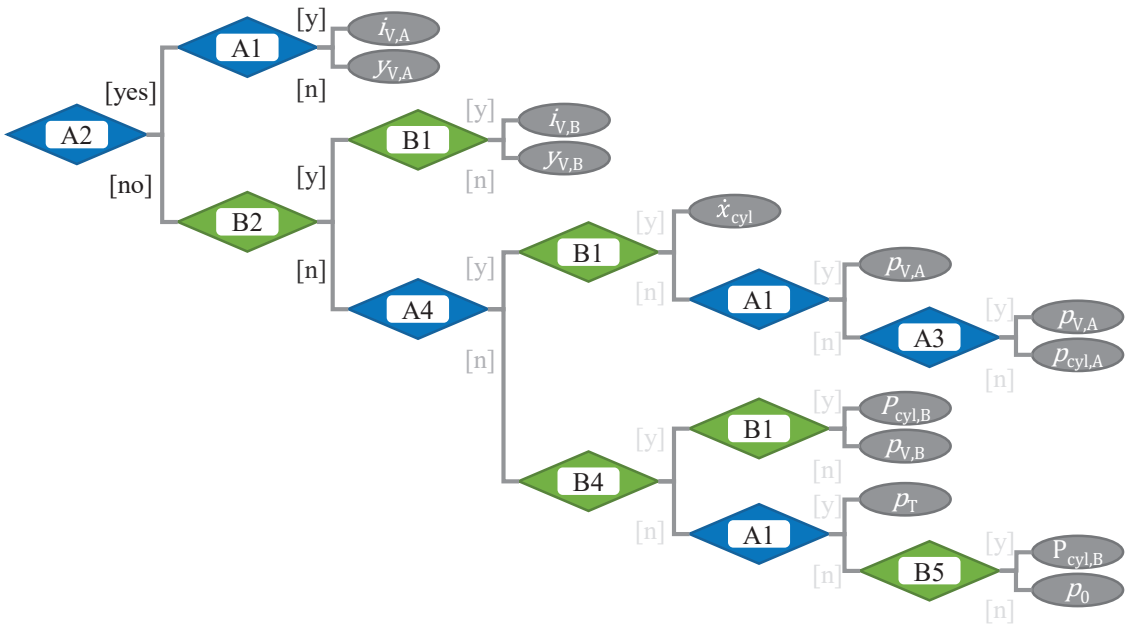



*Figure 7: Fault tree for the considered operating point.*

A simple way to determine the cause of faulty systems is the fault tree analysis. The data from the variant study is used to train a corresponding fault tree model. **Figure 7** shows the resulting fault tree. This model consists of up to 6 decision levels and achieves an accuracy of approximately 94% at the considered operating point. The majority of detected faults can therefore be correctly localized. Since only 2 possible fault scenarios were considered at the switching valves (faulty open, faulty closed), only few training data are available for these faults. The resulting fault tree therefore does not allow localization of these faulty components.

## 8 Summary and Conclusion

In this paper, a model-based fault detection for an independent metering system based on parity equations was presented. A software-in-the-loop approach supported the development and implementation of the parity equations. A simulative variant study enabled the testing of the model-based approach in a variety of different operational and fault scenarios. To validate the results of the variant study, a demonstrator test rig with the investigated IM system is available at the research center. This was equipped with additional sensor technology in order to be able to fully implement the parity equation set. The commissioning of the model-based fault detection is currently the focus of the work.

As a result, it could be shown that all critical faults can be detected with the set of parity equations used. For a high robustness, however, it is necessary to use certain temporal smoothing mechanisms, such as filtering the measured values or the occurrence of threshold crossings for a minimum period of time. Whether the detection performance that can be achieved in this way is sufficient must be checked in each individual case.

Fault localization on the basis of a fault tree delivers very good results. However, a systematic weakness of this approach lies in the hierarchical and binary approach. This results in a very high dependence on a few symptoms. Therefore, further variants for fault localization are being worked on.

## 9 Acknowledgements

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Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

## Nomenclature

| *Acronyms* | *Description* |
|---|---|
| COM | Component Object Model |
| FIU | Fault Insertion Unit |
| IM | Independent metering (system) |
| TCP/IP | Transmission Control Protocol/Internet Protocol |
| $V_{prop,A}$ / $V_{prop,B}$ | Proportional valve on the piston / rod side |
| $V_{svAP}$ / $V_{svAT}$ | Switching valve to connect the piston side with pump / reservoir |

| | |
|---|---|
| $V_{svBP}$ / $V_{svBT}$ | Switching valve to connect the rod side with pump / reservoir |

| ***Variable*** | ***Description*** | ***Unit*** |
|---|---|---|
| $a_k$ | Coefficient for valve description as 4th degree polynomial | $[l/(min \cdot \sqrt{bar} \cdot mm^k)]$ |
| $A_{cyl}$ | Cylinder area | [mm²] |
| $\alpha_{Pump}$ | Swivel angle of pump | [%] |
| $c_{oil}$ | Speed of sound in oil | [m/s] |
| $D_V, K_V, \omega_V, T_t$ | Parameters of valve dynamic: damping coefficient, gain, natural frequency, delay time | |
| $\bar{f}$ | Fault intensity averaged over time | |
| $i_V$ | Valve current | [mA] |
| $K, K'$ | Bulk modulus, Effective bulk modulus | [bar] |
| $n$ | Rotational speed | [rpm] |
| $p, \Delta p, p_0$ | Pressure, pressure difference, system pressure | [bar] |
| $Q, Q_{dp}, Q_V$ | Volume flow, volume flow for pressure build-up, Volume flow through the proportional valve | [l/min] |
| $\rho$ | Density | [kg/m³] |
| $r_{Pari_i}$ | Residual of parity equation i | |
| $\Delta r_{norm}$ | residual, normalized to the error-free case | |
| $T$ | Temperature of fluid | [K] |
| $t, t_F, t_O, t_{sim}$ | Time, time of fault insertion, observation time, simulation time | [s] |
| $V$ | Volume | [m³] |
| $x$ | displacement | [m] |
| $\dot{x}$ | velocity | [m/s] |
| $y_V$ | Valve displacement | [mm] |
| $y_{Pari}$ | Result of the parity equation | |

| ***Subscript*** | ***Description*** |
|---|---|
| A | Piston side of the cylinder |
| A1 ... A5 | Parity equation A1 … A5 |
| B | Rod side of the cylinder |
| B1 ... B2 | Parity equation B1 … B5 |
| cyl | Boom cylinder |
| meas | Measured value |

| | |
|---|---|
| oil | Oil |
| P | Pump |
| S1 | Parity equation S1 |
| set | Set point |
| sv | Switching valve |
| T | Reservoir |

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