A study on the fault tolerant control of a board machine

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ABSTRACT

This paper aims to propose and evaluate the practical schemes of Fault Tolerant Control (FTC) for modern control systems, combining the Model Predictive Control (MPC) and the traditional PI feedback control loops. In contrast to the existing FTC literature, mostly focusing either on MPC or solely on PI loops, the following three cases are studied. Firstly, we consider faults in the measurement of a controlled variable of a PI loop, which is a measured disturbance of an MPC at the same time. Secondly, faults in the measurement of the controlled variable of a PI loop are assumed, which is an input of an MPC at the same time. Thirdly, we study faults in the actuator of the control loop, receiving its setpoint from an MPC. To demonstrate the proposed FTC schemes, the MPC of a large-scale board machine is studied, which controls the key quality variables, the basis weight and the moisture content, by coordinating the operations of the stock preparation and the drying section. Thus, many PI loops of these sections are critical for the successful MPC operations. The proposed FTC system is tested on a board machine simulator model of the Stora Enso's Kaukopää mills implemented in Advanced Process Simulation Environment (APROS). Three fault scenarios are selected for the studies, including a consistency sensor fault in the stock preparation, a sensor fault in the pressure measurement in the drying group 5, and a valve blockage in the drying group 5.

1 INTRODUCTION

The increasing complexity makes industrial processes more and more vulnerable for faults and malfunctions. In particular, there has been increasing interest in the management of key component faults in the industrial processes aiming to continue process operations and to minimize the efficiency degradation in the presence of faults. To this end, Fault Tolerant Control (FTC) has obtained much attention in the engineering practice. An FTC system is a control system that is able to maintain the stability and acceptable degree of performance when there is component malfunction. Typically, the FTC schemes rely on the fault information provided by the Fault Detection and Diagnosis (FDD) unit. When a fault is discovered by the FDD unit, appropriate remedial action is chosen to adjust the control laws in order to reach the control objectives.

Recently, FTC has started to be successfully applied to the process industrial applications, for example, catalytic alkylation of benzene process, a desalination process, a polyethylene reactor, a three tank system, a distillation column, shaft furnace roasting system, a hydrogen production from bio-ethanol and others. Impressive economic savings can be sometimes achieved by an FTC handling a few critical faults, an example of which is provided for a dearomatizataion unit in /3, 4/. However, most of the above literature is focused on either a single model predictive control (MPC) or PI control loops. As the practical control strategies of modern industrial processes commonly involve both MPC for optimization and lots of PI loops receiving their setpoints from MPC, there is a clear demand for the practical implementation schemes of FTC that cover different control hierarchical levels.

This paper will propose and evaluate the practical schemes of FTC for modern control systems implemented in a large-scale board machine. The overall operation efficiency of the board machine is dependent on the MPC that is responsible for stabilizing the key quality variables: the basis weight and the moisture content. The MPC coordinates the operations of two machine units, namely the stock preparation and the drying section, which include a lot of PI control loops. Thus, the fault in the stock preparation and the drying section are the main contributors to the product quality variations. This has motivated extensive research on FDD methods for these two critical sections. In /1/, an enhanced dynamic causal digraph method was applied to detect and diagnose the faults in the stock preparation. Then in /5/, a nonlinear parity equation approach was initialed to detect and diagnose the faults in the drying section. Furthermore, in /2/, the outline of a fault diagnosis system was presented for a large-scale board machine.

In contrast to the existing FTC literature, mostly focusing either on MPC or solely on PI loops, three cases are studied for practical implementation. Firstly, we consider faults in the measurement of a controlled variable of a PI loop, which is a measured disturbance of an MPC at the same time. Secondly, faults in the measurement of the controlled variable of a PI loop are assumed, which is an input of an MPC at the same time. Thirdly, we study faults in the actuator of the control loop, receiving its setpoint from an MPC. The simulation tests are run on a board machine model of Stora Enso's Kaukopää mills in APROS, which highlights its applicability to the paper making industry. Corresponding to the three cases mentioned above, three fault scenarios are selected for the studies, including a consistency sensor fault in the stock preparation, a sensor fault in the pressure measurement in the drying group 5, and a valve blockage in the drying group 5.

2 PROCESS DESCRIPTION AND CONTROL STRATEGY

2.1 Process description

The three-layer board machine produces uncoated liquid packaging boards and cupboards. The raw materials are hard wood and soft wood kraft pulps, chemi-thermomechanical pulp (CTMP) and broke. The board-making process is composed of six different sections: stock preparation, wire section, press section, drying section, calender section, and reel and winder section. An overview of the board machine is presented in Fig. 1.

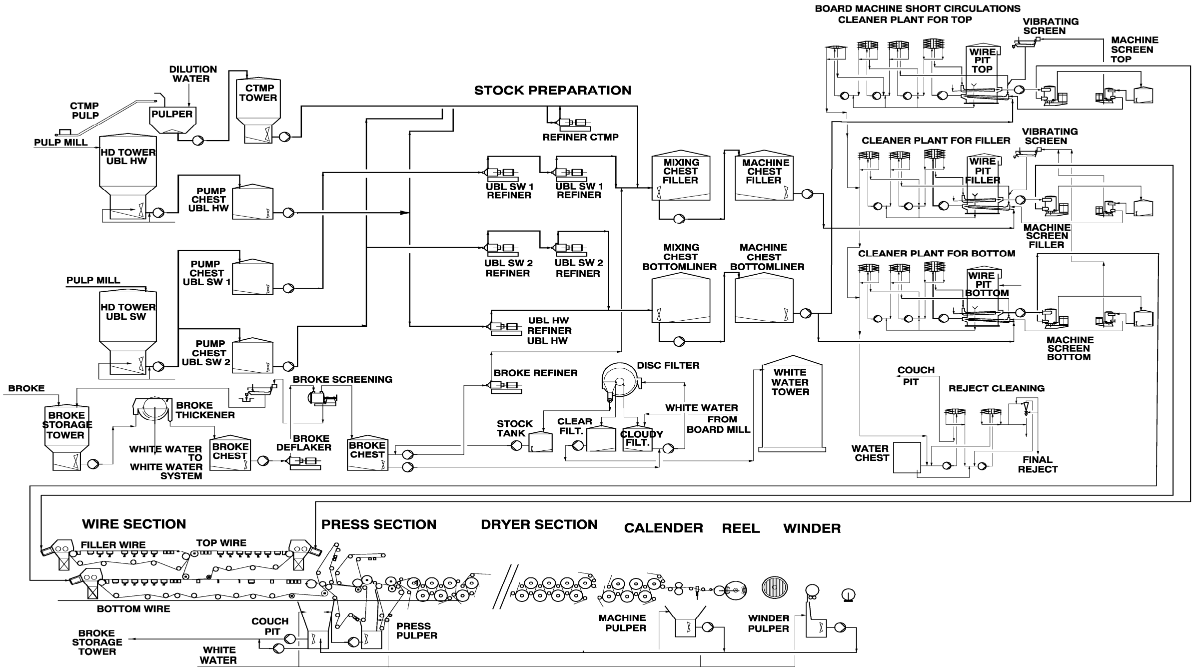


Figure 1: Overview of the board machine 4 process /2/

The board-making process starts from the stock preparation, the purpose of which is to provide the board machine with the required amount of stock of uniform quality and minimum variations. The first stage of stock preparation is refining, which is a mechanical treatment to modify the fibres to obtain the desired properties of the stock. This is followed by blending in a blend chest, into which the pulps are portioned according to a specific recipe. The mixture is then pumped to a machine chest while the consistency is controlled by dilution water. The machine chest has an overflow back to blend chest so that the level of machine chest is kept constant.

The blended stock passes from the stock preparation to the short circulation. First, the stock is diluted in the wire pit to the correct consistency for web formation. Next, the diluted stock is cleaned and screened, after which it passes to the head box, from where the stock is sprayed onto the wire in order to form a solid board web.

The excess water is first drained through the wire and later by pressing the board web between rolls in the press section. The remaining water is evaporated in the drying section using steam-heated drying cylinders. In the drying section, the efficient evaporation of water is achieved by regulating the steam usage and the temperature profile in the drying section. Steam is supplied by two steam feed flows to the steam groups (5 bar steam is used by groups 1A, 1B, 2, 3, 4, 6; 10 bar steam is used by group 5; 6 bar steam flow stems from 10 bar steam flow, it is used by groups 3, 4, 5, 7). After the drying section, the board is calendered in two phases in order to achieve the desired surface properties. Details of the three-layer board machine process can be found in /1/.

2.2 Control strategy

The control structure of the board machine can be divided into three layers: supervisory control, stabilizing control and basis controls. The highest level, supervisory control, comprises the QCS of paper machine. Its purpose is to control the quality variables of the board by providing setpoints for the lower level controllers. The next level is the stabilizing control level, where controllers are in a cascade to the QCS as they receive their setpoints from the QCS. Normally it contains the stock flow control after the stock preparation and the steam pressure control in the drying section. The lowest level, basis controls, consists of all single-input single-output controllers required to run the process, which includes tank level control, consistency control, flow control, pressure control, etc. On the supervisory control level, multivariable MPC is used, whereas on the stabilizing and basic levels the controllers are PI-controllers. The overall control strategy for board machine 4 can be observed from Fig. 2.

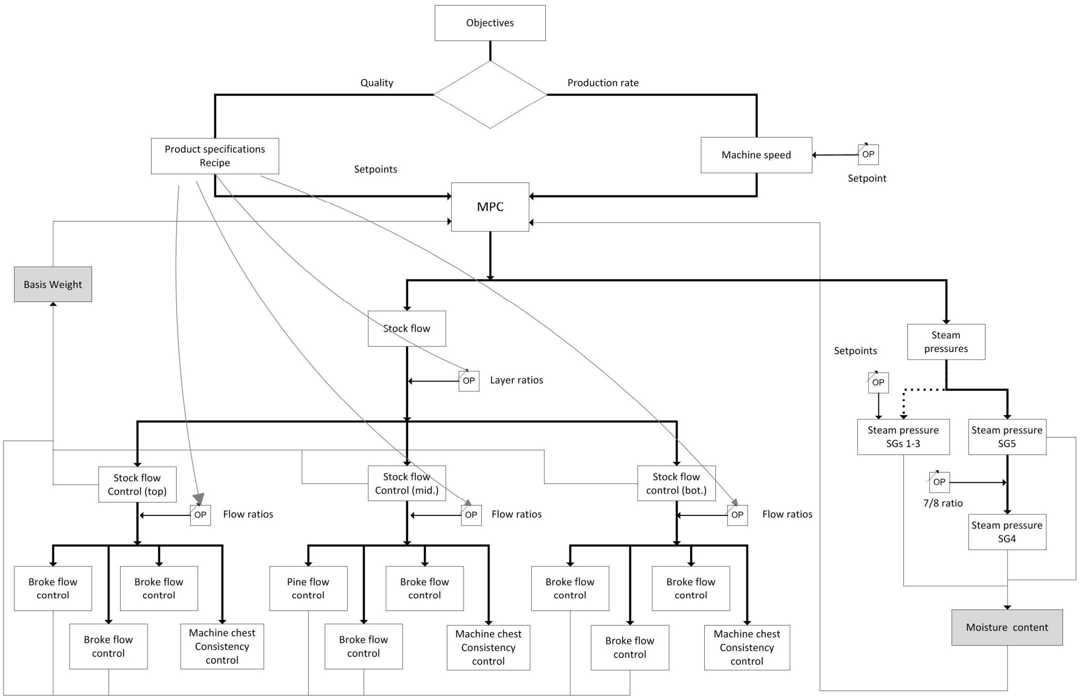


Figure 2: Overall control strategy of the board machine 4.

3 FTC SCHEMES FOR THE BOARD MACHINE

This section is devoted to the description of the FTC schemes for the board machine. Three fault scenarios are investigated, including a consistency sensor fault in the stock preparation, a sensor fault in the pressure measurement in the drying group 5, and a valve blockage in the drying group 5.

3.1 Scenario 1: Consistency sensor fault in stock preparation

Firstly, the FTC schemes are proposed to tolerate the faults in the consistency sensor of the pulp flow from the blend chest to the machine chest in the stock preparation, which is the controlled variable of the PI loop, and, at the same time, a measured disturbance of the considered MPC. Two FTC schemes are proposed at PI and MPC control levels respectively, both of which rely on the consistency soft-sensor. The first scheme in the PI control level replaces the faulty consistency measurement with the estimated value from soft-sensor, whereas other control loops in the stock preparation and the MPC remain unchanged. The second scheme in the MPC level allows deviations in the stock flow consistency by switching the consistency PI loop off. In this case, the fault effect compensation is based on considering the consistency as a measured disturbance of the MPC. In particular, the MPC, controlling the basis weight, needs to manipulate the dry fiber flowrate. When the fault happens, the compensation can be achieved explicitly by adjusting the stock flowrate setpoint.

3.2 Scenario 2: Steam pressure sensor fault in drying group 5

Secondly, the FTC is considered to tolerate the faults in the drying group 5 pressure, which is the controlled variable in the PI loop, and, at the same time, is a manipulated variable of the MPC. The first FTC scheme in the PI control level relies on the pressure soft-sensor. The pressure PI loop is modified to control the estimated value of the pressure instead of the measured one. In this way, the PI loop setpoint can be still utilized as a manipulated variable MPC, and thus, the MPC is kept unchanged. The second scheme in the MPC level relies on the control capacity of the board machine. In the original control strategy in Fig. 2, the MPC simultaneously manipulates the pressure in several drying groups by means of the ratio control. As a result, the increase of the control capacity is achieved, meaning that there is enough actuator capability to compensate even major disturbances in the board moisture. From the viewpoint of FTC, the setpoints for other group pressure loops represent redundant actuators of the MPC, which makes the FTC design possible. In more details, the drying group 5 pressure PI loop can be switched off, thus, allowing deviations of the pressure from the setpoint. Instead, the pressure in other drying groups is manipulated by the MPC to control the board moisture.

3.3 Scenario 3: Blockage of 10 bar feed steam valve in drying group 5

Thirdly, the FTC schemes are suggested to compensate the faults in the 10 bar feed steam valve in drying group 5, which is an actuator of the PI control loop that receives the pressure setpoint as a manipulated variable of MPC. The main redundant control capacity comes from the simultaneously running steam supply lines. If a fault is detected in the 10 bar feed line, one option is to replace the 10 bar feed line with the 6 bar one.

4 TESTING OF THE FTC SCHEMES ON THE BOARD MACHINE

In this section, the proposed FTC schemes are tested on the three-layered board machine simulator constructed in the APROS simulation environment. Test results of three fault scenarios will be presented respectively.

4.1 Scenario 1: Consistency sensor fault in stock preparation

The first fault considered is a sensor fault in the consistency measurement of the pulp flow from the blend chest to the machine chest. The fault can be detected from Fig. 3 which shows the residuals.

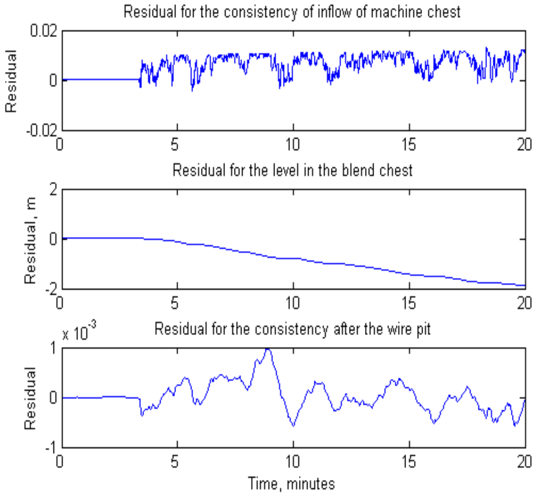
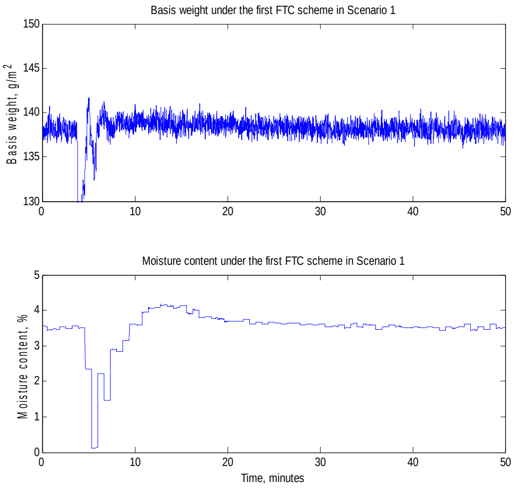


Figure 3: Residuals in Scenario 1

To accommodate the sensor fault of consistency measurement, we replace the faulty sensor by a “soft-sensor”, which has been developed from system model equations. The Fig. 4 shows that the quality variables, namely the basis weight and the moisture content, can converge to the setpoints after the implementation of “soft-sensor” as the first FTC scheme in the PI control level. The second FTC scheme in the MPC level is also tested, and the result is depicted in Fig. 5. Comparing Figs. 4 and 5, we can see that both FTC schemes work well in this scenario. The first FTC scheme, working in PI control level, performs slightly better as the quality variables can converge to the setpoint faster after the FTC action is implemented. This is because the response of PI loop is relatively faster than the compensation in the MPC level.



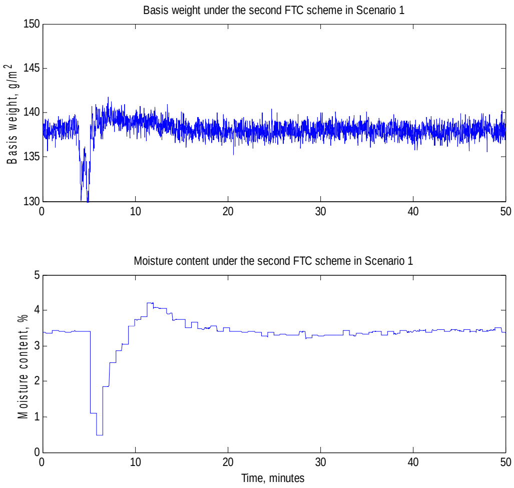
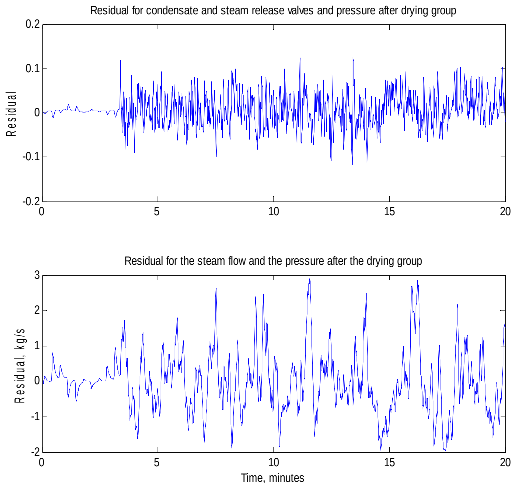


Figure 4: Quality variables under first FTC scheme **Figure 5**: Quality variables under second FTC scheme



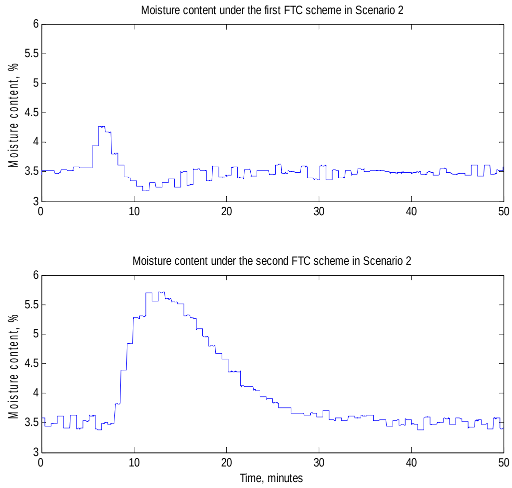


Figure 6: Residuals in Scenario 2

Figure 7: Moisture content under FTC

4.2 Scenario 2: Steam pressure sensor fault in drying group 5

The second fault considered is a sensor fault in the steam pressure measurement before drying group 5. The fault can be observed from the residuals of nonlinear parity equations, which is shown in Fig. 6.

To compensate the effects of faulty pressure measurement, the remedial action of first scheme is to replace the faulty sensor with a “soft-sensor” that has been identified from steady-state data. The Fig. 7 shows that the moisture content can converge to the setpoints after the implementation of “soft-sensor” as the first FTC scheme in the PI control level. As in the second FTC scheme in the MPC level, we switch the manipulated variables of

MPC to the drying group 4 by ratio control. The result is also depicted in Fig. 7. We can see that both FTC schemes can drive the moisture to the setpoint in this scenario. However, the first FTC scheme, working in PI control level, performs much better than the second scheme working in the MPC level. This is due to that the response of PI loop is faster than MPC operation. Further, the control capacity of drying group 5 is abandoned in the second scheme.

4.3 Scenario 3: Blockage of 10 bar feed steam valve in drying group 5

The third fault considered is a blockage of the valve placed on the 10 bar steam feed flow to drying group 5. The fault can be observed from the residuals of nonlinear parity equations, which is shown in Fig. 8. To overcome the fault in 10 bar feed steam flow, we reconfigure the control loop by resorting to 6 bar steam flow which is a backup flow in drying group 5. From Fig. 9, the moisture content can converge to the setpoint successfully after we switch the feed steam flow from 10 bar to the 6 bar one.

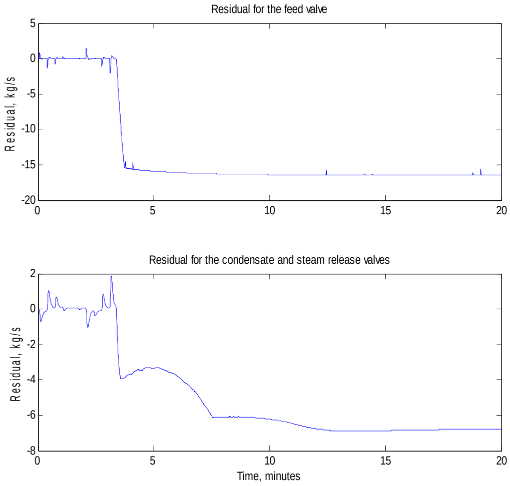


Figure 8: Residuals in Scenario 3

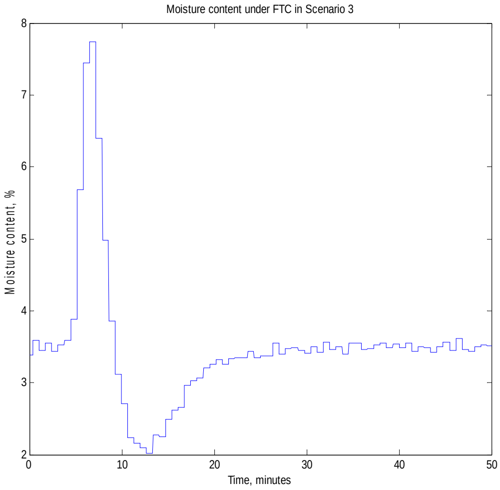


Figure 9: Moisture content under FTC

5 CONCLUSTIONS

The practical FTC schemes involving both MPC and PI control loops are proposed and evaluated for a large-scale board machine in this paper. Different FTC schemes are proposed based on the type and position of faults as well as the available control redundancy. The FTC schemes are tested in three fault scenarios of board machine respectively. It has been shown that the fault effects can be accommodated timely and satisfactorily.

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