# Machine Vision Based Measurement and Control of Zinc Flotation Circuit

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## 1. Introduction

Flotation as a method for separating valuable substances from waste was patented in 1906. It is a very efficient and thus popular method, especially in mining industry, but it is also used in other processes, for example for separating the ink from the recycled waste paper. Before flotation the mined ore rocks are mechanically ground to powder of desired grain size, typically 50-100 μm. The powder is mixed with water and chemicals and the resulting pulp is fed to a series of flotation cells. In the flotation cell air is fed into the pulp to produce bubbles that naturally move upwards and produce froth on top of the pulp. The grains, depending on their mineral contents, tend either to float and stick to the bubbles or to sink in the liquid. Due to variation in grain properties (size, shape, mineral content, etc.) the separation is far from ideal. Both the froth and pulp still contain grains having various mineral contents. Consequently the separated grains in the froth and in the remaining pulp are usually fed to the next flotation cells to continue the separation process and, for example, suitable chemicals are used to strengthen the separation. The main parts of a typical flotation cell used in mineral processing industry are represented in the following figure.

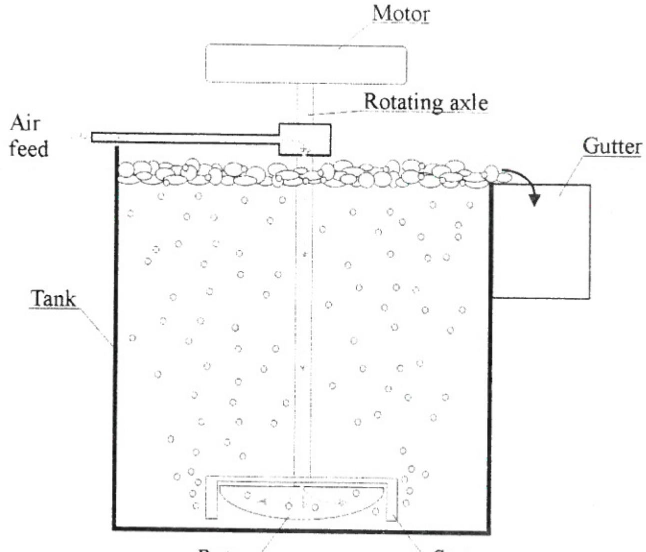



**Figure 1: Main parts of a flotation cell**

The flotation phenomenon, floating and sinking of grains, is sensitive and precarious in nature. This added to the great variety in grain properties makes the flotation process complex and difficult to control. For process control the flotation plants are provided with conventional and specialized sensors. Conventional instrumentation includes devices for reagent dosing, for measuring and controlling pH, volumetric flow and density of the pulp and for measuring and controlling airflow and pulp level in flotation cells. Special instruments have been developed for measuring the average particle size in the pulp and sometimes froth level measurement is also used. However, the basic instrument for effective flotation control is an X-ray fluorescence pulp analyzer, which continuously measures metal contents of different pulp streams. The typical measuring cycle for analyzing all streams takes 5-10 minutes.

Measurement and evaluation of certain variables in the flotation process are traditionally left to the visual observation of the human operator. Such variables include the type of the flotation froth including the size and form of the bubbles and their distribution, and the color and the brightness/darkness of the froth. These depend both on the type and grain size distribution of the mineral particles, on the properties of the liquid phase, and on the operational parameters of the equipment. The process operators rely on these dependencies by their long experience, but their chances are severely limited by the absence of physical, quantitative methods of measurement and characterization of the flotation froth. An example of the flotation froth from zinc rougher circuit in Pyhäsalmi Mine of Outokumpu Finnmines Oy (Finland) is presented in Figure 2.

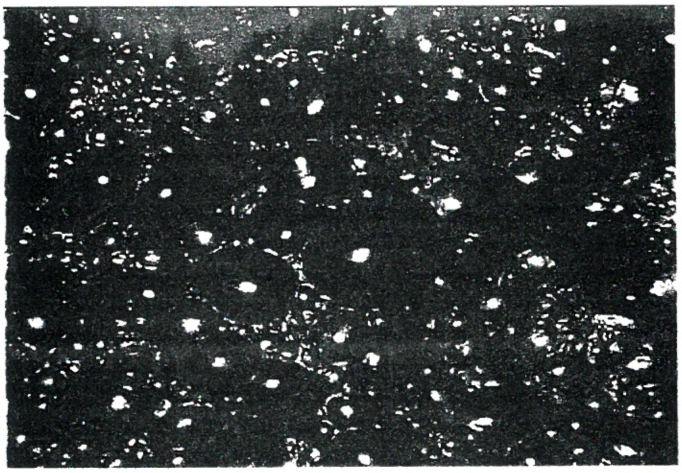


**Figure 2: An example of the flotation froth in Pyhäsalmi**

The primary source of the disturbances in flotation is the changing ore quality. Normally the ore is fed to the concentrator plant as a mixture of many types of ore coming from different parts of the mine. From some types of ore it may be easy to get simultaneously a high concentrate grade and a good recovery while from some other ore type both the grade and recovery remains low. The ore quality, except the metal grades, cannot be measured at the plant, which causes need for continuous adjustment of reagents. On the other hand an under- or overdose of reagent can be a secondary source of disturbances and due to long process delays the effect of corrective control actions cannot be seen immediately.

Instrumental vision based methods have been developed more recently to the observation and analysis of scenes of froth by Moolman et al. (1994, 1995) in South-Africa, Oestreich et al. (1995) in USA and Guarini et al. (1995) in Chile. While most of such developments have taken place in laboratory some instrument systems have been tested on line in flotation plant (Moolman et al. 1995a, Guarini et al. 1995). These are reported to be applicable to classification of froths or to extraction of physical features, like average size, size distribution and shape parameters of the bubbles, speed of froth and color parameters. The methods applied for textural characterization and classification of froths are based on statistical signal processing techniques like histograms, Fourier transforms, power spectrums (Moolman et al. 1994) and gray level dependence matrices (Moolman et al. 1995b). They produce either phenomenological or artificial features for classification. The classification is carried out by standard statistical techniques or by use of neural networks.

In this paper new results of continuous measurement and control of a mineral flotation circuit are presented. The research resulted to genesis of an on-line measurement station that is able to measure and calculate numerous different variables from RGB (Red, Green, Blue) images that are grabbed from the flotation froth. In addition to previously mentioned variables, also some new and important (for mineral flotation) variables are introduced (e.g. a variable telling the mineral load of the froth). The most important functions and features of the analyzer are discussed. Finally, a special controller that utilizes the image information and the economical results achieved with it are presented.

## 2. Objectives of the research

The technical objective of the research was to utilize machine vision equipment and software for obtaining quantitative information on the visual flotation froth characteristics and to use this information in the on-line control of the flotation process. A real measurement of the importance of the objectives can be assessed considering that actually there does not exist any system, neither research nor academic, that is able to fully quantify the aspect of the froth that strongly influences the process itself and is usually evaluated adopting a human based approach.

The specific objectives were:

1. To analyze mineral concentration of the flotation froth from the color of the froth.
2. To analyze the flotation froth structure (speed of the froth, the size and form of the bubbles, their distribution etc.).
3. Classification of the flotation froths (e.g. statistical methods and neural networks).
4. To develop an on-line froth analyzer (bubble size, speed etc.).
5. To develop process models for different types of flotation conditions.
6. To simulate the flotation process and develop control strategies for automatic control of flotation plant.
7. To install and test the resulting products at industrial flotation plants.

All these objectives were reached by comparing the "new proposed approach" with other classical different measurement techniques. The advantage of the proposed approach is mainly linked to the fact that by means of only one set of measurements (imaging based) it is possible to derive information usually obtained by different measurements techniques, more expensive in terms of hardware (several sensors) and software (integration of different information). The general objectives of the research are to optimize control and production at flotation plants and thus to give competitive advantage for European mining industry.

## 3. Results

The study resulted in new software tools and algorithms for the flotation froth analysis and for the flotation process control by using existing forefront hardware. The analysis itself gave rise to new scientific results on the dependencies of the froth characteristics on the process variables.

The main results are:

1. An on-line flotation froth analyzer (color and structure).
2. An on-line flotation froth classifier.
3. Mathematical models of the flotation process (especially the dependencies of the visual characteristics of the froth on the process variables). (See Kuopanportti et al. 2000a&b, Ylinen et al. 2000, Hasu 1999)
4. Control methods and algorithms for the flotation process control with machine vision.
5. Scientific results on the flotation process behavior and the dependencies of the flotation variables (concentration, etc.).

Each resulting item is separately useful in the flotation industry. For example, the froth analyzer and/or classifier installed in the plant highly increases the operators' ability to control the flotation process on-line. By utilizing the froth analyzer the most serious disturbances due to incorrect reagent dosages can be detected and eliminated much earlier than before, which brings better flotation results, i.e. higher recoveries, and cost savings in reagent consumption. The froth analyzer will also be useful tool in process studies and is expected to lead to better understanding of the process behavior.

The on-line froth analyzer developed is currently operating in Pyhäsalmi concentrator zinc rougher circuit in Finland and is used for on-line copper sulphate control, to calculate different variables based on images and spectra taken from the froth, to display froth images to the operators and for on-line froth classification. The analyzer and the tasks it is performing are described in the following.

## 3.1 On-line analyzer

In quite early phases of the research a special measurement station for froth measurement was constructed to Pyhäsalmi mines. Pyhäsalmi is located some 500 km north from Helsinki in the middle of Finland. The main functions of the measurement station were the froth image grabbing and spectral measurements of the froth. The measurement station was constructed on top of the first flotation cell in the zinc rougher circuit of Pyhäsalmi concentrator. The first cell was selected because it has strongest effect on the overall performance of the process. If the froth in the first cell looks good it usually looks good in the following cells also. On the other hand, if the froth in the first cell looks bad it usually looks bad also in the following cells. Another plus is that the information from the first cell can be obtained in very early stages of the process and thus corrective actions can be taken immediately if something starts to go wrong. This is very important in flotation since the delays can be very long. The indication of abnormal situation can easily have for example a 30-minute delay meaning that the process can be in an undesirable state for an hour before the situation can be corrected. This can mean significant losses both in product and in economics annually. (Kaartinen 2001)

Basic structure of the froth image and spectra gathering system built in Pyhäsalmi concentrator can be seen in Figure 3. It consists of a measuring hood attached on top of the zinc-flotation cell and a computer located next to the hood. In the hood there is an RGB-colour camera and a spectrophotometer.

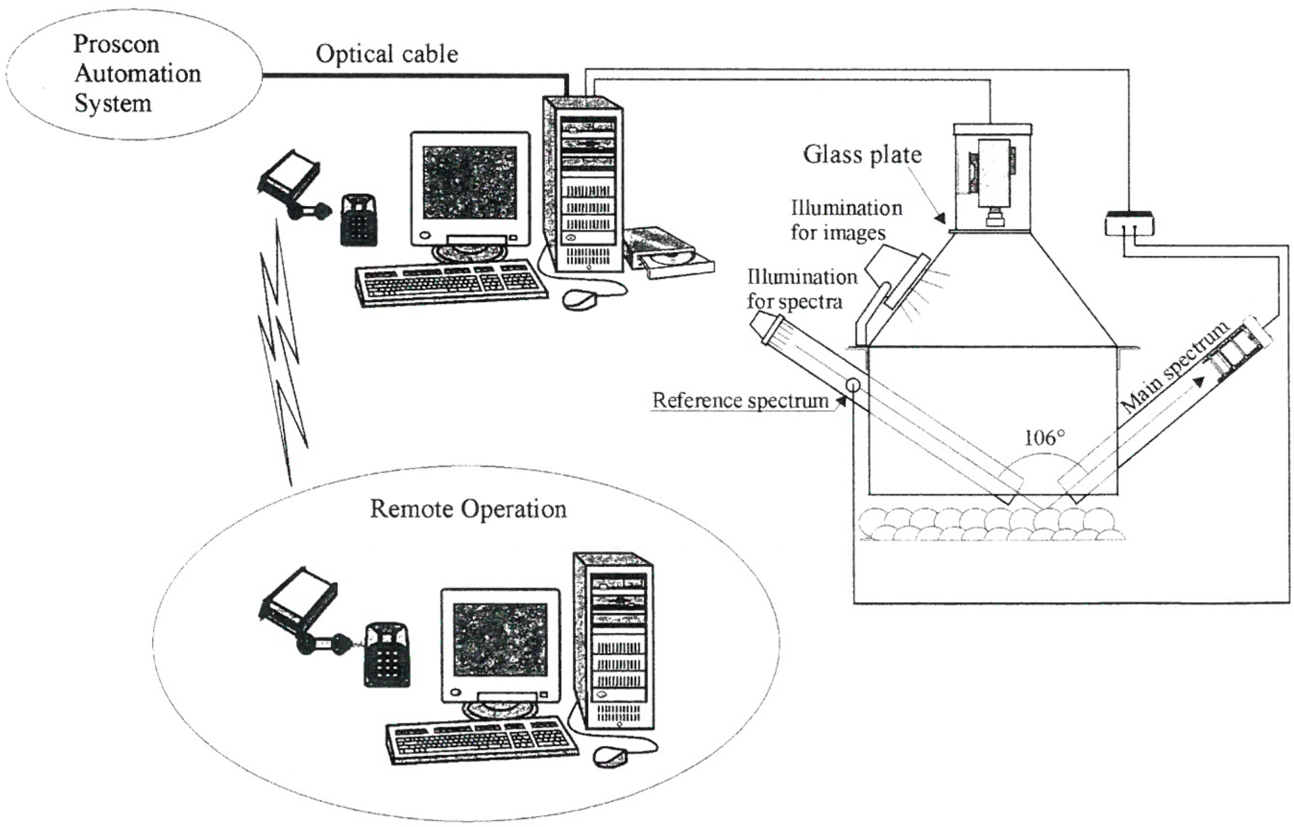



**Figure 3: Configuration of the on-line flotation froth analyzer built in the research**

The system is connected to Outokumpu's automation system (PROSCON®) and can also be accessed remotely using public telephone lines. The measurements were intended to be and are currently done mostly by using the RGB-color camera. The spectrophotometer is only used to give additional input to the measurements. The motivation for this was the accuracy of the instrument. RGB values retrieved from the

PAL signal can detect colour information with 3 channels and 8 bits per channel. The spectrophotometer on the other hand gives usable 12 bit data over 850 channels, which goes beyond the wavelength range seen by human eye (and standard RGB camera). (Kaartinen 2001)

### 3.1.1 Measured variables

With the image analyzer it is possible to get approximately 60-70 different variables from the froth. However, in these measurements there is some redundancy. A good example is different color plane representations of the image; the grabbed image is presented both in RGB (red, green, blue) and HSV (hue, saturation, value) color planes and for all these six variables first four moments of their distribution are calculated separately.

A few of the most interesting variables measured from the froth are, for example, speed of the froth, mean bubble size, bubble collapse rate, redness of the froth (since redness correlates with the amount of zinc in the froth) and transparency of the froth. The transparency variable was specially developed for zinc flotation. It indicates the amount of the transparent bubbles in the froth, which on the other hand correlates with the mineral load of the froth (See Miettunen et al. 2001). All measured variables are stored to the mine's database and are thus available for further investigation and for use in the automation system.

### 3.1.2 Froth Image Browser

Also the froth images are stored after analysis and displayed to the plant operators using a specially designed software called Froth Image Browser (Kaartinen 2001). Froth Image Browser is a program made with Visual Basic® for viewing newly captured RGB froth images and history image database, which includes 480 most recent images. The program is integrated to Outokumpu's automation system so that with a push of a button operators can see how the froth looks like.

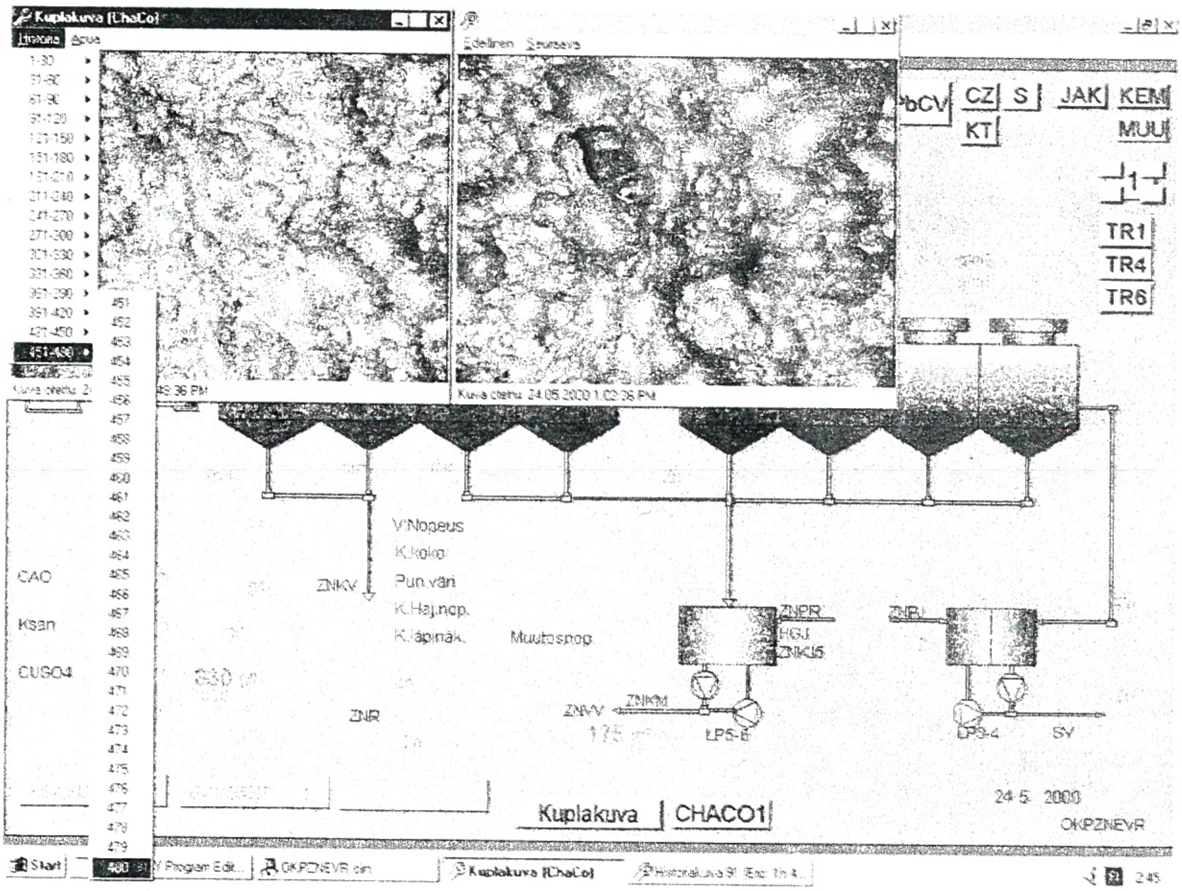



**Figure 4: Graphical User Interface of the Froth Image Browser – program**

The Graphical User Interface of the Froth Image Browser can be seen in Figure 4. In the leftmost window is the most current froth-picture and in the window on the right is a selectable froth-picture from the database. As mentioned, the database includes 480 most recent froth-pictures, which equals to approximately 8 hours in time. The history database has proven to be valuable plus for the operators, because the maximum time of history trends for other measurements is also 8 hours. This means that if the operators see something strange or interesting in their trend curves, they can track down the visual appearance of the froth at the time in question and thus get some additional information of the situation.

## 3.2 Froth classification

Five different froth classifiers were developed and studied. Also other classification methods (e.g. Principal Component Analysis (PCA) and Factorial Analysis) were tested but the following five were thought to be the best candidates for classification based on the results.

The tested methods were:

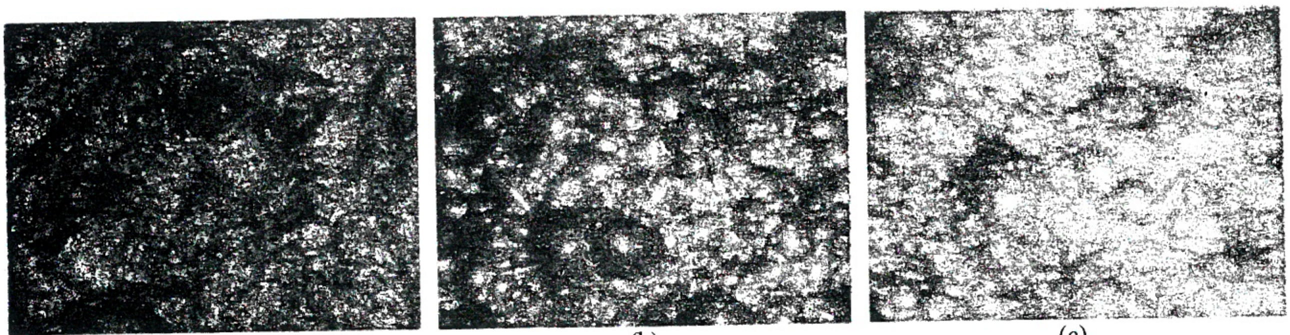
1. Inquiry-based heuristic classification method. (See below)
2. Inquiry-based fuzzy classification method (Fuzzytech software from Inform Ltd., Germany).
3. Statistical classifier (t.r.a.c.e. software developed at University Of Rome, Italy).
4. GGHA (Generalized Generalized Hebbian Algorithm) method. Neural network based classification method (See below).
5. Self Organizing Map (SOM) based classification method (Nexus Analyzer from Outokumpu Mintec Ltd., Finland).

First three methods are so called supervised methods and they all require introduction of a priori information into the classifier. The last two are unsupervised methods, which don't need any a priori information of the different froth classes in them, but they search for the "natural" clusters in the data based on its statistical structure. All the classification methods were tested and compared against each other. The result was that all methods gave more or less similar results so the most robust methods were selected for on-line operation.

Currently there are two classification methods running on-line at Pyhäsalmi concentrator. One is the inquiry-based heuristic method (1), which measures the similarity of a given froth image against predefined froth classes by using special "membership" functions which evaluate how strongly the variable in question corresponds to the definition of a certain froth class (Hätönen 1999, Ylinen et al. 2000). The other is GGHA based method (3), which analyses the statistical structure of the data and uses the latent variables produced by the algorithm as induced or "refined" variables for classification (Hyötyniemi 1999, Hyötyniemi and Ylinen 2000, Ylinen et al. 2000).

Based on the operator interview (Hätönen 1999) three different froth classes were introduced; namely stiff-, wet- and dry-class. This seemed to be a natural selection of the classes because the operators could identify and accommodate themselves to the results more easily.

In Figure 5 the three different classes are presented based on real data classification done with the inquiry-based heuristic classification method. The results were also verified with the operators.



(a) (b) (c)

**Figure 5: Stiff (a), wet (b) and dry (c) classes defined by inquiry-based heuristic classification method.**

## 3.3 Closed-loop controller

Two different versions of an on-line closed-loop controller that utilizes the calculated image variables were constructed during the research. The first version controlled the volumetric feed of xanthate and the second the volumetric feed of copper sulphate ($CuSO_4$). Both controllers use both the image variables and other process variables for control and are implemented using built-in tools of the PROSCON® automation system. The controllers are based on a priori operator knowledge and on knowledge obtained during the research.

The basic idea behind the controllers is that they have a rule base, in which different comparisons can be made. For example if the bubble collapse rate is smaller than a predefined lower alarm limit, then copper sulphate is increased (rule n:o 3 in Figure 6). The rules are periodically evaluated starting with the first one and when a rule that is true is found, the copper sulphate set point is changed using a predefined step and the rest of the rules are skipped. This means that the first rule has highest priority, the second has the second highest priority and so on.

The $CuSO_4$ controller (Figure 6) is currently operating in Pyhäsalmi concentrator. It was selected because the results obtained with it were tested to be better than those obtained with the xanthate controller. The controller utilizes four image variables: froth speed, bubble collapse rate, bubble transparency and mean bubble size. In some variations of the controller also mean value of the red channel in the RGB image was used.

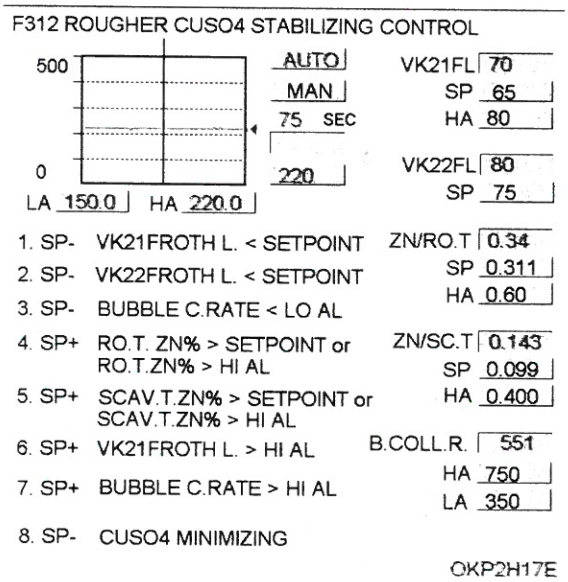



**Figure 6: Copper sulphate control logic**

The controller was also implemented using fuzzy logic but the main advantage achieved with a controller implemented using PROSCON® was that the operators at the plant were already familiar with this type of construction and thus could learn the logic behind the controller and fine tune it by themselves. This constant fine tuning seems to be necessary because of the complexity and changing conditions of the flotation process. The aim of research, however, is to construct more sophisticated methods for supervisory control of the process (Ylinen et al. 2000).

The $CuSO_4$ controller has been running continuously in the plant since the end of the year 2000 and it has been giving reasonably good results. This can be seen by examining the following table, which presents the annual results of the zinc flotation circuit in the Pyhäsalmi mine between 1975 and 2001. The profit index in the table presents how much more the plant is making money on a daily basis than was expected (the numbers are in Euros). The index in the Table 1 was calculated using zinc prize of the year 2001 so that the prize changes will not influence the result.

**Table 1. Results of the zinc flotation circuit in Pyhäsalmi mine.**

| Year | Feed Zn% | Concentrate Zn% | Recovery % | Profit Index [€ / day] |
|---|---|---|---|---|
| 1975 | 2.7 | 50.0 | 85.7 | -3700 |
| 1976 | 2.7 | 51.2 | 88.8 | -1329 |
| 1977 | 2.7 | 51.4 | 90.2 | -622 |
| 1978 | 1.9 | 50.1 | 86.4 | -1716 |
| 1979 | 2.0 | 48.1 | 85.8 | -3296 |
| 1980 | 1.9 | 49.2 | 84.7 | -2556 |
| 1981 | 2.1 | 50.1 | 86.7 | -1867 |
| 1982 | 1.9 | 49.7 | 88.4 | -1329 |
| 1983 | 1.8 | 49.5 | 87.4 | -1446 |
| 1984 | 2.9 | 49.2 | 89.7 | -3078 |
| 1985 | 2.7 | 48.1 | 89.5 | -3767 |
| 1986 | 2.0 | 48.3 | 89.4 | -2170 |
| 1987 | 2.1 | 51.0 | 87.6 | -1026 |
| 1988 | 2.8 | 52.1 | 90.4 | -34 |
| 1989 | 2.3 | 51.8 | 88.7 | -320 |
| 1990 | 2.2 | 51.9 | 88.3 | -303 |
| 1991 | 2.4 | 51.5 | 90.0 | -269 |
| 1992 | 1.9 | 50.9 | 88.5 | -505 |
| 1993 | 2.1 | 51.7 | 89.1 | -118 |
| 1994 | 1.9 | 51.7 | 87.9 | -219 |
| 1995 | 1.8 | 51.7 | 88.4 | 118 |
| 1996 | 1.8 | 51.2 | 87.5 | -454 |
| 1997 | 1.8 | 51.3 | 87.4 | -488 |
| 1998 | 1.7 | 52.6 | 90.0 | 1076 |
| 1999 | 1.6 | 52.1 | 87.9 | 370 |
| 2000 | 1.3 | 51.9 | 85.9 | 118 |
| 2001 | 2.0 | 54.0 | 90.6 | 1901 |
| 1975 - 2000 | 2.1 | 50.7 | 88.1 | -1113 |

As can be seen from the results, none of the three indicators (Concentrate Zn%, Recovery % and Profit Index) have ever been higher. The good results can be partly explained by the increase in the Zn% of the incoming ore but as can be seen from the Table 1 it has been much higher before and was in fact below average, when the $CuSO_4$ controller was installed and became active.

It was estimated by the mine staff that since the $CuSO_4$ controller was introduced to the zinc circuit they have had increase of one percentage point in both recovery and concentrate grade. This accounts roughly for half of the improvement achieved in the year 2001. Since the mine had 330 operating days last year, this means that profit for the mine in 2001 due to the $CuSO_4$ controller was about 300 000 €.

## Conclusions

This paper presents key points of the research done for improving the process control of mineral flotation. The special measurement station that was built for Pyhäsalmi mines is described as well as some of the most important calculations that are performed. Also, the closed-loop controller that was introduced as a result of the research and some economical results achieved are presented.

As a conclusion it could be said that the results of the research were very satisfying since many different and useful parameters were derived from the RGB images and spectra of the flotation froth. These parameters (and images) themselves bring additional information of the state of the process and were integrated (most interesting ones) to the automation system. Also, some reasonably good economical results were achieved by a closed-loop controller that was implemented to stabilize the process by adjusting the setpoint for volumetric flow of copper sulphate.

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