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A survey on the status of industrial flotation control

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Abstract: A survey was conducted to establish the status-quo of industrial flotation control. The survey focussed on the measurements and actuators generally available in industry, the reliability and accuracy of measurements, and how important process variables are controlled. It is evident from the survey that regulatory control is well established with reliable and relatively accurate measurements available throughout a plant. The introduction of froth image analysers seems to gain good traction and enables improved control of mass pull to achieve consistent concentrate grade. Although supervisory control may soon be the new standard for flotation plants, on-line grade optimisation requires further work.

Keywords: flotation, mineral processing, optimisation, process control, survey

1. INTRODUCTION

The objectives of a control system to optimise the metallurgical performance of a flotation circuit generally proceed in the following order: stabilize the circuit, achieve grade target, and maximise recovery to maximise the economic performance of the circuit (McKee, 1991). This is akin to the classical hierarchical control design approach of regulatory control, supervisory control, and optimisation (Skogestad, 2004). Each layer depends on its predecessor, as the final economic performance can only be optimised if the supervisory layer can maintain economic variables at setpoint, and the economic variables can only be controlled if the regulatory layer can maintain the plant within an operable range (Le Roux and Craig, 2019).

The three layers of the control hierarchy, regulatory, supervisory, and optimisation, have reached different degrees of maturity at industrial flotation plants. Whereas regulatory control may have been an area of concern three decades ago (McKee, 1991), advances in hardware (sensors, data transmission, and computers) and software (data management, process models, and control algorithms) within the mineral processing industry (Hodouin et al., 2001) enabled the implementation of reliable regulatory controllers on industrial flotation plants (Schubert et al., 1995). However, the successful implementation of long-term automated supervisory and optimisation based strategies remain scarce (Shean and Cilliers, 2011), whether for mechanical (Jovanovic and Miljanovic, 2015) or column flotation cells (Bouchard et al., 2009).

The lack of successful implementation of long-term automated supervisory and optimisation control strategies is generally attributed to a lack of accurate and reliable process models, measurement instrumentation, and actuators (Bergh and Yianatos, 2011). The lack of suitable dynamic process models cannot be separated from the issue of insufficient measurement data. Although there is a plethora of flotation models available, the models cannot be calibrated without sufficient on-line measurement data. The models require frequent recalibration as they are generally limited to small regions of operation (Oosthuizen et al., 2017). It should be noted that poor measurements and actuation not only affect the supervisory and optimisation layers, but will also impede the success of the regulatory layer.

The considerable advances in data science enabled new measurement technology within flotation. Since visual froth surface features are closely related to the flotation performance, machine vision receives and processes images from cameras positioned above flotation cells to extract froth features for monitoring and control purposes. In the case of Supomo et al. (2008), cameras are used to measure the froth velocity for individual rougher cells. Since the froth velocity is related to the mass pull, the control system adjusts the froth depth to optimise the mass pull.

Although there is much research in the area, it remains difficult to accurately measure concentrate grade from the flotation froth appearance using cameras (Bergh and Yianatos, 2011; McCoy and Auret, 2019). Since the measurable variables such as colour, bubble size and shape do not correspond to a specific metallurgical condition, different ores and cell conditions may produce similar images (Reddick et al., 2009). According to Aldrich et al. (2010), successful long-term fully automated control systems based on machine vision to control concentrate grade and recovery have yet to materialize.

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The aim of the discussion above is to indicate that economic optimisation of flotation circuits will only be achieved once measurement and actuation is trustworthy and accurate and regulatory control is well established within plants.

In light of the above, a survey was conducted to establish the status-quo of control of industrial flotation plants, and to indicate the main control and measurement issues hindering plants from improving their overall economic performance. In other words, the survey attempts to establish where plants are on the road towards supervisory control and optimisation. The survey address the following issues:

- What measurements and actuators are generally available at an industrial plant?
- What is the reliability and accuracy of measured variables?
- How are important process variables controlled, and how is the controller performance evaluated?
- How do machine vision systems influence plant operation?

Section 2 describes the survey in terms of its structure and general response. Section 3.1 discusses manipulated variables at plants in terms of measurement and actuation, measurement errors, and controllers. Similarly, Section 3.2 discusses process variables in terms of measurement and control, measurement errors, and controllers. Image analysers, packages, and a wish list are briefly discussed in Sections 3.3-3.5. Section 4 provides a conclusion of the survey results.

2. SURVEY DESCRIPTION

2.1 Structure

The questionnaire was structured in similar fashion as the survey by Wei and Craig (2009). The validity of questions was determined through interviews with industry experts. The aim was to provide meaningful and objective questions. The questionnaire was constructed in SurveyMonkey [2] and distributed via email among the authors' contacts and among referrals from colleagues. Data was collected between August 2018 and February 2019.

The survey was divided into the four sections below:

- Manipulated variables
- Process variables
- Image Analysers
- Control Packages

For manipulated and process variables, the focus was on the type of measurement and actuation/manipulation, the degree of measurement accuracy and reliability, and the type of control used. For image analysers and control packages, the focus was on their impact on plant operation. Each section is treated separately below.

2.2 Response

A total of 18 respondents completed the survey. Each respondent represents a different plant. The global distribution of respondents is 10 from Southern Africa, 3 from Europe, 2 from Australia and 3 from Northern America. The sample size is small and skewed towards Southern Africa.

The majority of plants surveyed treat PGMs (50%), copper (45%), and/or zinc (35%). Not all participants answered all questions. The following process units are common: 16 plants make use of surge tanks, 19 plants have rougher cells, 16 have scavenger cells, 18 have cleaner cells, 15 have regrinding mills, and 15 have re-cleaner cells. Mechanical cells were reported on all plants, whereas only 5 of the 18 plants surveyed made use of column flotation cells. Only one plant in Southern Africa used columns cells, whereas all plants surveyed outside of Southern Africa had column cells. Plants surveyed in the Southern Hemisphere primarily make use of mechanical cells, whereas plants elsewhere make use of both mechanical and column flotation cells.

3. SURVEY RESULTS

3.1 Manipulated variables

Oosthuizen et al. (2017) identified the following manipulated variables as the most common to drive a process into a desired direction:

- Air flow-rates into cells
- Pulp level
- Reagent addition
- Froth wash-water

Respondents were asked how they measure and actuate each variable, what measurement errors they experience, the importance of the variable for control, and what type of controller is connected to each variable. A selection of results are shown in Tables 1 and 2.

Measurement and Actuation As seen in Table 1, all plants indicate that they measure air flow-rates and pulp levels on-line, and that they manipulate these variables with automated valves. Air flow-rate is predominantly measured with differential pressure transmitters (44%) or thermal gas flow sensors (39%). Pulp level is predominantly measured with float-and-target-plates (78%). Almost all plants measure reagent addition with magnetic flow-meters (78%), and more than half of plants (59%) use automated pumps to add the reagents. More than half of the plants (59%) surveyed do not measure or automate froth-wash water addition.

As expected, air flow-rate and pulp level are well instrumented, whereas froth-wash water instruments do not feature for most plants. Reagent addition is generally automated, but as seen in later responses, it is not clear how this manipulated variable should be controlled to influence process conditions.

Measurement Errors As seen in Table 2, the most common reason attributed to errors in the air flow-rate, pulp level or reagent addition measurement is an instrument which fails/breaks. Drift, bias and noise are not regarded as the main reasons for faulty measurements. These three measurements are regarded as very accurate and reliable. All plants regard air flow-rate and pulp level as important

[2] Visit: www.surveymonkey.com/r/FlotationSurvey2

Table 1. Manipulated variables: Measurement and actuation.

Manipulated variable	How do you measure the variable?	How do you actuate the variable?
Air flowrates	0% No measurement 0% Manual reading from instrument 39% Thermal gas flow sensor 44% Differential pressure transmitter 17% Other	100% Automated valve
Pulp level	0% No measurement 0% Manual reading from instrument 78% Float with target plate 17% Conductivity and capacitance 5% Other	100% Automated valve
Reagent addition	0% No measurement 6% Manual reading from instrument 78% Magnetic flow meters 17% Other	0% No Actuator 12% Manual valve 59% Automated pump 29% Other
Froth wash water	59% No measurement 6% Manual reading sent to lab 35% Other	23% No Actuator 31% Manual valve 23% Automated pump 23% Other

Table 2. Manipulated variables: Measurement errors, measurement reliability, controllers, and control satisfaction.

	Air flowrates	Pulp level	Reagent addition	Froth wash water
Common reasons for measurement errors.				
Bias fault	0%	11%	17%	0%
Drift	22%	22%	27%	6%
Noisy-measurement	17%	17%	6%	0%
Instrument fails	67%	67%	44%	12%
Not applicable	6%	0%	11%	82%
Adequacy / reliability / accuracy of measurement.				
100% (Always reliable)	39%	28%	50%	13%
75%	50%	61%	28%	13%
50%	11%	11%	17%	0%
25% (Almost never reliable)	0%	0%	0%	0%
Not applicable	0%	0%	6%	75%
Type of controller.				
Manual operator	0%	0%	29%	38%
PID control	22%	17%	35%	15%
Multi-variable	61%	61%	12%	0%
Expert system	17%	22%	18%	8%
Other	0%	0%	6%	39%
Satisfaction with controller performance.				
Yes	94%	89%	56%	27%
No	6%	11%	27%	0%
Not applicable	0%	0%	17%	73%

to control the plant. Almost all plants regard reagent addition as important to control the plant, while only one is neutral about its importance for control. Almost all plants are either neutral or disregard the importance of froth-wash water for control.

A comment regarding froth wash water should be made. Since the survey primarily covers Southern Africa which mostly use mechanical flotation cells, it is not surprising that froth wash water rate is not regarded as important. Mechanical cells do not generally make use of froth wash water (Jovanovic and Miljanovic, 2015), whereas flotation columns are highly dependent on froth wash water as a manipulated variable (Bouchard et al., 2009).

Controllers To control the process, plants manipulate air flow-rate first, followed by either pulp level or reagent addition. As seen at the bottom of Table 2, 61% of respondents indicate that multi-variable control is used to control air flow-rate and pulp level, 17% of plants use expert systems for air flow-rate, and 22% of plants use expert systems for pulp level. Reagent addition is generally either manually controlled (29%) or with PID controllers (35%), with only a few plants using multi-variable control (12%) or expert systems (18%). Almost all plants (≈90%) are satisfied with their air flow-rate and pulp level controllers. Slightly more than half of plants (56%) are satisfied with their reagent addition control.

3.2 Process variables

There are numerous variables which influence a flotation circuit (Laurila et al., 2002). Only the following main process variables are considered:

- Pulp (or slurry) density
- Ore particle size
- Mass pull
- Concentrate grade

The pulp density and ore particle size are properties of the flotation circuit feed, and are determined by upstream processes such as a comminution circuit. They can also be considered as disturbance variables which enter the plant. The mass pull and concentrate grade are the main outputs which relate to the economic performance of the process (Oosthuizen et al., 2017). Because recovery is computed for steady-state operation, recovery is not included here as a process variable which is measured on-line.

Respondents were asked how they measure and control each variable, what measurement errors they experience, what is the impact of fluctuations of these variables on plant performance, and how the variables are controlled. A selection of results are shown in Tables 3 to 5.

Measurement and Control As seen in Table 3, the pulp slurry density is generally measured with nuclear based sensors (50%) or other types of density meters (39%). Only 6% of plants do not measure pulp density and 6% use manual samples. Pulp density is controlled in 61% of plants with an automated water addition valve.

Ore particle size is measured through manual sampling in 56% of plants, 27% have on-line measurement analysers (X-ray fluorescence (XRF) (Laurila et al., 2002) or laser diffraction (Ma et al., 2000)), and 16% have no measurement. About 75% of plants indicate they rely on the

Table 3. Process variables: Measurement and manipulation.

Process variable	How do you measure the variable?	How do you manipulate the variable?
Slurry density	6% No measurement 6% Manual sample sent to laboratory 50% Nuclear based 39% Density meter 0% Other	17% No actuator 11% Manual valve adds water 61% Automated valve adds water 11% Other
Ore particle size	16% No measurement 56% Manual sample sent to laboratory 11% XRF analyser 16% Laser diffraction 0% Other	19% No actuator 75% Controlled by comminution 6% Re-grinding stage 0% Other
Mass pull	17% No measurement 0% Manual reading from instrument 56% Magnetic flow meters 28% Other	13% No actuator 0% Manual pump control 47% Automated pump control 40% Other
Concentrate grade	0% No measurement 39% Sample sent to laboratory 44% XRF analysers 11% Reflective spectroscopy 6% Other	6% No actuator 47% Level and air 41% Mass pull 6% Other

Table 4. Process variables: Measurement errors, measurement reliability, controllers, and control satisfaction.

	Slurry density	Ore particle size	Mass pull	Concentrate grade
Common reasons for measurement errors.				
Bias fault	24%	19%	19%	33%
Drift	59%	25%	38%	39%
Noisy-measurement	18%	6%	32%	11%
Instrument fails	12%	19%	19%	22%
Not applicable	0%	38%	19%	22%
Adequacy / reliability / accuracy of measurement.				
100% (Always reliable)	22%	22%	28%	33%
75%	61%	39%	50%	50%
50%	11%	6%%	6%	17%
25% (Almost never reliable)	6%	11%	0%	0%
Not applicable	0%	22%	17%	0%
Type of controller.				
Manual operator	44%	53%	13%	-
PID control	28%	6%	6%	-
Multi-variable	22%	29%	56%	-
Expert system	0%	6%	25%	-
Other	6%	6%	0%	-
Satisfaction with controller performance.				
Yes	77%	56%	94%	50%
No	11%	17%	6%	28%
Not applicable	11%	28%	0%	22%

comminution plant to ensure correct particle size, whereas 19% indicate that no actuator or mechanism is used to manipulate the ore particle size, and the remaining 6% depend on the regrinding stage to manipulate the ore particle size.

Table 5. Process variables: Variable fluctuation and plant operability.

	Slurry density	Ore particle size	Mass pull	Concentrate grade
Severity of fluctuation in variable on plant operability.				
Detrimental	61%	67%	76%	-
Neutral	39%	33%	26%	-
Negligible	0%	0%	0%	-
Main causes of fluctuations in variables.				
Incorrect operation of comminution plant	56%	67%	0%	28%
Change in ore hardness	6%	50%	6%	17%
Under grinding	11%	17%	12%	22%
Over grinding	11%	6%	0%	16%
Operation of flotation fluctuates	39%	0%	71%	78%
Other	22%	0%	18%	28%

Only 17% of plants do not measure mass pull. In the case where it is measured, 56% of plants use magnetic flow meters. A typical positioning of magnetic flow meters is on a vertically orientated discharge pipe to minimize air effects, after a concentrate collection sump equipped with a pump. However, the accuracy of the flow measurement is typically determined by the equipment suppliers and plants. If signals are noisy for whatever reason, some signal conditioning through filtering will be done for control purposes. To manipulate this variable, 47% of plants use automated pumps together with flotation pulp level and air flow-rate. More specifically, a combined overflow of froth from multiple flotation tanks, which is typically unmeasured, is achieved by adjusting the pulp levels and air flow-rates. Consequently, this will affect the steady-state level in the concentrate collection sump. To maintain the same steady-state sump level, the variable speed pump is adjusted which ultimately gives an indication of overflow mass pull through the flow-meters.

The concentrate grade is measured on-line using XRF analysers (44%) or reflective spectroscopy (11%), whereas 39% of plants send manual samples to a laboratory. None of the plants indicated that they use cameras to measure concentrate grade. About 47% indicate they control concentrate grade directly with pulp level and air, whereas 41% of plants indicate they use mass pull to control concentrate grade indirectly.

The final concentrate grade is measured in all plants (100%), regardless of the measurement type; 61% of plants measure the grade at the feed, 67% at the tailings, and 72% between flotation banks. Final tails grade was mentioned by two respondents as an additional variable which they control.

Measurement Errors The measurement errors and measurement reliability is shown in Table 4. Whereas instrument failure was the dominant reason for measurement errors for manipulated variables, this is not the case for process variables. Drift is the main reason for errors in pulp density measurements (59%), whereas mass pull measurements are erroneous as a result of drift (38%) and noise (32%). Bias (33%) and drift (39%) are the main reasons for errors in concentrate grade measurements. Ore particle size is generally shows errors as a result of drift (25%). Although measurement instruments for process variables are regarded as less reliable than for manipulated variables, respondents show that process variable measurements have good degrees of reliability.

Controllers As seen in Table 4, about 44% of plants control pulp density through manual operator intervention. The remainder of plants use either PID (28%) or multivariable systems (28%). About 77% of plants are satisfied with the performance of the pulp density controllers. Pulp density is also regarded as the easiest variable to control from the four listed. One would expect automatic controllers for pulp density on more plants since it is relatively easy to control and controller performance is satisfactory. However, since a third of plants are neutral towards the impact of fluctuations of pulp density on process variability, it makes sense that 44% of plants do not automate this variable.

Approximately half of plants (53%) use manual operator intervention to control ore particle size. The remainder use either PID control (6%), multi-variable controllers (35%), or expert systems such as fuzzy control (6%). Approximately half of plants (56%) are satisfied with controller performance. However, since only 27% of plants have on-line measurements of ore particle size, this result is contradictory to previous results. Further questions are necessary to determine and understand the control structures employed by the various plants for ore particle size. Along with concentrate grade, ore particle size is regarded as more difficult to control than pulp density and mass pull.

About 56% of plants control mass pull with multi-variable controllers, 25% with expert systems, and 13% with manual operators. Almost all plants are satisfied with the controller performance, and this variable is the second easiest variable to control after pulp density.

In the case where concentrate grade controllers are used, half of respondents are satisfied with the controller performance.

As shown in Table 5, two thirds of plants (64%) believe a fluctuation in pulp density and ore particle size has a detrimental effect on steady-state plant operation, whereas 76% of plants regard fluctuations in mass pull as detrimental for plant operability. The remainder of plants are neutral with regards to the severity of fluctuations of these variables on plant operability.

The two main causes for fluctuations in pulp density is either regarded as incorrect operation of the comminution plant (56%), or variability in the operation of the flotation plant (39%). Fluctuations in the ore size is attributed to either incorrect operation of the comminution stage (67%), or changes in the ore hardness (50%). Fluctuations in mass pull and concentrate grade are attributed predominantly to high process variability in the operation of the flotation plant (75%).

Respondents were asked what the key performance indices (KPIs) are which contribute most to the evaluation of a controllers performance. The main KPI's are reduced process variability and improved grade/recovery. Throughput increase and reagent consumption decrease are much less important as KPIs for controller performance. A reduction in energy consumption counts the least towards evaluating controller performance.

According to the respondents, the dominant reason for switching from automatic control to manual control appears to be faulty instruments. This implies that new developments in fault detection and isolation (FDI) and measurement reconstruction can make a large impact to keep controllers on-line (Brooks and Bauer, 2018).

3.3 Image analysers and cameras

When asked if a plant needs a froth image analyser, only 60% said yes. Of the plants surveyed, 67% of plants had froth image analysers. More than half of the plants (58%) with image analysers connect the analysers to an automated control loop, or display the information to operators to make control decisions. A sixth of plants (17%) do not use the information from the image analysers. The information from the cameras is mostly used to control mass pull between cells (50%), and sometimes used to control the air addition rate to maintain a peak-air-recovery ratio (25%). The mass pull is controlled by measuring the froth velocity with the cameras. Two thirds of plants (67%) believe the information from the analysers are important to operate the process, whereas the remainder (33%) are neutral towards its importance. None regard the information as unimportant.

3.4 Packages

About 90% of plants make use of a commercial package to control their plants. These packages are generally either AspenTech, Mintek Floatstar, or Outotec FrothSense. 73% of respondents with packages indicate that the packages perform very well since operator intervention is rarely required, and the remaining 27% indicate that it performs only reasonably well as operator intervention and supervision remains necessary. The main benefits of the packages appear to be consistency, reduced process variability, reagent reduction, and the fact that operators are freed to perform other tasks on the plant. A potential disadvantage is the loss of operator knowledge and understanding, especially how to handle abnormal situations.

3.5 Wish list

The respondents gave a wide variety of answers in terms of a wish list of variables to measure, manipulate and/or control, and topics requiring further investigation. The dominant ideas revolved around on-line measurements of grade and grind, and up to date knowledge of the mineralogy of the ore from the mine. One respondent commented that the survey did not cover feed-forward or disturbance variables which are essential for an effective control solution.

4. DISCUSSION AND CONCLUSION

The manipulated variables considered for the survey were air flow-rate, pulp level, reagent addition, and froth wash-water. The survey indicates that air flow-rate and pulp level is well instrumented, actuated, and automated. However, although reagent addition is generally automated, satisfaction with controller performance is much less than for air flow-rate or pulp level. Froth wash-water is generally not used, but this is because most respondents are from the Southern Hemisphere where mechanical cells dominate. Froth wash-water is common in column flotation cells. The measurement of the manipulated variables is considered as reliable and accurate, and the reason for failure is generally the result of an instrument which breaks. It is positive to see that the manipulated variables within a regulatory control layer at an industrial flotation plant are well instrumented and reliable. However, further research is required to use reagent addition as a manipulated variable to control the metallurgical performance of the plant, i.e. grade and recovery.

The process variables considered in the survey include feed characteristics and economic concerns: pulp density, ore particle size, mass pull, and concentrate grade. Just more than half of plants use automated valves to control pulp density, whereas the rest still use manual control. More automatic controllers for pulp density would be expected as it is a relatively easy variable to control. The ore particle size is generally considered to be controlled by the comminution plant. Although fluctuations in ore particle size will have a detrimental impact on plant operability, very few plants have on-line measurements of ore particle size and most plants use operator intervention at the grinding circuit. Mass pull is measured on-line on the majority of plants and can be controlled with an automated pump. Concentrate grade is measured by all plants, with many plants measuring grade between flotation banks. It is positive to see that many plants can measure grade on-line, and that many plants are satisfied with grade controllers.

Image analysers appear to make a considerable impact on plant operation. Most plants with image analysers use it to measure froth velocity to control mass pull between cells. Some plants use the image analysers to control the air addition rate for peak-air-recovery.

The survey confirms that regulatory control is well established within flotation circuits with reliable and accurate measurement instrumentation. The introduction of froth cameras enables plants to drive the mass pull continuously such that the best grade is achieved. Therefore, the platform for long-term supervisory control and optimisation has been laid for plants to achieve optimal economic performance.

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