The Art and Science of Operator-Less, Plant-Floor, Advanced Rougher Flotation Control

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ABSTRACT

Many consider rougher flotation control to be more of an art than a science. Some have even thought it impossible to make process control decisions and changes without human interaction. Controlling flotation bank pulp levels to maintain consistent pulling-rates in the face of changing feed slurry flow rates, varying mineral types, and inconsistent reagent additions can be daunting. However, an advanced supervisory control strategy was installed on the plant-floor to control an industrial rougher flotation circuit with little or no operator interaction. Plant staff monitored the flotation circuit under supervisory control and reported benefits of up to 4% improvement in copper recovery above that achieved with an older supervisory control strategy. To accomplish this work, a novel use of instrumentation to solve a flotation bank pulp level control problem was employed, a new implementation approach was used to correct some flaws in the older approach, and careful attention was paid to a few key process control principles. This paper discusses important aspects of these activities.

INTRODUCTION

Think of how easy process control problems seem when they are described, but in practice are really quite difficult to achieve. To illustrate this point, consider the control problem that is depicted in Figure 1 and described below.

This problem is referred to as the Autonomous Flying Machine problem or the flying machine problem for short. Figure 1 represents a large grass field about the size of a regulation football or soccer field. The objective is to build a flying machine that completes the mission without any human interaction. The mission is:

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1. The flying machine must start from the starting box, represented in the lower left-hand corner of Figure 1, and once the machine leaves the start box it must fly completely autonomously.
2. The flying machine has to search for and find the closest target. Filled black circles represent targets in Figure 1. The line labeled, “Step 1” represents one possible flight path from the start box to the closest target.
3. The flying machine must pick-up one of the disks on the target. The white circles in the target closest to the starting box represent disks.
4. The flying machine must search and find the furthest target. The line labeled, “Step 2” represents one possible fight path from the closest black circle to the furthest black circle. While searching for the furthest target, the flying machine must clear a three-foot tall fence that separates the two black targets. The fence is represented in Figure 1 by the thick line between the two targets.
5. The flying machine must place the disk it is carrying on the furthest target.

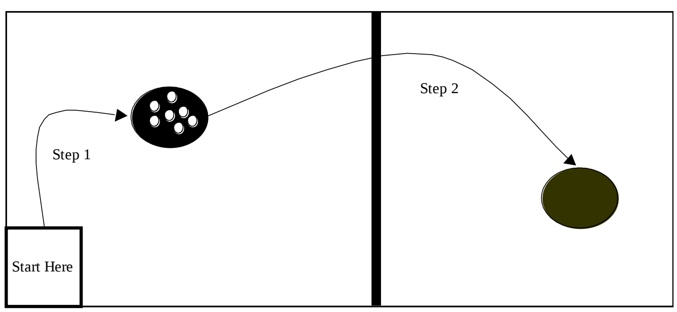


FIGURE 1 Autonomous flying machine problem landscape

From the description, this problem sounds relatively easy. One might think that in today’s world of advanced science, computer technology, and global positioning instrumentation that this control mission could easily be accomplished. After all, man first walked on the moon 30 years ago. However, to date, in a yearly competition including competitors from around the globe, the mission has not been successfully completed outdoors. A few have almost completed the mission and, in the near future, will likely be successful. But once it is successfully completed, the complexity of the mission will be extended to transport every disk from the first target to the second target. And after that happens, the complexity will be increased to accomplish more complex tasks.

The flying machine problem is an excellent metaphor for the control system development discussed in this paper, specifically an operator-less, plant floor, rougher flotation control system. The objective of the flying machine problem is to successfully complete the mission. The objective of the rougher flotation control system is to achieve high concentrate recoveries while maintaining adequate rougher flotation concentrate grades. Achieving the flying machine goals is difficult because environment variables such as wind velocity and direction are constantly changing. Achieving the rougher flotation control goals is also influenced by process disturbances in flotation feed grade, feed mineralogical composition and feed slurry flow rates. Once the flying machine takes off, it must fly autonomously. When the rougher flotation control strategy is enabled, it should control the flotation circuit without human intervention. A comprehensive suite of instrumentation must be employed by the flying machine to complete its mission. The same is true for rougher flotation control. After the flying machine mission is successfully completed, the complexity of the mission will increase. The same will be true for rougher flotation control.

Just as the flying machine problem appears to be simple, the task of implementing an advanced supervisory control strategy to autonomously control an industrial rougher flotation circuit sounds simple. After all, man first walked on the moon 30 years ago. However, it is possible that the recent work, culminating in this paper, to implement an advanced supervisory control strategy for autonomous rougher flotation control is the first successful accomplishment of the mission. To accomplish this work, a novel use of instrumentation to solve a flotation bank pulp level control problem was employed, a new implementation approach was used to correct some flaws in the older approach, and careful attention was paid to a few key process control principles. This paper discusses important aspects of the activities accomplished while working in conjunction with the operations and control staff of a large United States copper producing concentrator.

A NOVEL INSTRUMENTATION APPROACH

Traditional pulp level control in rougher flotation banks is the stabilizing-control-workhorse of industrial process control for rougher flotation. A variety of level sensing and control approaches have been investigated over the years in many plants throughout the world. However, flotation bank pulp level control does not provide the granularity of control necessary to optimize the performance of a rougher flotation circuit using an advanced supervisory control system. To illustrate this point, consider the typical flotation bank pulp level control depicted in Figure 2. Figure 2 provides a cutout of a Process and Instrumentation Diagram (P&ID) for a flotation bank of a rougher flotation circuit.

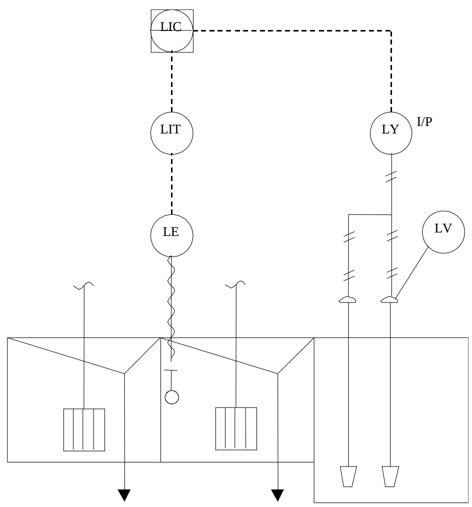


FIGURE 2 Typical flotation bank pulp level instrumentation and controls

Two flotation cells and a discharge box constitute the flotation bank shown in Figure 2. Rougher flotation circuits are often configured with multiple stages of flotation banks containing various flotation cells to provide the required retention time for flotation. Each bank will have instrumentation and controls similar to that shown in Figure 2. The item labeled “LE” represents the level element or sensor that measures the pulp level. The item labeled “LIT” is a field-mounted level-indicating transmitter responsible for sending the data from the level sensor to the process control system. The item labeled “LIC” represents the level controller configured in the process control system. The input to the level controller is the measurement of the level from the level sensor. The item labeled

“LY” represents the device that converts the level controller output signal to a pneumatic signal that controls the position of the discharge box dart valves. The item labeled “LV” identifies the discharge box dart valves.

The most common type of instruments used today for sensing the pulp level in a flotation bank is an ultrasonic level sensor. Ultrasonic level sensors are quite reliable and economical for this service. However, simple level sensing and level control does not always guarantee that the flotation bank contributes to the overall recovery achieved by the rougher flotation circuit. Consider the situation where the flotation bank pulp level is 6 inches below the overflow lip of the flotation bank while the froth is 5 inches deep. In this case, the top of the froth will be one inch below the lip of the flotation bank and no froth will be extracted from the flotation bank. When this occurs in a flotation circuit, the flotation bank with this situation contributes to the over-all retention time, acting as a mixing tank, but does not contribute as an extraction unit, and thereby reduces overall flotation circuit performance.

The addition of another inexpensive level sensor can provide information for more intelligent level control and is the foundation for adaptive, optimizing supervisory control. Compare the following Figure 3 with Figure 2.

The additional level sensor measures the height of the froth above the overflow lip of the flotation bank. This measurement provides direct feedback to the control system about the extraction rate and the performance of the flotation bank. Various control loop configurations, although their description is not the subject of this paper, can be configured and used to intelligently control the pulp level of every flotation bank in the flotation circuit. With the froth height level sensor, an advanced, expert control strategy can determine which flotation banks are not extracting concentrate and can take corrective actions on a timely basis.

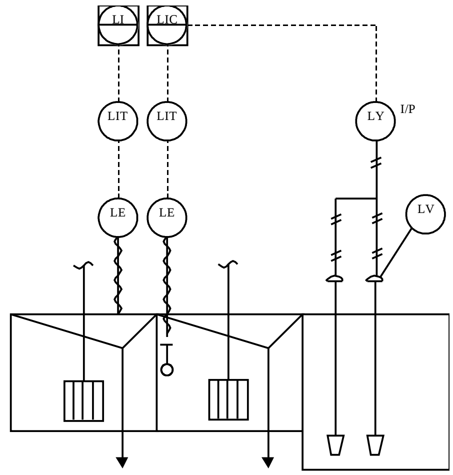


FIGURE 3 Flotation bank froth height instrumentation and pulp level instrumentation and controls

Recall the statement made earlier that flotation bank pulp level control does not provide the granularity of control necessary to optimize the performance of a rougher flotation circuit using an advanced supervisory control system. With froth height measurements on each flotation bank, the advanced supervisory control system has new flotation bank performance data. With this data for example, the control strategy can increase the pulp level of one particular flotation bank, while decreasing the pulp level in every other flotation bank in the flotation circuit. The result is a more finely tuned control strategy that can optimize the flotation circuit performance and respond to a wider range of process disturbances. To illustrate this point, consider Figure 4 that depicts the water additions to a Semi-Autogenous Grinding (SAG) mill. In Figure 4, only one automatic control valve is installed in the water header piping to control the feed-end water addition and discharge-end jet water addition.

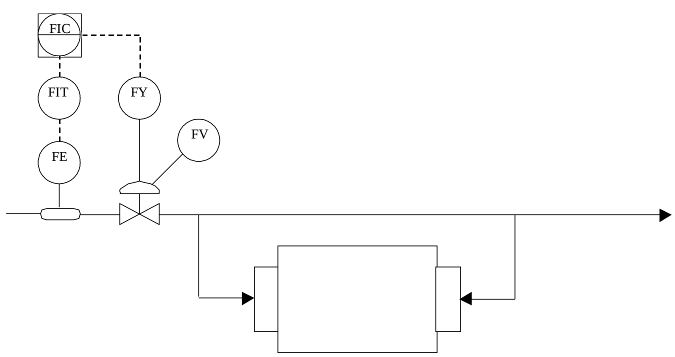


FIGURE 4 Total water flow instrumentation and controls for a semi-autogenous grinding mill

Performance of the SAG mill is quite sensitive to the feed-end water flow rate and the discharge-end jet water flow rate. Using only one flow meter and control valve results in automatic control of the total flow rate of water, but does not provide fine-tuned control of the feed-end or discharge-end water additions. Compare the Figure 4 with Figure 5.

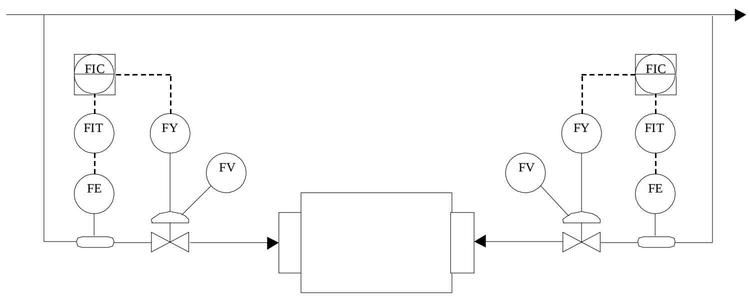


FIGURE 5 Individual water flow instrumentation and controls for a semi-autogenous grinding mill

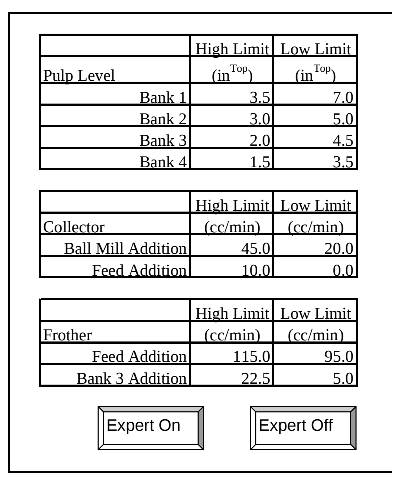
Figure 5 shows instrumentation and controls for each of the water flows to the SAG mill. It takes little more than intuition to realize that this second process control solution will result in better operation and performance of the SAG mill when managed by a knowledgeable operator or a good supervisory control strategy.

The analogy of the SAG mill water control illustrates the same instrumentation and control concepts for flotation bank pulp level control in rougher flotation circuits and necessitates the addition of an additional ultrasonic level sensor to measure froth height in each flotation bank. The additional information gleaned from the froth height data can be used by a knowledgeable operator or advanced supervisory control strategy to improve operation and performance of each flotation bank in the rougher flotation circuit.

In order to prepare for the implementation of a new advanced supervisory control system in the copper producing concentrator, each of the rougher flotation banks in the rougher flotation circuit was instrumented with froth height sensors. The sensors were connected to the Distributed Control System (DCS) and were available to the advanced supervisory control system through a communications channel with the DCS.

A NEW APPROACH FOR IMPLEMENTING THE ADVANCED SUPERVISORY CONTROL SYSTEM

Advanced supervisory control systems for rougher flotation circuits, and for flotation circuits in general, have achieved well-documented benefits that typically include higher-grade concentrate, higher recoveries and reagent savings. The fundamental approach taken by implementers of many supervisory control strategies for flotation is to rely on plant-floor operators to walk through the flotation circuit at regular intervals and visually analyze its performance and select limits that define control ranges for the control variables in the flotation circuit. In this way, plant-floor operators provide integral input and define the behavior of the supervisory control strategy depending on the limits that they enter. This can be illustrated by examining Figure 6. It shows a portion of the user interface of one supervisory control system programmed into a DCS for rougher flotation circuit control using the G2 expert system shell.



Pulp Level	High Limit (in^{Top})	Low Limit (in^{Top})
Bank 1	3.5	7.0
Bank 2	3.0	5.0
Bank 3	2.0	4.5
Bank 4	1.5	3.5

Collector	High Limit (cc/min)	Low Limit (cc/min)
Ball Mill Addition	45.0	20.0
Feed Addition	10.0	0.0

Frother	High Limit (cc/min)	Low Limit (cc/min)
Feed Addition	115.0	95.0
Bank 3 Addition	22.5	5.0

FIGURE 6 Partial view of the user interface for a rougher flotation supervisory control strategy

The display contains three tables, including; 1) the flotation bank pulp level limits table, 2) the collector addition limits table, and 3) the frother addition limits table. The table entries containing numeric data are input fields that can be changed by plant operators. For example, a plant-floor operator may observe that the pulp level of flotation bank 1 is running somewhat low and decides that the strategy should “pull” the flotation bank harder. Therefore, he changes the high limit from 3.5 inches to 2.0 inches. Then, to keep the strategy controlling the flotation bank pulp level setpoint within a 3.5-inch range, he decides to change the low limit from 7.0 inches to 5.5 inches.

Before froth height measurement, this implementation approach was almost the only viable approach available because the control system did not have reliable information that could identify a single misbehaving flotation bank in the rougher circuit. Additionally, the benefits achieved by and documented for these strategies justify their installation and use. However, the key weaknesses of this implementation approach are:

1. Plant-floor operators are required to monitor the flotation circuit performance and change the supervisory control strategy parameters to match operating conditions. Optimal performance of the control strategy can only be achieved when plant-floor operators have a detailed understanding of the control strategy and accurately assess flotation circuit performance and status.
2. Operators can and often do over-constrain the control strategy by configuring the high limit too close to the low limit for a particular control variable. This results in a narrow operating range that can be essentially equivalent to entering a single setpoint for the control variable.
3. Operators often select limits that constrain the flotation circuit to run in well-defined operating ranges that prevent any possible overload conditions as opposed to selecting operating ranges that allow process or equipment constraints to determine rougher flotation performance. In this case, the control strategy encounters a control variable limit before any process constraint is reached.

All of these situations result in lost opportunity and benefits that might otherwise be realized.

After reassessing some of these shortcomings in conjunction with the performance of prior implementations of supervisory control strategies, it was determined that a new approach for implementing a new advanced control strategy was required. The new approach had three main objectives:

1. Remove the need for constant supervision of the supervisory control strategy by plant-floor operators.
2. Remove as many control strategy limits that do not represent process or equipment constraints as possible.
3. Remove any operator-entered targets and objectives that could easily be calculated by the supervisory control strategy itself.

Accomplishing the first objectives results in a supervisory control strategy that is autonomous. Accomplishing the second objective ensures that processing or equipment operating constraints limit the control strategy performance. Accomplishing the third objective results in a control strategy that can react to process disturbances in a more optimal way; i.e. the control strategy selects achievable targets instead of using predefined objectives that are set by the operators.

These objectives were successfully accomplished and resulted in a simplified user interface that contained only one button used by the operators to enable or disable the advanced supervisory control strategy. This represented a vast simplification in the operation of the supervisory control strategy and minimized the amount of training required for plant operating personnel. Note that the user interface for the previous strategy contained over 60 operator-entered limits or targets for rougher flotation control.

KEY UNDERLYING PROCESS CONTROL PRINCIPLES

The goal of an operator-less, plant floor, rougher flotation control strategy implemented for a copper producing concentrator is to maximize copper recovery while producing target or higher concentrate grade. The concentrate grade target is usually defined by purchasing contract specifications for concentrate grade and quality governing the sale of the final concentrate product. Since downstream processing occurs to further clean and concentrate the rougher flotation product, the concentrate grade and quality specifications of the purchasing contracts must be adjusted to a range that allows downstream processes to produce the required final concentrate grade and quality.

A consequence of this line of reasoning is that measurement of the rougher flotation concentrate grade is one of the most important measurements for the advanced control strategy that is measured by the on-stream analysis system. If the on-stream analysis system could only produce one measurement for the advanced rougher flotation control strategy, the rougher concentrate grade would be the measurement of choice. This conclusion seems at odds with the objective of maximizing rougher flotation recovery. However, consider the concentrate grade versus copper recovery graph shown in Figure 7.

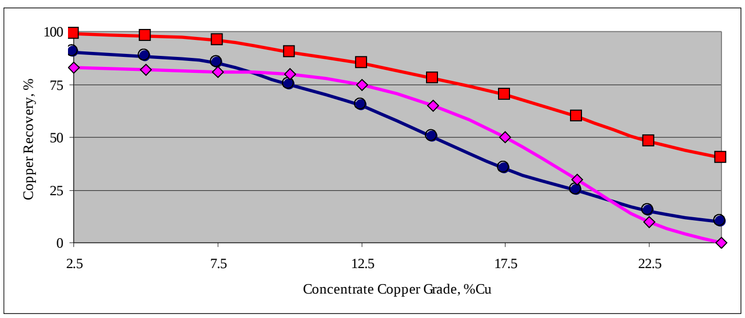


FIGURE 7 Rougher flotation response curve of three different ore-types and particle size distributions

Each trace in Figure 7 represents the highest copper recovery that can be achieved at the stated concentrate copper grade for a given ore-type and particle size distribution. For example, at a concentrate grade of 12.5 %Cu, the highest copper recoveries that can be achieved are 65%, 75% and 85% for the three ore-types depicted in Figure 7. Rarely do plants respond with the definitive consistency that is implied in Figure 7. These types of relationships are the result of gathering and analyzing a lot of data that often has a great deal of variability and scatter. It is this variability that requires advanced process control to optimize the performance of the rougher flotation circuit. The point being illustrated by the data in Figure 7 is that for a given ore-type, particle size distribution, and operating conditions, the lowest acceptable concentrate grade will generally produce the highest recovery and thereby meet the objective.

A frequent mistake made during design and implementation of an advanced supervisory control strategy is to configure data from the ore-type with the highest recoveries (top trace) in the grade versus recovery graph as the criteria that defines when the control strategy objectives are achieved. The variability of ore-types, feed composition and fluctuations in the plant production rates in conjunction with random measurement error can sometimes mask the effects of process control decisions on the grade and recovery. The control strategy will respond, in effect, similarly to the situation when deploying a Proportional-Integral-Derivative (PID) controller to control a system with a measured variable that contains a significant amount of scatter and measurement error. For the PID controller, an active derivative component causes it to take the wrong control actions in response to the scatter and measurement error instead of actual changes in the process. If the rougher control strategy takes actions based on the highest maximum recovery when the ore-type being processed obeys a different grade versus recovery relationship, then the control decisions will generally not match the process response and may cause some process control instability.

Another important principle to note is that downstream processing generally represents the processing or equipment constraints of a rougher flotation circuit. For example, the concentrate collection sump may overflow or the regrind hydrocyclone mass flow rate may be enough to cause the hydrocyclones to rope. Under these circumstances, the quickest way to relieve the problem is to reduce the pulling rate of some or all of the flotation banks in the rougher flotation circuit. Additional changes to reagents and other control variables can help reestablish acceptable operating conditions in downstream processes.

These are just a few of the important control principles that were identified and employed during design and implementation of the advanced supervisory control strategy installed in the rougher flotation circuit of the target copper concentrator. Frequently, the task of implementing an advanced supervisory control system is greatly simplified and the control strategy is more robust when it is tailored to the governing control principles such as these.

PUTTING IT ALL TOGETHER -- IMPLEMENTATION AND RESULTS

The instrumentation, implementation approach and control principles discussed in this paper were all employed when commissioning an advanced, operator-less, supervisory control strategy for the rougher flotation circuit of a western United States copper producer. Discussion of each of these areas in this paper does not provide an exhaustive treatment, but gives descriptive examples of the myriad of process control principles, implementation approaches and instrumentation that were required to successfully accomplish its implementation.

The software used to implement the supervisory control strategy is the KnowledgeScape software. KnowledgeScape is an adaptive, optimizing, process control software that provides fuzzy logic expert system facilities in conjunction with self-learning, neural network models and genetic algorithm optimizers. This unique set of Artificial Intelligence tools allows KnowledgeScape to control, model and optimize a wide variety of processes, including the rougher flotation circuit of the target copper concentrator. The KnowledgeScape implementation replaced an older implementation using the G2 software.

KnowledgeScape was deployed on a computer platform using a client-server architecture. The server computer was a 200 MHz Pentium dual-processor computer with 24 GB of hard drive space to allow up to 16 GB of database storage. The server computer runs the Windows NT 4.0 Server operating system. Client computers were not required for this application, but can easily be networked to the server when the control strategy expands to the point that additional computer resources are required.

Although the specifics of the data are not generally published, the benefit measured and reported by plant staff averaged between 3% and 4% improvement in rougher flotation circuit recovery. One means used to assess these benefits was to allow plant-floor flotation operators to take control of the flotation circuit from the supervisory control strategy and operate the plant as was usual before the advanced supervisory control system was commissioned. During periods of operator control, plant staff consistently measured a decrease in the rougher flotation circuit recovery. When the supervisory control strategy was enabled again, an increase in the flotation circuit recovery was observed and measured.

CONCLUSIONS

Many consider rougher flotation control to be more of an art than a science. However, novel instrumentation, new implementation approaches and sound process control principles make it possible to implement a supervisory control strategy that makes process control decisions and changes without human interaction. A supervisory control strategy was installed on the plant-floor to control an industrial rougher flotation circuit that requires no operator interaction. Plant staff monitored the flotation circuit under supervisory control and reported benefits of up to 4% improvement in copper recovery above that achieved with another supervisory control system. It is possible that the work reported in this paper, to implement an advanced supervisory control strategy for autonomous rougher flotation control, is the first successful accomplishment of this mission.