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Hardware-in-the-loop simulation platform for supervisory control of mineral grinding process

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ABSTRACT

Supervisory control technology is widely used to improve product quality in mineral grinding process (MGP). To ensure safety, new supervisory control method needs to be fully tested before practical application. However, conducting tests in a running process is costly and may put the process equipment in danger, which necessitates extensive simulations to ensure the stability and performance of supervisory controllers. Comparing with the field based test, the numerical simulation is more economic and safer. However, numerical simulations cannot capture all aspects of controlled object, such as sensors, actuators, process, control systems themselves and signal transmissions, which are important to evaluate the control performances. To solve this problem, this paper presents a novel hardware-in-the-loop simulation (HILS) platform for the supervisory control of MGP. By integrating a supervisory control system, a basic loop control system, a virtual actuator and sensor system, and a virtual plant system in to a coherent whole, the HILS platform provides a full-scope simulation environment for the supervisory control. The supervisory control system and the basic loop control system adopt real control systems. The detailed process dynamics are modeled and visualized by the virtual plant system. Further, as an interface between the physical controllers and virtual plant, the virtual actuator and sensor system is used to realize the signal conversion and to simulate the dynamics and faults of the actuators and sensors using data acquisition (DAQ) hardware and configuration software. Effectiveness of platform is demonstrated with a case study, where an intelligent supervisory control method for a typical one stage MGP is tested.

1. Introduction

As a crucial component of the beneficiation process, mineral grinding process (MGP) is used to grind the run-of-mine ore into suitable particle size such that the valuable mineral constituent can be exposed to be recovered in the subsequent classification process [1,2]. In the past, the process control research of the MGP was focused on the basic loop control methods to ensure the process variables follow their setpoints in a stable operation. In order to realize the basic loop control method easily, distributed control systems are widely used.

Long term production practice, however, shows that it is difficult to obtain the desired production only using the basic loop controller. This is because that the inappropriate control loop setpoints will make the MGP work under a non-optimized economic status, thereby leading to high cost and low quality of products. Therefore, a high-performance process control system should ensure that not only process variables can follow their setpoints stably, but also these setpoints are suitable for the optimal process operation. For this reason, a hierarchical approach as shown in Fig. 1 is proposed in [3]. In this framework, a supervisory control system is installed on top of the basic loop control to optimize the control loop setpoints online. The development of a new supervisory control system usually needs to undergo intensive experiments until the control performance meets with the technical requirements.

Experiment in an industrial environment is effective, direct but expensive and often unsafe. Hence, the alternative approach of modeling and simulation is cheap, quick and conclusive. The modeling of mineral process has been discussed for many years [4–7], but the simulation doesn't play a role until personal computers became available in about mid-1980s [8]. The first generation of simulation uses steady state models to offer the best and cheapest way to handle the difficult problems of flowsheet design and optimization. In this period, because of the success of simulation it is also necessary to have a reservoir of professional skills and models, some commercial simulators, such as JKSimMet and USIM Pac, have thus been developed to provide well technical supports [9]. By 1990s, new requirements for high-capacity and high-quality have led mineral processing industry to be concerned with the operation process control and optimization, which requires the modeling of the dynamic relationship between the process variables and the manipulated variables. Hence, a number of researchers began to study the dynamic modeling and simulation [10–14]. Today, there have

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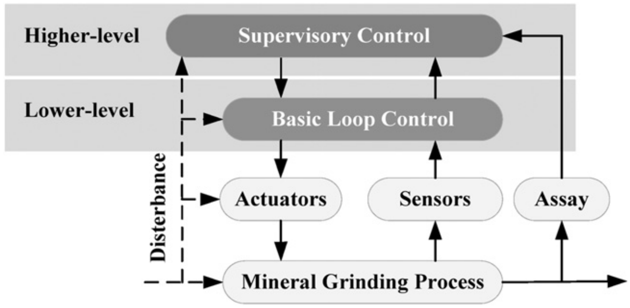

Fig. 1. Hierarchical control strategy for the MGP.

been commercially available dynamic simulators widely used in this field, such as MetSim and SysCAD.

The above simulators have been used to test the software simulated control system. This is the so-called numerical simulation. But the drawbacks of numerical simulation are that they cannot capture the whole grinding system including sensors, actuators, process, control systems themselves and signal transmissions [6,15], and neither do these packages provide a control algorithm programming environment similar to the real control system. This leads to unconvincing results of numerical simulation because programming and testing of the controller are still necessary in practical application.

The gap between the numerical simulation and the actual application had persisted for years until the use of hardware-in-the-loop simulation (HILS) [16–24]. By combining the simulated system with physical hardware, the HILS realizes a full-scope simulation of integrated control system including sensors, actuators, real control units and so forth, which is difficult to achieve solely by the numerical simulator. The HILS has been as an effective verification and validation tool for controller to be applied in many industrial fields. A HILS platform is developed in [16] to verify and validate the safety of nuclear control systems. In [17], a HILS platform consisting of a simulated power system and a real hardware propulsion motor set is proposed to research the performance of electrical ship power system. A HILS platform performed in [18] is used to assess the high-integrity embedded automotive control systems. In recent years, the applications of HILS platform in robotics and automotive systems have been discussed in [19,20] and [21–24], respectively. These applications illustrate the HILS can effectively reduce the risk of accidents at various stages of development: design, implementation, testing, operation, and maintenance stages. For the MGP, the improper loop setpoints will result in the unsatisfying product as well as some faults such as mill overload or underload faults. If the faults cannot be eliminated in time, they will cause damage to devices or even cause suspension of the operation. A HILS platform is thus required for the design and test of the supervisory controller. To our knowledge, however, such platform has not been reported.

Motivated by this issue, this paper focuses on providing a full-scope HILS platform for the design and test of the supervisory control system of the MGP. The proposed platform consists of a supervisory control system, a basic loop control system, a virtual actuator and sensor system, and a virtual plant system. The simulated grinding process (i.e., virtual plant) is linked with the real control systems (i.e., supervisory control system and basic loop control system) through the virtual actuator and sensor system, so that the whole platform can be operated similar to the real system. The major contributions of this work include the following aspects:

- A HILS architecture approaching to industrial grinding system is proposed by integrating actual control system and simulated actuators, sensors and grinding process.
- A virtual actuator and sensor system is developed not only to bridge the simulated grinding process and the actual control system under test, but also to simulate the equipment dynamics and faults.
- A configurable software for supervisory control is developed to assist the design and development of a newly developed supervisory control algorithm for a MGP.
- A flexible modular based simulation environment for the MGP is proposed, where a 3-D visualization component is used to visualize the grinding process vividly.

The paper proceeds as follows. In Section 2, the MGP and its control situation are introduced. The structure, hardware, software and communication protocols of the developed HILS platform are presented in Section 3. An intelligent supervisory control method is designed and tested using the HILS platform in Section 4. Concluding remarks are drawn in the final section.

2. Description of mineral grinding process control

2.1. Process description

The MGP usually consists of a great mill and grader as shown in Fig. 2. The mill is a metal cylinder rotating around its axis at a fixed speed with heavy media inside. Owing to the combined effect of knocking, chipping, and tumbling caused by grinding media, the lump ore is crushed to fine particles. According to the different grinding media, the mill can be categorized based on the grinding media, such as the steel balls and steel rods. The grader is a classification unit used to filter particles grinded from mill and transfer the coarse particles to the mill for regrinding. The overflow slurry with finer particles, as product, is transported to the subsequent procedure. The grader usually employs hydro-cyclone or spiral classifier.

2.2. Control situation

In most grinding process operations, the important production index is product particle size (PPS) (% < 74 μm), which is the key metric indicating the grinding product quality. Due to the fact that undersized and oversized PPS are both unfavorable for the subsequent separation process and those situations may even cause negative economic impact on the whole plant, the control objective is to maintain the PPS within specified range. To realize the above objective, some control loops have to be deployed to ensure the relevant process variables stable, as the PPS is sensitive to some key process variables.

Today, the distributed control systems (DCS) or programmable logic controller (PLC) are deployed in almost all of the control loops in the grinding process. Unfortunately, production practice indicates that the plant still often operates under a non-optimized economic status, thereby producing low quality product in high-energy production. The reason is that "with respect to the economic performance of a MGP plant, the controller performance is most probably not as important as the right selection of the setpoints" [1]. In practice, these loop setpoints are normally regulated by on-site operators. For the operators, however,

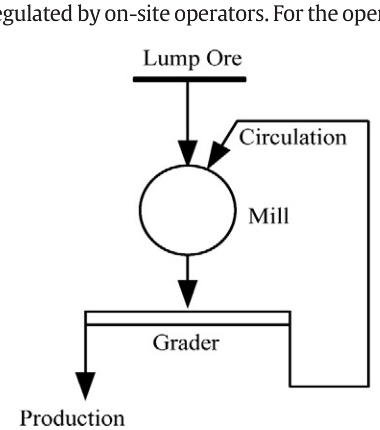

Fig. 2. Flowsheet of grinding process.