Jani Kaartinen, Olli Haavisto, and Heikki Hyötyniemi. 2006. On-line colour measurement of flotation froth. In: V. L. Syrmos (editor). Proceedings of the 9th IASTED International Conference on Intelligent Systems and Control (ISC 2006). Honolulu, Hawaii, USA. 14-16 August 2006, pages 164-169.

ON-LINE COLOUR MEASUREMENT OF FLOTATION FROTH

Jani Kaartinen, Olli Haavisto, Heikki Hyötyniemi
Helsinki University of Technology – Control Engineering Laboratory
P.O.Box 5500, FI-02015 TKK, Finland
jani.kaartinen@tkk.fi, olli.haavisto@tkk.fi, heikki.hyotyniemi@tkk.fi

ABSTRACT
This paper reports new results regarding the usefulness of colour measurements in flotation process. Colour measurements coming simultaneously from RGB-camera and a spectrophotometer (and from the same measurement point) are compared. The measured variables are used to construct a partial least squares (PLS) model and a multilinear regression (MLR) model for the prediction of the zinc content in the froth. The study shows that both the RGB-camera and spectrophotometer are able to make reliable prediction and makes comparisons between the two modelling techniques.

KEY WORDS
Colour, RGB-colour, spectral measurements, PLS, MLR, mineral flotation

1. Introduction

Flotation is a common method for separating the valuable particles from waste. 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. This paper concentrates on the application regarding mineral processing but the methods are general and could be applied also elsewhere.

In mineral processing it is widely known that the visual appearance of the flotation froth has great value as an indicator of the state of the process and thus a number of image analysis techniques for flotation froth have been introduced (See e.g. [1-6]). Typically they include calculations for static and dynamic variables as well as colour measurements. Measurements are usually done with off-the-shelf colour cameras that produce RGB-images. One of this type of systems is installed in the flotation hall of the Pyhäsalmi Mine, Finland. The research in Pyhäsalmi has continued uninterruptedly since 1997 and the results have been reported widely (See e.g. [7-13]). This paper concentrates on the latest improvements regarding colour measurements, where – by utilizing a 2-D spectrophotometer – it is possible to make comparisons between a traditional RGB-measurements as well as on-line process measurements. The first results indicate that colour measurements are important in the control strategy of the flotation plant and the measurement accuracy of the current process measurements can be improved with the aid of a visual sensor (RGB-camera or a spectrophotometer).

Pyhäsalmi mine is located some 500km's north from Helsinki. Mining started in 1962 as an open pit mine. Currently all mining is done under ground level and the deepest point reaches 1440 meters. In its current state the Pyhäsalmi Mine is one of the most modern mines in the world. The most important minerals produced are chalcopyrite ($CuFeS_2$, 2.5%), sphalerite (ZnS, 4.5%) and pyrite (FeS_2, 64.0%) [9].

The overall process is depicted in Fig 1. The ore is produced some 200 meters over the deepest point and dropped to the ore passes that are shown in the figure. To ensure fluent and reliable operation of the transportation system the largest particles are crushed already in the mine by a large jaw crusher. Further grinding takes place on the surface.

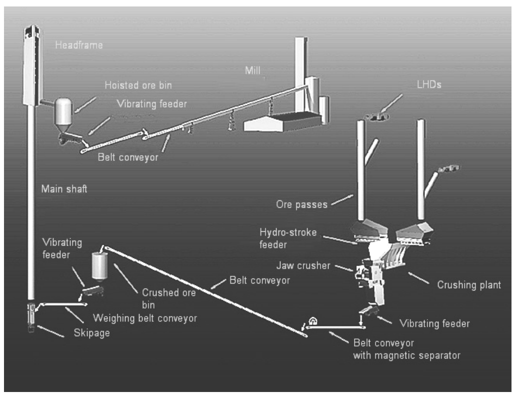

Figure 1. Illustration of the overall process in Pyhäsalmi

The crushed ore is fed to a large underground ore bin from where it is gradually moved to the surface in 21t loads by means of a hoisting system. Finally, the ore is transported by conveyor belt to the mill. The transportation system is fully automatic and it is controlled and monitored from the mill with the help of video cameras.

2. Flotation process

First stage in the flotation process is grinding, where the particle size is reduced to 50-100 µm. The resulting "powder" is mixed with water and chemicals and the resulting pulp is fed to a series of flotation cells. In Pyhäsalmi the first flotation stage is copper flotation, second is zinc and the last is pyrite flotation. General illustration of the process is provided in Fig. 2. Each of the three flotation circuits consist of several interconnected flotation cells. Most of the cells are connected in series so that the valuable mineral particles that are not successfully separated from the waste continue as a feed to the adjacent flotation cell. This type of structure increases the recovery percentage. However, to further improve the performance there are feed-back connections, re-grinding stations etc. that introduce a great deal of complexity to the system.

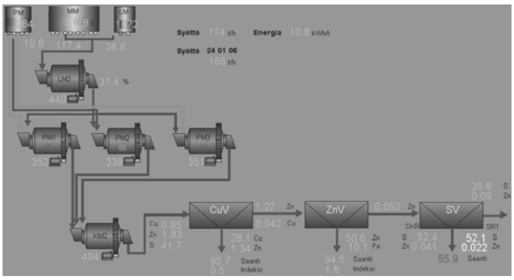

Figure 2. Different stages of the flotation process

In a single flotation cell air is fed into the pulp to produce bubbles that naturally move upwards and produce froth onto the pulp. The grains, depending on their mineral contents and the levels of the chemical reagents in the pulp, tend either to float and stick to the bubbles or to sink in the liquid. This is the fundamental phenomena behind flotation. Finally the top layer of the froth is skimmed of and water is removed leaving a dry concentrate for further processing. The main parts of a typical flotation cell as well as the location of the analysis point are displayed in Fig 3.

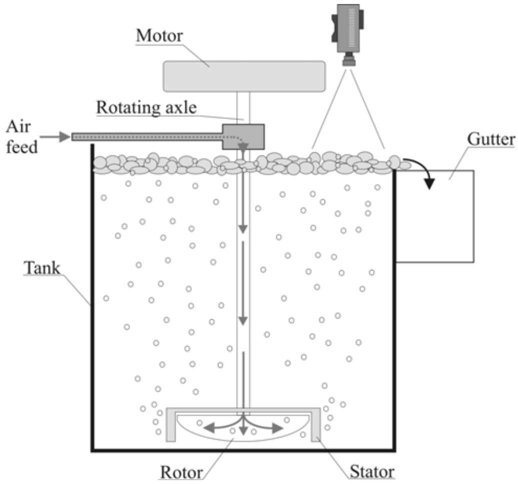

Figure 3. Main parts of a flotation cell

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.

3. Measurements

The current image analysis system in Pyhäsalmi is capable of measuring several different variables (froth speed, bubble size, bubble collapse rate, etc.) from a froth image-pair and there are currently 8 RGB-cameras installed in zinc and copper circuits. Also, all the traditional process measurements are available and the most important of them is the X-Ray Courier analysis that measures the proportions of different elements in the froth. From all these measurements the ones that are relevant to this study are listed in the table below.

Table 1. Measured variables

Measurement	Source
Mean R	Image analyzer, RGB-image
Mean G	Image analyzer, RGB-image
Mean B	Image analyzer, RGB-image
Mean Intensity	Image analyzer, RGB-image
Spectrum [400-1000nm]	Spectrophotometer
Courier analysis (see text for description)	Automation system

Since the current analysis system already includes several RGB-cameras, it was convenient to select one camera to be accompanied with a spectrophotometer in order to do comparisons and more accurate color analysis. This was accomplished by constructing an enclosure where a RGB-camera and a spectrophotometer are mounted side by side (Fig. 4). The enclosure is a compact structure and thus it is easy to change the measurement point to another flotation cell if needed. The data from the RGB-camera is transferred to the existing image analyzer system (see e.g. [8]) and the Courier measurements can be easily obtained from the automation system. The spectral measurements are done with a FireWire-camera equipped with an imaging spectrograph (Imspector). The camera is connected to a portable laptop computer which is connected to the plant's Ethernet network via Wireless Local Area Network (WLAN) connection. This further improves the mobility of the data collection system.

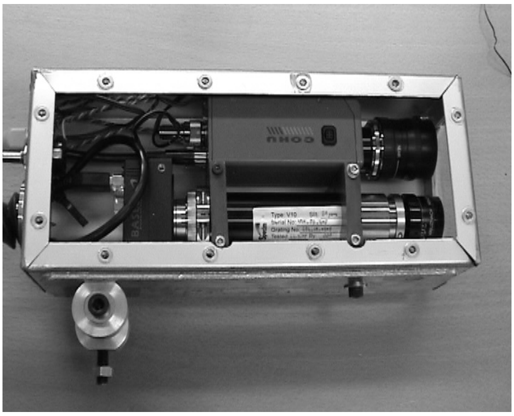

Figure 4. A device for RGB- and spectral-measurements

The spectrophotometer provides 1024 point spectra from 400nm to 1000nm at 9nm spectral resolution. Together these spectra form a line which is located in the middle of the RGB-image. Figure 5 shows an example of zinc froth as well as an illustration of the line along which the spectra are measured.

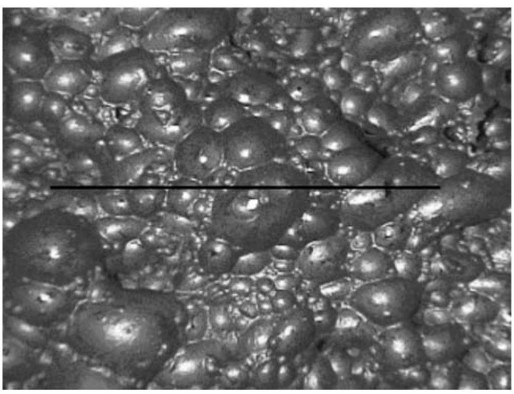

Figure 5. Illustration of the line spectrum measurement point

Actually, spectral measurements have been carried out already in the earlier stages of the project (see. [8]). However, the new 2D-spectrophotometers as the one used here were not available at that time and the measurement was just a spectrum of a single point. This made the cancellation of the total reflection point (i.e. the white spot on top of each bubble) very difficult and made the use of on-line spectral measurements practically impossible. This was the case since the total reflection points had to be cancelled out by using a combination of the polarizing effect of the Brewster's angle (106 degrees) and a polarizing filter. The wide angle meant that the instruments were vulnerable to the harsh conditions of the flotation hall and only short data collection (< 30minutes) campaigns were possible before the equipment got dirty.

The introduction of the 2D-spectrophotometer makes it possible to cancel unwanted spectra out by computational means. The local differences in the line spectrum are easily detected and valid measurements can be selected for example by using a simple thresholding. Figure 6 illustrates an example of a line spectrum. As can be seen the total reflection point as well as the "dark valleys" between the bubbles are clearly visible in the data (i.e. along the position-axis).

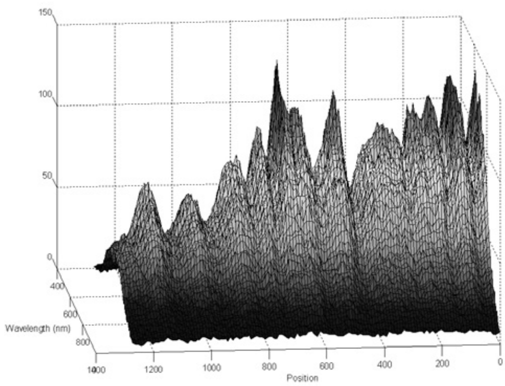

Figure 6. An example of the line spectrum

The first measurement point for the improved colour measurements was selected to be the last cell of the zinc circuit which produces the final zinc concentrate. This cell was selected as a starting point because the best estimate of the mineral content of the froth comes from this cell. Since there are measurements coming simultaneously from three different sources, the clocks of the three computers are synchronized and the data is recorded to their local hard drives in one minute intervals. However, even if the collected data is recorded for analysis only once per minute, the measurement speed can be much faster and pre-computing has been carried out. For example, the measurement interval for spectrum is 5s and every measurement provides 1024 spectra. So for every saved entry 12 x 1024 = 12 288 spectra have been processed and filtered. The one minute interval is a limitation from the automation system, but since the process is so slow (time constants are typically tens of minutes) that is not a big problem.

4. Modelling and validation

The aim of the modeling was to find out whether the improved colour measurements given by the spectrophotometer could describe the system state more accurately than the previous measurements obtained using the RGB camera images. As a preliminary approach to compare the two measurement methods, two static multivariate regression models were calculated from the measured variables to the mineral content measurements of the Courier analyser. The first model used the RGB camera colour measurements as regressors to predict the mineral contents in the final concentrate of the zinc circuit. The actual regressor values were the relative mean red, green and blue intensities and the total mean intensity value of the RGB image, whereas the dependent variables of the model were the iron, copper and zinc contents of the concentrate. As the number of input and output variables were low, a regular multilinear regression (MLR) model (see e.g. [14]) was used.

The second model was calculated using the collected spectra values as regressors, and the aim was to predict the same concentrate contents as with the first model. However, since the frequency band of the spectrum is divided into 960 values, the number of input variables was much higher than in the RGB case. To reduce the input dimension of the model, the frequency values were compressed to 96 by averaging every ten adjacent spectrum values. It was detected that this operation did not notably reduce the spectrum information content. However, the input dimension was still quite high, so a partial least squares (PLS) model (see e.g. [14]) was selected to map the spectrum values to the content measurements. The advantage of the PLS approach is that it reduces the input dimension by projecting both the inputs and outputs to lower-dimensional subspaces. The regression mapping is formed by maximising the correlation of data in the two subspaces.

The two models were evaluated by calculating the content measurements for a validation data set measured from the flotation process and comparing the measured and predicted values. Figure 5 shows that the both models are able to estimate the real content values with reasonable accuracy. However, it seems that the PLS model utilizing the spectrum measurements can better follow the measured changes of the content values. Indeed, when the correlation coefficients between the measured and predicted values for both models are calculated, it is evident that the PLS model can outperform the MLR model (Table 2).

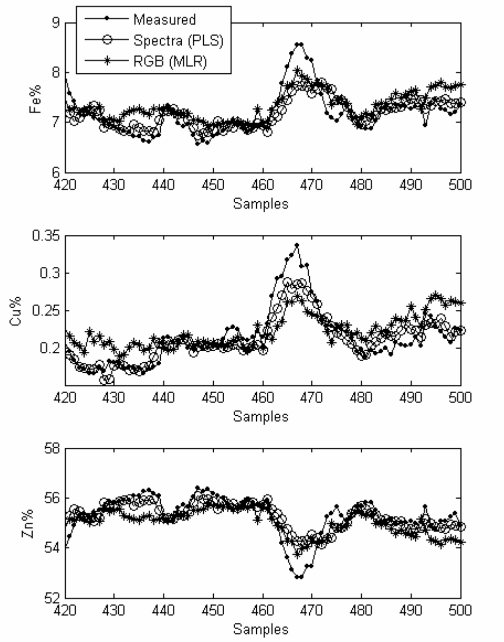

Figure 5. Prediction results of the two models

Table 2. Correlation coefficients of the predicted and measured mineral contents

Model/Mineral	Fe	Cu	Zn
PLS	0.78	0.92	0.80
MLR	0.71	0.87	0.75

Based on the results in Table 2 it is also obvious that the copper content can be estimated from the colour measurements more accurately than the other two minerals.

5. Future research

Future work will concentrate on better utilization of the spectrum measurements for mineral content estimation. This is an important issue since the sample time of the Courier analyser is long (almost twenty minutes) and the concentrate contents are important variables in the flotation process control. Thus, using the spectral measurements to predict the mineral contents between the consecutive Courier measurements could provide a valuable tool for improving the control of the process. For this purpose, more delicate models should be developed; for example the dynamics of the process could be taken into account using dynamic modeling methods. Additionally, the effect of process delays should be considered.

One important goal of the research is to evaluate the improvement of the colour measurements when the more expensive spectrophotometer is available instead of the ordinary and cheaper RGB cameras. If the spectral measurements prove to be remarkably useful in the flotation process modeling and control, more spectrophotometers could be purchased to cover the other parts of the concentration plant.

6. Conclusion

This paper presents new results on the usefulness of colour measurements in a flotation process. Pyhäsalmi mine has been used as a testing place for comparing colour data coming from a standard RGB camera and from a 2D-spectrophotometer. Courier analyzer has been used as a validation tool.

The results show that the colour information is a good indicator of the mineral content in the flotation froth. Since the current Courier analysis is rather slow (roughly 20 minutes per sample), the colour information can be used to improve the measurement quality between adjacent samples. Also the colour-based concentration measurement can be used as a replacement if the Courier measurement is not available.

Firstly, an overall view of the plant and the production procedure is given. Then the flotation process is described and some basic information regarding the flotation phenomena is presented. After that a detailed description of the measurement explaining the hardware as well as the measured variables and data pre-processing is presented. Also the data recording procedure is discussed. The results of the data-analysis, modelling and validation are shown. Finally, directions for future research are given.

The presented method for comparing the two devices has proven to be very useful and since it is mobile and provides on-line data, long data collection campaigns can be organized and thus the amount of data is sufficient for multivariate data analysis. Also, constructed models can be put to on-line operation to the plant. Furthermore the system can be fully controlled remotely via Internet connection.

The current analysis results are very promising and the research group expects the utilization of the colour information to be an important asset to the flotation plant as well as to the manufacturers of the Courier analyzers.

Acknowledgements

This study has been financed by Finnish Funding Agency for Technology and Innovation, Pyhäsalmi Mine Oy and Outokumpu Technology Minerals Oy. We would also like to thank Mr. Jorma Miettunen for the close co-operation in the arranging of the flotation circuit measurements in Pyhäsalmi.

References

[1] Cipriano A., Guarini M., Vidal R., Soto A., Sepulveda C., Mery D., and Briseno H. (1998): *"A real time visual sensor for supervision of flotation cells"*, Minerals Engineering, 11 (6), pp. 489-499.

[2] Guarini M., Cipriano A., Soto A., Cuesalaga A. (1995): *"Using image processing techniques to evaluate the quality of mineral flotation process"*, In proceedings of the 6th International Conference on Signal Processing, Applications and Technology, 24-25 October 1995, Boston.

[3] Moolman D.W., Aldrich C., Van Deventer J.S.J., Stange W.W. (1994): *"Digital image processing as a tool for on-line monitoring of froth in flotation plants",* Mineral Engineering, 7 (9), 1149-1164.

[4] Moolman D.W., Aldrich C., Van Deventer J.S.J., Bradshaw D.B. (1995a): *"The characterisation of froth surfaces and relation to process performance by using connectionist image processing techniques"*, Mineral Engineering, 8 (1-2), 23-30.

[5] Moolman D.W., Aldrich C., Van Deventer J.S.J., Bradshaw D.B. (1995b): *"The interpretation of flotation froth surfaces by using digital image analysis and neural networks",* Chemical Engineering Science, 50 (22), 3501-3513.

[6] Oestreich J.M., Tolley W.K., Rice D.A. (1995): *"The development of a colour sensor system to measure mineral composition",* Mineral Engineering, 8, 31-39.

[7] Hyötyniemi H., Ylinen R. (2000): "*Modeling of visual flotation froth data",* Control Engineering Practice, Vol. 8, Nr 3, March 2000, pp. 313-318.

[8] Kaartinen J. (2001): *"Data acquisition and analysis system for mineral flotation",* Helsinki University of Technology, Control Engineering Laboratory, Report 126, Finland.

[9] Hätönen J. (1999): *"Image analysis in mineral flotation",* Helsinki University of Technology, Control Engineering Laboratory, Report 116, Finland.

[10] Kaartinen J., Koivo H. (2002): *"Machine Vision Based Measurement and Control of Zinc Flotation Circuit"*, Int. Journal of Studies in Informatics and Control, vol. 11, no. 1, pp. 97-105.

[11] Kuopanportti H., Roikola H., Suorsa T. (2000a): *"Use of froth characteristics in modeling the flotation process. Part I: Model for fine zinc particles",* Flotation 2000, 29-31 March 2000, Adelaine, Australia

[12] Kuopanportti H., Roikola H., Suorsa T. (2000b): "Use of froth characteristics in modeling the flotation process. Part II: Model for coarse and intermediate zinc particles", IFAC Workshop 22- 24 August 2000, Finland

[13] Miettunen J., Kaartinen J., Hätönen J. (2001): "*Image analysis based control of zinc flotation",* In proceedings of The 4th Regional Symposium on Computer Applications in the Mineral Industries (APCOM 2001), 3-5 September 2001, Tampere, Finland, pp. 267-275.

[14] Hyötyniemi H. (2001): "*Multivariate regression - Techniques and tools",* Helsinki University of Technology, Control Engineering Laboratory, Report 125, Finland.