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ADVANCED MODEL BASED PROCESS SUPERVISION IN HOT STEEL MILLING

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Abstract: This paper presents the principles, as well as a prototype implementation, of a model-based supervisory system for the hot steel milling process. Here, a set of simulation models builds the core of the system and possess updated processes information. A model-based setup calculation and tendency prediction, as well as an online fault detection and equipment diagnostics, enhance the performance of the facility control procedure. Concepts of hierarchical modeling, distributed control and decentralized process data acquisition are studied in order to design a methodology for low-cost development of advanced supervision and control systems in industry. *Copyright © 2002 IFAC*

Keywords: Steel industry, Modeling, Model-based control, Diagnosis, Fuzzy supervision.

1. INTRODUCTION

The increasing complexity of modern process plants requires using adequate control and supervision systems that provide an efficient, stable, and safe functionality of the plant facilities as well as a high production quality. Advanced modeling and control technologies are needed to develop such control and supervision systems, to improve their functionality, their testing, adaptation and optimization.

The application of advanced modeling and control technologies in the steel milling was the main issue of the PROQUS project. The main result of the investigation is the development of principles and a prototype implementation of modules for model-based distributed supervisory system for the hot steel milling process. Here, a set of simulation models builds the core of the system and possesses updated process information. A model-based setup calculation and tendency prediction, as well as an online fault detection and equipment diagnostics, enhance the performance of the facility control procedure. Concepts of hierarchical modeling, distributed simulation and decentralized process data acquisition are studied as well. Thereby, the usage of standard hardware components and software solutions must guide the development on low cost base.

The achieved project results are briefly summarized as below:

- model components for steel milling processes,
- methods for modeling of scalable systems,
- object oriented architecture for scalable simulation models,
- measurement based tuning of phenomenological models,
- methods for model based fault detection and equipment diagnostics,
- intelligent control software architecture,
- model-based validation of sensor data.

The described investigation is being elaborated by a consortium of 6 partners. The consortium includes the research institutions Fraunhofer-IPK (Germany), Universidad Nacional de San Juan (Argentina), Pontificia Universidad Catolica de Chile, and Universidad Politecnica de Madrid (Spain), specialists in the fields of modeling, supervision and control theory as well as applications. From the other side, end-user SIDERAR S.A. (Argentina) and engineering company ELPRO EPE GmbH (Germany) experienced in supervision and control systems for the steel milling industry as well as for the process industry in general, are also in the consortium.

2. PRINCIPLE SCHEME

The classical process control tasks (compensation of processing deviations, keeping the facility in a safe functional interval) as well as advanced control tasks (product quality supervision, equipment diagnostic, improvement of the control structure and parameters) are based on having the adequate process and facility mechanisms knowledge. The knowledge basis can practically be accumulated in form of facility operator experience (subjective knowledge) and process measurement archives (objective knowledge). The interpretation of the accumulated knowledge for the process control can be performed in the form of a mathematical model and knowledge based control and supervisory procedures.

Considering fast technological processes in general and the hot milling process especially, a possibility to integrate an advanced process knowledge in the plant control system on low-cost basis was investigated. Thus, three basic tasks in their interaction will be studied:

- model tuning based on process measurements,
- model based process behavior prediction,
- model based process supervision and diagnostic.

Simultaneously, an entire control architecture and implementation methodology must be revised. Figure 1 depict the main components of the advanced control with their corresponding functional responsibilities. In this way, the coordinated investigation of the following subjects is needed.

Hierarchical informational structuring and modeling of the technological process and facility. The defining the sub-processes and the corresponding interfaces has an essential importance for the simulation and control procedures. The model upgrade possibilities as well as efficient numerical handling directly depends on the process structuring. A system of such sub-models for the steel milling will be designed within the project.

Robust and easy-to-use *model based diagnostic procedures* which allow online supervision of facility components.

Use of Ethernet network with TCP/IP Protocol for the implementation of the real-time communication bus system. The rush development of the Internet technology has stimulated the design of robust, efficient and low cost network solutions based on .

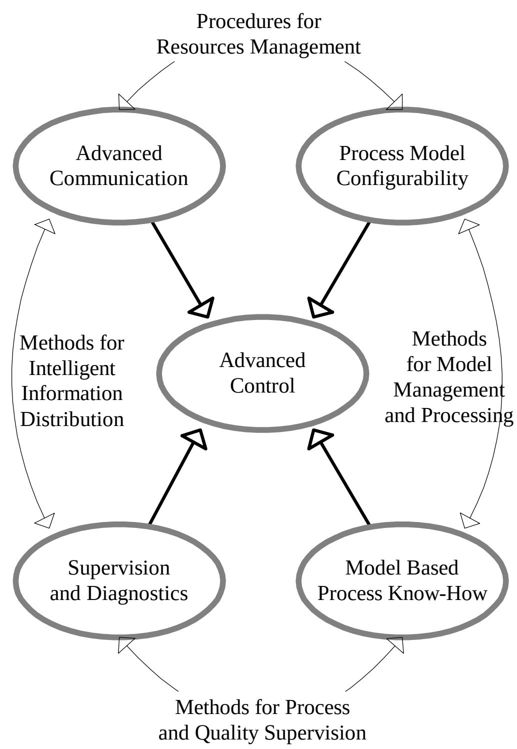

Fig. 1. Relation and responsibilities of Advanced Control components.

TCP/IP protocol and has made such systems ready for real-time applications.

Use of CORBA based communication architecture. CORBA based interfaces and communication mechanisms support the software design and maintenance of distributed heterogeneous computer systems and build a base for an efficient implementation of flexible and redundant control systems. Meanwhile, the CORBA standard has been expanded for real-time applications.

Supervision of numerical and communicational procedures. The complexity of numerical procedures for on-line evaluation of process information is being constantly increased. In order to have accurate control over the progress and state of the numerical procedures, a numerical supervisor is being developed. The communication supervisor will support an efficient exploitation of hardware resources in the system.

Intelligent sensors/actuators. The hardware elements of the facility must be upgraded in their interface in order to be integrated into an advanced control system.

3. MODEL ARCHITECTURE

For real time control and on-line quality supervision, data field based (or phenomenological) models for the representation of the process behavior are usually used (Lisounkin, 1996). For the milling facilities,

the mathematical model has a clear hierarchical structure and possesses the scalability property as well (see Figure 2 and Figure 3).

As shown in the figures, the steel milling process model can be considered in following structural parts or partial models (Lage, *et al.*, 2000):

- material flow model;
- geometry model of deformation zone;
- processing velocity model;
- material plasticity-elasticity model;
- stand elasticity model;
- force-torque model;
- temperature evolution model,
- tension/stress model between stands (including looper),
- strip transport model between stands.

4. MODEL PROCESSING

Providing the analysis of the mathematical tasks – model tuning, process prediction, and fault diagnostic – the three-level functional architecture of the model processing modules has been derived.

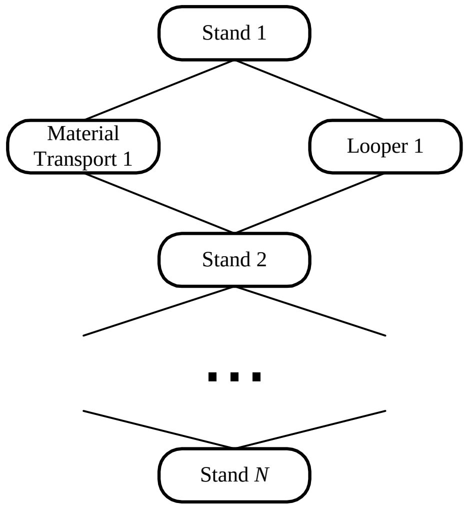

Fig. 2. Structure of the milling facility model.

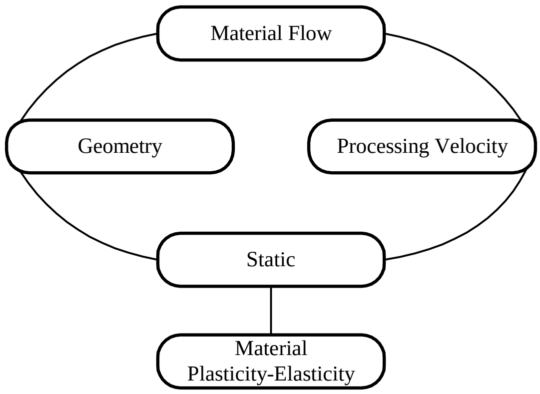

Fig. 3. Structure of the milling stand model.

The model levels are listed below:

- Level 1: Partial sub-system behavior modeling.
- Level 2: Procedures and scenarios for the facility simulation.
- Level 3: Model tuning, fault detection and diagnostics procedures.

Thus, Level 1 represents the engineering view on the model. This level implements data structures of the process model and partial functional dependencies between the process attributes. With this, the scalable systems (as in our case the line of milling stands) can also be easily instantiated.

Level 2 contains scenarios for the facility model processing. Here, the main objective is to calculate a model behavior by given input values, to compare the model prediction with the corresponding measured process variables, and to calculate an objective function – model quality function.

Level 3 represents model tuning, fault detection and diagnostic tasks in abstract mathematical form. General purpose solvers (Newton algorithm) and libraries (linear algebra library) are housed here.

We divided the mathematical tasks in the described three levels in order to separate the functionality and to achieve the independence of the corresponding classes. This approach supports an efficient model maintenance and improvement.

5. FAULT DETECTION AND DIAGNOSTICS

A model based fault detection and diagnosis system was designed based on linear and second order transfer function models and uses a Fuzzy expert procedure to determine the cause of the detected faults. The main field of application for the system is the online supervision of actuating equipment in a facility.
The diagnostic system includes 4 components: identification, prediction, detection, and fuzzification. The identification component estimates the parameters of the ARX model using recursive identification routines. The model based prediction generates the controlled variable residual which is statistically analyzed by the detection component. The results are fuzzified and processed in the diagnosis component to determine the fault's origin.

For the hot rolling mill, the fault diagnostic focuses on work rolls, screw mechanism, and looper. The actuating systems are considered as second order linear dynamic systems.

5.1 *Model Parameter Identification.*

The identification problem can be solved applying different methods: on-line identification, by using one-shot or recursive algorithms for the parameter estimation of the model (Ljung, 1987), and off-line identification, by using historical data for parameter estimation of the model.

The identification subsystem module estimates, for linear dynamic processes, the parameters static gain K_p, dumping factor x, angular frequency w_m, zero time constant a and process time delay T_d of the second order transfer function with fixed delay shown in equation (1).

$$G(s) = \frac{(a \cdot s + 1) \cdot Kp\, w_m^{\;2}}{s^2 + 2xw_m s + w_m^{\;2}} \cdot e^{-T_d \cdot s} \qquad (1)$$

Parameter estimation is made by analysis of the closed loop step response of the process. The method is able to give a direct relation between the model parameters a, x, w_m and indexes E_1, E_2, E_3

$$E_1 = \int_{T_d}^{\infty} e(t)\,dt\ ,\quad E_2 = \int_{T_d}^{\infty} e^2(t)\,dt\ ,\quad E_2 = \int_{T_d}^{\infty} t \cdot e(t)\,dt\ .$$

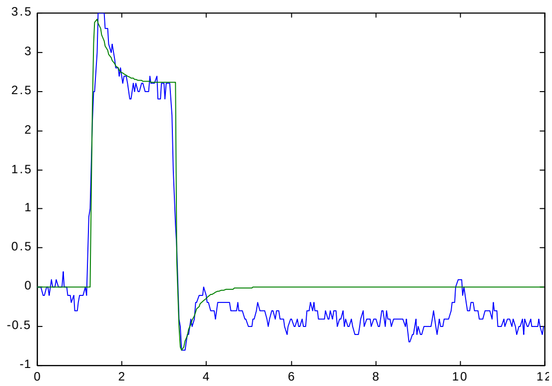

Fig. 4. Process and model output comparison.

calculated from processes' response to a step input of amplitude b in time $t = 0$ (see Orchard, *et al.*, 2000)

In Figure 4, a measured main motor response and simulated motor response are depicted in order to illustrate the identification results.

5.2 *Online Fault Detection and diagnostics.*

The fault detection and diagnosis subsystem module is in charge of the analysis of a given set of data that contains the operation behaviour of the actuators, by giving the appropriate alarm signals. The obtained speed residual is analysed statistically by calculating the mean and the standard deviation in a sliding window.

The basis for the fault detection is given by Scheffeé test:

$$f_{0i}(k) = \left(\left|r_i(k)\right| / s_i(k)\right)^2 \cdot \left(N\left(N-m\right) / \left(\left(N-1\right)m\right)\right), \quad (2)$$

here r_i – mean of the residual i, s_i – variance of the residual i, N – number of samples. According to Fisher probability distribution, the condition $f_{0i} \le F^a{}_{m,\,N-m}$ indicates the absence of changes in f_{0i} with a trust degree a, for m variables and N samples. For example: $F^{0.99}{}_{2,\,23} = 5.66$.

The value of the Scheffeé test will be analysed by a Fuzzy Expert routine that makes a final diagnosis of the detected abnormalities ("faults"). The input is fuzzified into "Low" or "High" sets with trapezoidal membership functions according to their magnitude. Then, the expert system provides the diagnosis of the abnormalities based on a set of rules. Finally, the outputs of the expert system are de-fuzzified using the "smallest of maximum" criteria.

The expert system is defined by the following rules:

- Any fault or disturbance in a supervised process will generate a set point change (SPC) which magnitude is directly related with the importance of the disturbance.
- If the identified model of the sub-process is not able to predict the controlled variable (motor speed) and there are important changes in the mean speed set point, the detected abnormalities are related to an "Operation Point Change" (OPC). This situation could be caused by temporary disturbance or permanent process faults.
- If the identified model is not able to predict the controlled variable (motor speed) and there are no recent important changes in the mean speed set point, the detected abnormalities are caused by a "Process Fault" (PF).

In Figure 5, a process fault alarm for real process data is depicted.

6. CORBA BASED CONTROL ARCHITECTURE

The Intelligent Control Architecture (ICA) is a methodology for distributed object-oriented systems development in the process control field of knowledge. ICA has been entirely written in C++ but it is capable of interoperating with other environments such as JAVA or DCOM. At your own convenience, it is possible to write some parts of a project using C++ and to use other programming languages such as Visual Basic in other project areas where these languages yield different advantages.

One of the most important ICA characteristics is that of compatibility with libraries of classes previously developed in other projects. If these classes do not exhibit behaviors clearly forbidden in distributed systems such as sharing pointers (pointers have no meaning in different address spaces and computers), then it is possible to simply write an agent declaration file and use the existing classes together with the ICA compiler to generate the communications code.

ICA way of working is simple. Firstly, agents are described by means of an Agent Definition Language (ICA ADL). These files basically contain the agents public interface definition, although they are also able to include protected and private parts of the interface and specific details of the agent implementation. Secondly, through the use of the ICA ADL compiler, source code for clients and servers is generated (C++ or JAVA) as well as other interface definition files containing only the public interface of the agent.

ICA possesses some unique particularities for distributed computing along with standard behaviours following the current technology trends. Unless it is explicitly stated, the remainder of this document follows the Object Management Group's (OMG) Common Object Request Broker Architecture (CORBA 2.1) specification. CORBA is worldwide accepted as the public-license open reference standard for the construction of distributed complex applications. Real-time functions needed for the control system, as well as a supervision component, are included within the system.

ICA components support a flexible distributed operation of the developed supervision and diagnostic system within an Ethernet based facility network (see Figure 6).

7. VALIDATION OF SENSOR DATA

The process predicting model can also be used for validation of measurements supplied by sensors of the facility. The simulating information can help to filter the measurement noise and to detect early enough sensor faults. A system for model based sensor validation was implemented.

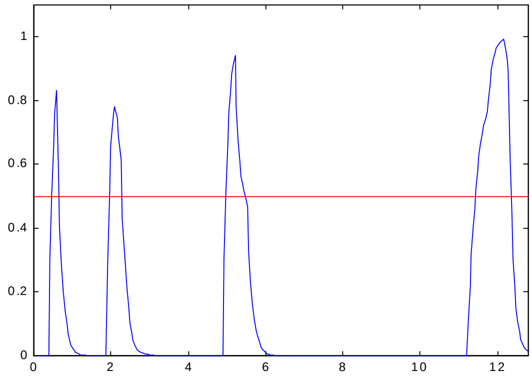

Fig. 5. Process Fault Alarm.

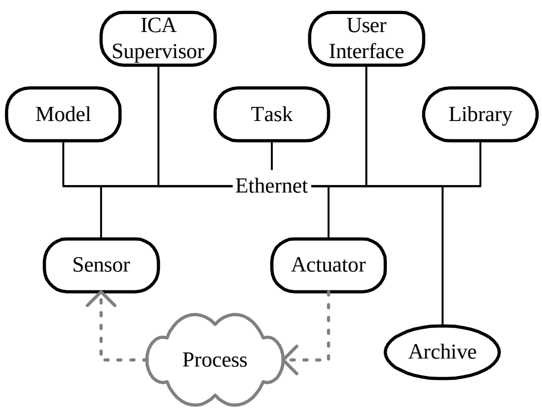

Fig. 6. ICA based infrastructure of a facility supervision network.

The system involves substantially the CORBA based control architecture ICA. The intelligent sensor components are provided with ICA interfaces, which make them able to send the measured information direct into the network of the advanced control. The complementary elements – *validators* – compare the measurements with the data of the predicting models. The validation tasks, also equipped by the ICA interface and located anywhere within the local network, send warning messages if the residuum is out of tolerance. The validators are processed in shadow mode, if resources are appropriate.

8. CONCLUSION

The developed supervision and fault detection system is being tested at the end-user site. With this, the performance of the system components will be tested, the parameters of the algorithm will be tuned. (The detailed results will be shown in the final paper.)

9. ACKNOWLEDGMENTS

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