UNIVERSITI PUTRA MALAYSIA

AUTOMATIC CONTROL OF FLOTATION PROCESS USING COMPUTER VISION

ALI JAHED SARAVANI

AUTOMATIC CONTROL OF FLOTATION PROCESS USING COMPUTER VISION

By

ALI JAHED SARAVANI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

August 2015

DEDICATION

This dissertation is specifically dedicated to my lovely parents and wife, for their encouragement, faith, and belief in me.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in Fulfilment of the Requirement for the Degree of Doctor of Philosophy

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August 2015

Chairman: Mohammad Hamiruce Marhaban, PhD
Faculty: Engineering

In the mineral production industry, the separation of valuable material from waste material is generally carried out using the flotation process. Metallurgical parameters of the process reflect the quality and quantity of the product. Online measurement and control of these parameters is currently not possible, due to lack of scientific relationship between froth structure and various aspects of flotation process.

Bubble size distribution which is regarded as the most important characteristics of froth structure, is being addressed in this thesis by using a segmentation algorithm. A marker based watershed algorithm had been adopted and improved so as to prevent the over-segmentation of big bubbles and able to adapt itself with different scenario of froth images. This results in a measurement of bubble size with high precision. The performance of improved marker based watershed algorithm was validated by using several industrial and laboratory froth images. In addition, several algorithms were implemented to measure the other important image variables such as froth velocity, froth color and bubble collapse rate.

A froth model correlating the image variables to process variables and a prediction system estimating the metallurgical parameters based on image variables were then developed by using a neural network structure. A control strategy based on froth model was then designed in order to optimize the visual characteristics of froth, which lead to the control of the metallurgical parameters in an indirect manner. Finally, a control strategy implementing the developed froth model and prediction system was introduced for direct optimization of metallurgical parameters. Simulation results indicated the effective performance of the designed control schemes in enhancing the overall efficiency of the process.

Abstrak tesis ini di bentangkan kepada senat Universiti Putra Malaysia bagi memenuhi syarat pengijazahan darjah Doktor Falsafah

KAWALAN AUTOMATIK PROSES PENGAPUNGAN MENGGUNAKAN PENGLIHATAN KOMPUTER

Oleh

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Dalam industri pengeluaran mineral, pemisahan bahan berharga daripada bahan buangan biasanya dilakukan dengan menggunakan proses pengapungan. Parameter pelogaman proses tersebut mencerminkan kualiti dan kuantiti produk. Pengukuran dan kawalan parameter dalam talian pada masa ini adalah terhad, kerana kekurangan hubungan saintifik antara struktur buih dan pelbagai aspek proses pengapungan.

Taburan saiz buih yang dianggap sebagai ciri yang paling penting dalam struktur buih, dibincangkan dalam tesis ini dengan menggunakan algoritma segmentasi. Algoritma legeh berasaskan penanda telah diadaptasi dan diperbaiki untuk mengelakkan segmentasi buih besar secara berlebihan dan dapat menyesuaikan diri dengan senario imej buih yang berbeza. Hasilnya, satu ukuran saiz buih dengan ketepatan yang tinggi berjaya diperolehi. Prestasi mantap algoritma legeh berasaskan penanda diperbaik ini telah disahkan dengan menggunakan beberapa imej buih industri dan makmal. Di samping itu, beberapa algoritma telah dilaksanakan untuk mengukur pemboleh ubah imej lain yang penting seperti halaju buih, warna buih dan kadar pecah gelembung.

Model buih yang menghubungkaitkan antara pembolehubah gambar dan pembolehubah proses, dan sistem ramalan yang menganggarkan parameter pelogaman berdasarkan pembolehubah imej kemudiannya dibangunkan dengan menggunakan struktur rangkaian neural. Satu strategi kawalan berdasarkan model buih kemudiannya direka untuk mengoptimumkan ciri-ciri visual buih, yang membawa kepada kawalan parameter pelogaman secara tak-langsung. Akhir sekali, strategi kawalan yang dilaksanakan melalui model buih dan sistem ramalan yang dibangunkan telah diperkenalkan untuk pengoptimuman parameter pelogaman secara langsung. Keputusan simulasi menunjukkan prestasi yang berkesan daripada skim kawalan yang direka dalam meningkatkan kecekapan keseluruhan proses.

ACKNOWLEDGEMENTS

In the name of Allah, the most Compassionate and the most merciful. To whom I owe the strength and sense of purpose that have enable me to undertake this dissertation, and without His grace and blessing it would not have been completed.

First, I would like to show my sincere gratitude and appreciation to my supervisor, Associate Professor Mohammad Hamiruce Marhaban for his guidance, and patience through the entire process of my PhD dissertation. Also, I would like to thank my committee members, Dr. Iqbal Saripan, Dr. Samsul Bahari Noor and Dr Mohammad Massinei for their careful review my draft and insightful comments contributed vastly to the development of the overall dissertation.

I would like to thank my parents and my wife, without their love, patience, support, through my education and through my life, I would not be who I am or where I am today. Thank you and I love you all.

This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Declaration by graduate student

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LIST OF ABBREVIATIONS

AFC	Advanced Flotation Control
ANFIS	Adaptive Neuro-Fuzzy Inference System
ANN	Artificial Neural Network
BMA	Block Matching Algorithm
DFT	Discrete Fourier Transform
FCM	Fuzzy C-Mean
FT	Fourier Transform
GGHA	Generalization of Generalized Hebbian Algorithm
GLCM	Gray Level Co-occurrence Matrix
GLDM	Gray Level Dependence Matrix
JKMRC	Julius Kruttschnitt Mineral Research Center
LNE	Large Number Emphasis
LVQ	Linear Vector Quantization
MIA	Multivariate Image Analysis
MIMO	Multi Input Multi Output
MISO	Multi Input Single Output
NGLDM	Neighboring Gray Level Dependence Matrix
NNU	Number Non Uniformity
OSA	On Stream Analyzer
PCA	Principle Component Analysis
PCR	Principle Component Regression
PGM	Platinum Group Metal
PLS	Partial Least Square

RBF	Radial Basis Function
RTO	Real Time Optimization
SGLDM	Spatial Gray Level Dependence Matrix
SM	Second Moment
SNE	Small Number Emphasis
SOM	Self-Organizing Map
TS	Texture Spectrum
TU	Texture Unit
VED	Valley Edge Detection
WTA	Wavelet Texture Analysis
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

LIST OF NOTATIONS

G_{Cu}	Cu grade
R_{Cu}	Cu recovery
R_m	Mass recovery
R_w	Water recovery
D_b	Bubble diameter
V_f	Froth velocity
C_f	Froth color
Cr_b	Bubble collapse rate
J_g	Air flow rate
C_f	Frother dosage
pH	pH
C_l	Collector dosage
ρ_{s1}	Slurry solids

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

In the past, with attention to the existence of full-grade reserves, mineral materials were used directly or with some changes as primary materials in other industrial applications after extraction; however, nowadays, low-grade reserves have become more important because of the lack or shortage of full-grade reserves. Low-grade mineral materials need concentration operations to be suitable for industrial utilization.

Extracted ore from metal mines has no proper grade to be used in other industries, and, hence, needs to be concentrated through several processing operations. The common method to concentrate metal ores is the flotation process. Flotation, which is an industrial process with complicated physical and chemical features, is widely used in copper, zinc and lead plants. The flotation process entered mining areas at the beginning of the twentieth century and found a special place in processing industry rapidly. Today, this method is one of the best known and most efficient techniques for metal mineral processing.

Separating valuable material from waste, in other words, enhancing the grade of minerals, is achieved using the flotation process. The direct effect of the efficiency of the process on the overall efficiency of production and the complicated physical and chemical characteristic features involved, have made the regular and accurate control of the flotation process an inevitable necessity.

The physical-chemical process of flotation takes place in the container known as the flotation cell. A combination of crushed mineral, water and chemical reactants are entered into the flotation cell, and, by flowing air into the cell, bubbles, which contain the valuable material (concentrate), form at the surface (Figure 1.1). The final output of the flotation process is the concentrate, which is obtained by washing away the froth gathered at the surface of the cell, and which is evaluated using indexes called metallurgical parameters that reflect the quality and quantity of the product (Geng et al., 2008).

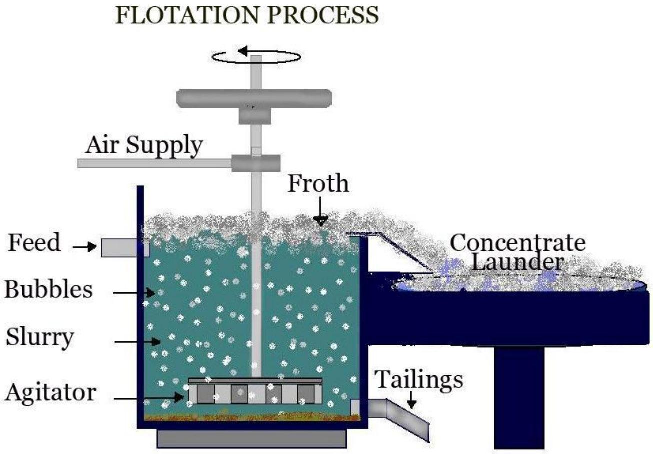

Figure 1.1. Flotation cell

1.2 Problem Statements

In the past, the control of the flotation process was based on visual observation of the froth, empirical interpretation of this image, and, finally, the adjustment of the control variables of the process based on their importance and role in the process by experienced operators. This method of control was completely based on the human operator's knowledge, which is inconsistent. The absence of quantitative parameters in the control of the process makes the optimal control of the process practically impossible, as well as increasing the possibility of error. Today, to quantify the flotation process and eliminate the problems mentioned above, the use of various measurement procedures based on machine vision and various modeling methods, as well as intelligent control, have been considered (Aldrich et al., 2010).

The machine vision system can measure the non-visual features, such as textural features of froth images as well as the visual froth features including bubble size, froth velocity, froth color and bubble collapse rate. Bubble size distribution is acknowledged to be the most significant froth feature being strongly related to process efficiency and operating conditions (Mehrabi et al., 2014). In contrast, experience has demonstrated the lack of a comprehensive algorithm for accurate segmentation of froth images which usually suffer from over segmentation and under segmentation of big and small bubbles, respectively(Forbes, 2007; Mehrshad & Massinaei, 2011). As froth images contain small and large bubbles located beside each other, the implementation of a technique that is able to differentiate the large bubbles from the small ones in a segmentation algorithm may increase the segmentation accuracy of the large bubbles, which usually suffer from over-segmentation. In addition, if the segmentation algorithm can adapt itself to each kind of froth image, especially those containing a wide range of bubble size, then the bubble edges may be recognized with more precision.

To administer an automatic control system for maximizing the metallurgical parameters, it is necessary for these indexes to be measured online, which is very costly, inaccurate and sometimes impossible using the current tools; hence, these indices can be optimized indirectly through a froth model similar to the work of factory operators. The effective control of the flotation process therefore calls for the existence of a comprehensive froth model. The number of variables as well as the lack of knowledge about the relations between these variables have prevented such a comprehensive model from being proposed for the description of this process (Bergh & Yianatos, 2011; Liu & MacGregor, 2008). Up to now, just one model has been established as a froth model by Liu and MacGregor (2008) but they used some visual froth features as output variables which were not understood by operators. Thus, obtained froth model cannot be accepted by operators. Hence, froth model must be completely interpretable for metallurgists and capable of accurately describing the relation between the froth features with manipulated variables (Bergh & Yianatos, 2011). System identification by using a complete set of data seems a good way to obtain a froth model. If the fitted model does not reveal a large error then it will be capable of providing an appropriate estimate of the froth features.

The indirect control of metallurgical parameters of the flotation process done by optimization of froth features, can be replaced by direct control of the metallurgical parameters so as to improve the process efficiency. Fortunately, the structure of the froth at the surface of the flotation cells is related to the metallurgical parameters of the valuable mineral material in the concentrate, and, therefore, the important features of the froth structure can be used for online prediction of the metallurgical features of the process. The important structure indices of the froth, which experienced operators use as indexes for evaluation of the flotation process efficiency, are bubble size, froth velocity, froth color, and bubble collapse rate, etc. (Aldrich et al., 2010; Shean & Cilliers, 2011). Although some prediction systems have been proposed in literature, no control scheme which use a prediction system to optimize the metallurgical parameters directly, was found. The ultimate goal of controlling the flotation process is to obtain an optimum combination of favorable metallurgical factors of the final product from the input variables of the process. Therefore, a control scheme implementing an online prediction system will probably increase the metallurgical parameters more in comparison to the indirect control of the flotation process. In conclusion, because of the absence in the literature of a froth model based control of flotation and flotation control based on a computer vision system, the absence of a control system that completely automates the whole flotation process is obvious (Bergh & Yianatos, 2011).

In summary, the following problems are considered to be solved in the current investigation:

- A lack of segmentation algorithm, which can be adapted to each kind of froth image for measurement of the bubble size distribution.

- The absence of an interpretable froth model to be implemented in a control system for control of the froth structure.

- The absence of a control strategy for direct control of the metallurgical parameters of the flotation process.

1.3 Objectives of the Study

The aim of this study is to automate the whole flotation process by using a computer vision based measurement system. Thus, the present study is motivated by the need to take into consideration the three significant existing problems in flotation technology; therefore, the three specific objectives are defined as follows:

1- Improvement of bubble segmentation accuracy by modifying a watershed algorithm that is capable of providing the same precise bubble size distribution as manual segmentation for any kind of froth image.

2- Developing a froth model describing the relationships between the key visual features of the froth and process variables of the flotation process, and designing a froth model based control system for indirect control of the metallurgical parameters.

3- Intelligent control of the flotation process by real time prediction of the copper grade and recovery through a computer vision system for direct control of the metallurgical parameters.

1.4 Scope

This study explores the possibilities of implementing a computer vision system to be used as a monitoring device in a control system. Development of a computer vision system includes different algorithms used to measure the froth's visual features. For this purpose, a comprehensive algorithm is proposed for segmentation of froth images whereas other visual characteristics of froth are quantified using the most accurate and simplest algorithm in this field. These algorithms are tested using a video data base which is collected from experimental tests on a batch flotation cell. Next, these algorithms are used to develop two control schemes for optimization of the flotation process.

However this study addresses some issues considering the control and optimization solutions for flotation process, establishment of control system hardware is beyond the thesis scope and therefore, suggested control systems are evaluated in a Simulink environment.

1.5 Thesis Contribution

In order to cover all the defined objectives, firstly, a video data set including 81 laboratory experiments is established to investigate the role of flotation froth in different operating conditions, following which each of these videos is processed using different computer vision algorithms for measurement of the key visual features of froth. Afterwards, a froth model is identified using the collected data, and the relationships between the input and output of the froth model are discussed.

Consequently, a froth model based control scheme is designed in order to control the froth status leading to controlling the metallurgical parameters indirectly. Froth is classified based on the measured froth features and metallurgical parameters in order to find the optimal set points for the control system. Next, another control strategy implementing the computer vision system is developed for online control of the metallurgical parameters. In this procedure, firstly, a prediction system is identified for online measurement of the metallurgical parameters based on the froth features. A schematic of what has been accomplished in the current study is provided in Figure 1.2. The highlighted part of the diagram indicates the author's contribution in the current thesis. As shown in Figure 1.2, experimental tests are conducted using different process variables and then for each experiment, metallurgical parameters are measured and froth appearance is captured by a video camera. Four different visual features of froth structure are measured using different computer vision algorithms and then a froth model is developed based on process variables in order to describe the froth properties. The developed froth model is followed by a control system for control of the most important froth features. On the other side, the froth features are used for prediction of metallurgical parameters of flotation process. Identified prediction system is employed in the heart of a control system for direct control of metallurgical variables.

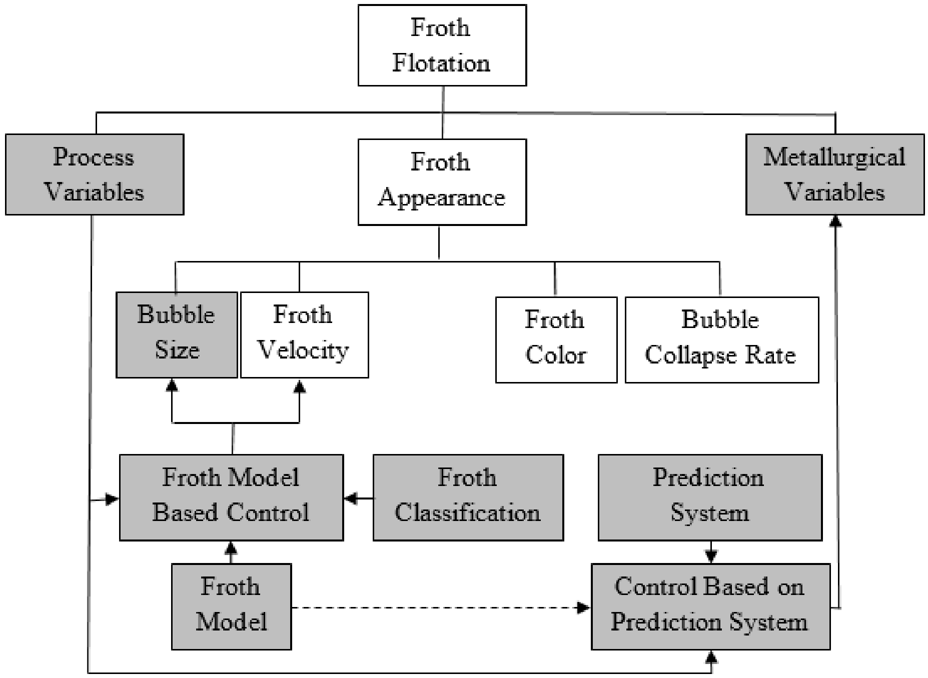

Figure 1.2. Schematic of using computer vision system in flotation process

1.6 Organization of the Thesis

The current thesis is organized into six chapters, as shown in Figure 1.3. In the second chapter, the froth flotation process and its input and output variables are briefly discussed and then all the computer vision algorithms designed for measurement of the significant froth features are comprehensively reviewed, and, finally, the different control systems implementing the computer vision measurements are investigated. In the third chapter, details of data collection are explained and the chief visual features of the froth are measured using designed algorithms. And then the first control strategy, which implements the developed froth model and the second control strategy utilizing a prediction system are discussed. The results of designed computer vision algorithms, evaluations of identified froth model and prediction system as well as two introduced control schemes are presented in next chapter. Finally, a summary of the thesis and some suggestions for further investigation are provided in the last chapter.

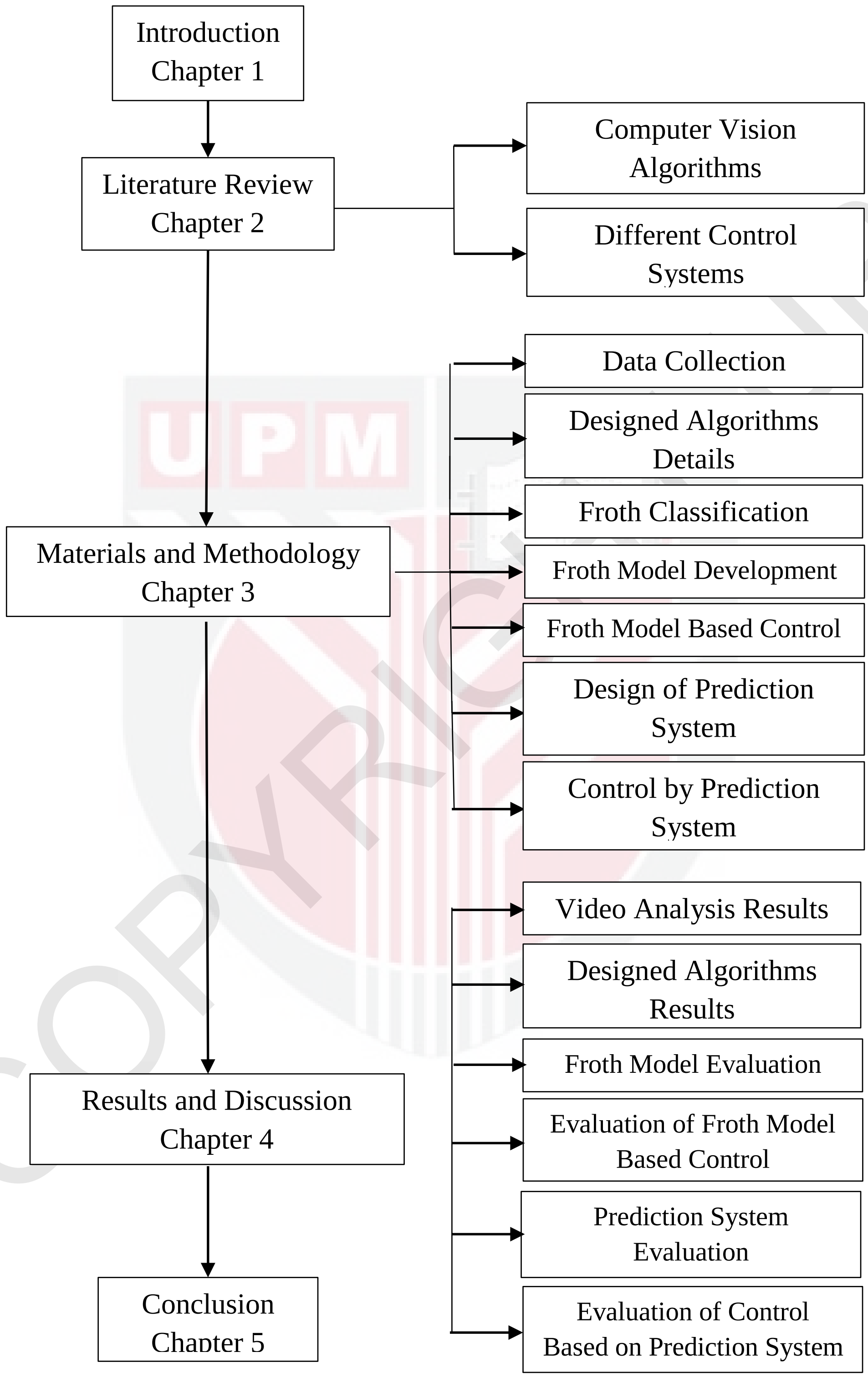

Figure 1.3. Thesis layout

REFERENCES

Aldrich, C., Gardner, S., & Le Roux, N. (2004). Monitoring of metallurgical process plants by using biplots. *AIChE journal, 50*(9): 2167-2186.

Aldrich, C., Marais, C., Shean, B., & Cilliers, J. (2010). Online monitoring and control of froth flotation systems with machine vision: A review. *International journal of mineral processing, 96*(1): 1-13.

Aldrich, C., Moolman, D., Bunkell, S.-J., Harris, M., & Theron, D. (1997). Relationship between surface froth features and process conditions in the batch flotation of a sulphide ore. *Minerals Engineering, 10*(11): 1207-1218.

Arbiter, N., & Harris, C. (1962). Flotation kinetics. *Froth flotation-50th anniversary volume. DW Fuerstenau, American Institute of Mining, Metallurgical, and Petroleum Engineers*.

Barbian, N., Cilliers, J. J., Morar, S. H., & Bradshaw, D. J. (2007). Froth imaging, air recovery and bubble loading to describe flotation bank performance. *International journal of mineral processing, 84*(1): 81-88.

Barbian, N., Hadler, K., & Cilliers, J. J. (2006). The froth stability column: measuring froth stability at an industrial scale. *Minerals Engineering, 19*(6): 713-718.

Barbian, N., Hadler, K., Ventura-Medina, E., & Cilliers, J. (2005). The froth stability column: linking froth stability and flotation performance. *Minerals Engineering, 18*(3): 317-324.

Barbian, N., Ventura-Medina, E., & Cilliers, J. (2003). Dynamic froth stability in froth flotation. *Minerals Engineering, 16*(11): 1111-1116.

Bartolacci, G., Pelletier Jr, P., Tessier Jr, J., Duchesne, C., Bossé, P.-A., & Fournier, J. (2006). Application of numerical image analysis to process diagnosis and physical parameter measurement in mineral processes—part I: flotation control based on froth textural characteristics. *Minerals Engineering, 19*(6): 734-747.

Bergh, L., & Yianatos, J. (2011). The long way toward multivariate predictive control of flotation processes. *Journal of Process Control, 21*(2): 226-234.

Bezdek, J. C. (1981). *Pattern recognition with fuzzy objective function algorithms*: Kluwer Academic Publishers.

Bonifazi, G., Giancontieri, V., Meloni, A., Serranti, S., Volpe, F., Zuco, R., Koivo, H., Hätönen, J., Hyötyniemi, H., & Niemi, A. (2000a). Characterization of the flotation froth structure and color by machine vision (ChaCo). *Developments in Mineral Processing, 13*: C8a-39-C38a-49.

Bonifazi, G., Massacci, P., & Meloni, A. (2000b). Prediction of complex sulfide flotation performances by a combined 3D fractal and colour analysis of the froths. *Minerals Engineering, 13*(7): 737-746.

Bonifazi, G., Serranti, S., Volpe, F., & Zuco, R. (1998). Proceedings of 4th International Conference On Quality Control by Artificial Vision: *Flotation froth characterisation by optical-digital sectioning techniques.* Takamatsu, Japan.

Bonifazi, G., Serranti, S., Volpe, F., & Zuco, R. (1999). Intelligent Processing and Manufacturing of Materials, 1999. IPMM'99. Proceedings of the Second International Conference on: *A combined morphological and color based approach to characterize flotation froth bubbles.*

Bonifazi, G., Serranti, S., Volpe, F., & Zuco, R. (2001). Characterisation of flotation froth colour and structure by machine vision. *Computers & Geosciences, 27*(9): 1111-1117.

Botha, C., Weber, D., Van Olst, M., & Moolman, D. (1999). Africon, 1999 IEEE: *A practical system for real-time on-plant flotation froth visual parameter extraction.*

Botha, C. P. (1999). *An on-line machine vision flotation froth analysis platform.* (MSc Thesis), University of Stellenbosch.

Bouchard, J., Desbiens, A., del Villar, R., & Nunez, E. (2009). Column flotation simulation and control: An overview. *Minerals Engineering, 22*(6): 519-529.

Bradshaw, D., Upton, A., & O'Connor, C. (1992). A study of the pyrite flotation efficiency of dithiocarbamates using factorial design techniques. *Minerals Engineering, 5*(3): 317-329.

Bulatovic, S. M. (2007). *Handbook of flotation reagents: chemistry, theory and practice: Volume 1: flotation of sulfide ores*: Elsevier Science & Technology Books.

Cao, B., Xie, Y., Gui, W., Wei, L., & Yang, C. (2013). Integrated prediction model of bauxite concentrate grade based on distributed machine vision. *Minerals Engineering, 53*: 31-38.

Carvalho, M. T., & Durão, F. (2002). Control of a flotation column using fuzzy logic inference. *Fuzzy sets and systems, 125*(1): 121-133.

Chopra, S., Mitra, R., & Kumar, V. (2004). Machine Learning and Cybernetics, 2004. Proceedings of 2004 International Conference on: *Identification of rules using subtractive clustering with application to fuzzy controllers.*

Cipriano, A., Guarini, M., Vidal, R., Soto, A., Sepúlveda, C., Mery, D., & Briseno, H. (1998). A real time visual sensor for supervision of flotation cells. *Minerals Engineering, 11*(6): 489-499.

Cipriano, A., Sepulveda, C., & Guarini, M. (1997). Industrial Electronics, 1997. ISIE'97., Proceedings of the IEEE International Symposium on: *Expert system for supervision of mineral flotation cells using artificial vision.*

Citir, C., Aktas, Z., & Berber, R. (2004). Off-line image analysis for froth flotation of coal. *Computers & chemical engineering*, *28*(5): 625-632.

Doukim, C. A., Dargham, J. A., & Chekima, A. (2010). Information Sciences Signal Processing and their Applications (ISSPA), 2010 10th International Conference on: *Finding the number of hidden neurons for an MLP neural network using coarse to fine search technique.*

Du Plessis, F., & Keet, K. (2010). 13th IFAC Symposium on Automation in Mining, Mineral and Metal Processing, Industry Papers: *The importance of a high sample frequency measurement of grade to avoid aliasing.*

Dunn, J. C. (1973). A Fuzzy Relative of the ISODATA Process and Its Use in Detecting Compact Well-Separated Clusters. *Journal of Cybernetics, 3*(3): 32-57.

Farrokhpay, S. (2011). The significance of froth stability in mineral flotation—A review. *Advances in colloid and interface science, 166*(1): 1-7.

Fausett, L. (1994). Fundamentals of Neural Networks: Architectures, Algorithms, and Applications. : Prentice-Hall Inc.

Forbes, G. (2007). *Texture and bubble size measurements for modelling concentrate grade in flotation froth systems.* (PhD Thesis), University of Cape Town.

Forbes, G., & de Jager, G. (2004). Fifteenth Annual Symposium of the Pattern Recognition Association of South Africa: *Texture measures for improved watershed segmentation of froth images.*

Forbes, G., & de Jager, G. (2005). Sixteenth Annual Symposium of the Pattern Recognition Association of South Africa: *Bubble size distributions for froth classification.* Fred Nicolls, Ed., Langebaan, South Africa.

Forbes, G., & de Jager, G. (2007). Unsupervised classification of dynamic froths. *SAIEE Africa Research Journal, 98*(2): 38-44.

Francis, J. (2001). *Machine vision for froth flotation.* (PhD Thesis), University of Cape Town.

Geng, Z., Chai, T., & Yue, H. (2008). Intelligent Control and Automation, 2008. WCICA 2008. 7th World Congress on: *A method of hybrid intelligent optimal setting control for flotation process.*

Gui, W., Liu, J., Yang, C., Chen, N., & Liao, X. (2013). Color co-occurrence matrix based froth image texture extraction for mineral flotation. *Minerals Engineering, 46*: 60-67.

Guoying, Z., Hong, Z., & Ning, X. (2011). Flotation bubble image segmentation based on seed region boundary growing. *Mining Science and Technology (China), 21*(2): 239-242.

Guoying, Z., Quanli, F., Chunjie, M., Yun, S., & Chen, Y. (2010). Networking, Sensing and Control (ICNSC), 2010 International Conference on: *Froth image segmentation based on adaptive ray cluster.*

Haavisto, O. (2009). *Reflectance spectrum analysis of mineral flotation froths and slurries.* (PhD Thesis), Helsinki University of Technology.

Hallila, S. U. (2014). *Utilizing froth phase behaviour and machine vision to indicate flotation performance*, (MSc Thesis), University of Uluo.

Hargrave, J., & Hall, S. (1997). Diagnosis of concentrate grade and mass flowrate in tin flotation from colour and surface texture analysis. *Minerals Engineering, 10*(6): 613-621.

Hätönen, J. (1999). *Image analysis in mineral flotation.* (MSc Thesis), Helsinki University of Technology.

Heinrich, G. (2003). *An investigation into the use of froth colour as sensor for metallurgical grade in a copper system.* (MSc Thesis), University of Cape Town.

Holtham, P., & Nguyen, K. (2002). On-line analysis of froth surface in coal and mineral flotation using JKFrothCam. *International journal of mineral processing*, *64*(2): 163-180.

Jemwa, G. T., & Aldrich, C. (2006). Kernel-based fault diagnosis on mineral processing plants. *Minerals Engineering*, *19*(11): 1149-1162.

Jinping, L., Weihua, G., Zhaohui, T., Xuemin, M., & Lijuan, M. (2011). Control Conference (CCC): *Production conditions classification for froth flotation based on froth image processing.* Chinese.

Jovanović, I., & Miljanović, I. (2015). Contemporary advanced control techniques for flotation plants with mechanical flotation cells–A review. *Minerals Engineering, 70*: 228-249.

Kaartinen, J. (2009). *Machine vision in measurement and control of mineral concentration process.* (PhD Thesis), Helsinki University Technology.

Kaartinen, J., Haavisto, O., & Hyötyniemi, H. (2006a). The Ninth IASTED International Conference on Intelligent Systems and Control: *On-line colour measurement of flotation froth.* Hawaii, USA.

Kaartinen, J., Hätönen, J., Hyötyniemi, H., & Miettunen, J. (2006b). Machine-vision-based control of zinc flotation—a case study. *Control Engineering Practice, 14*(12): 1455-1466.

Kaartinen, J., & Koivo, H. (2002). Machine vision based measurement and control of zinc flotation circuit. *Studies in Informatics and Control*, *11*(1): 97-106.

Kistner, M., Jemwa, G. T., & Aldrich, C. (2013). Monitoring of mineral processing systems by using textural image analysis. *Minerals Engineering*, *52*: 169-177.

Kohonen, T. (1982). Self-organized formation of topologically correct feature maps. *Biological cybernetics*, *43*(1): 59-69.

Lang, F.-L., & Jiang, D.-L. (2011). Floatation Froth Image Segmentation Algorithm Based on Mathematical Morphology and Wavelet, *Theoretical and Mathematical Foundations of Computer Science* (pp. 501-507): Springer.

Laurila, H., Karesvuori, J., & Tiili, O. (2002). Strategies for instrumentation and control of flotation circuits. *Mineral Processing Plant Design, Practice and Control*, *2*: 2174-2195.

Lim, J. S. (1990). Two-dimensional signal and image processing. *Englewood Cliffs, NJ, Prentice Hall, 1990, 710 p., 1*.

Lin, B., Recke, B., Knudsen, J. K., & Jørgensen, S. B. (2008). Bubble size estimation for flotation processes. *Minerals Engineering*, *21*(7): 539-548.

Liu, J., MacGregor, J., Duchesne, C., & Bartolacci, G. (2005). Flotation froth monitoring using multiresolutional multivariate image analysis. *Minerals Engineering*, *18*(1): 65-76.

Liu, J. J., & MacGregor, J. F. (2008). Froth-based modeling and control of flotation processes. *Minerals Engineering*, *21*(9): 642-651.

Marais, C. (2010). *Estimation of concentrate grade in platinum flotation based on froth image analysis.* (MSc Thesis), Stellenbosch: University of Stellenbosch.

Marais, C., & Aldrich, C. (2011a). The estimation of platinum flotation grade from froth image features by using artificial neural networks. *Journal of the South African Institute of Mining and Metallurgy, 111*(2): 81.

Marais, C., & Aldrich, C. (2011b). Estimation of platinum flotation grades from froth image data. *Minerals Engineering*, *24*(5): 433-441.

Mehrabi, A., Mehrshad, N., & Massinaei, M. (2014). Machine vision based monitoring of an industrial flotation cell in an Iron flotation plant. *International journal of mineral processing*, *133*: 60-66.

Mehrshad, N., & Massinaei, M. (2011). New image-processing algorithm for measurement of bubble size distribution from flotation froth images. *Minerals & Metallurgical Processing Journal*, *28*(3): 146-150.

Moolman, D., Aldrich, C., Schmitz, G., & Van Deventer, J. (1996a). The interrelationship between surface froth characteristics and industrial flotation performance. *Minerals Engineering*, *9*(8): 837-854.

Moolman, D., Aldrich, C., & Van Deventer, J. (1995a). The monitoring of froth surfaces on industrial flotation plants using connectionist image processing techniques. *Minerals Engineering*, *8*(1): 23-30.

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

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

Moolman, D., Aldrich, C., Van Deventer, J., & Stange, W. (1995c). The classification of froth structures in a copper flotation plant by means of a neural net. *International journal of mineral processing, 43*(3): 193-208.

Moolman, D., Eksteen, J., Aldrich, C., & Van Deventer, J. (1996b). The significance of flotation froth appearance for machine vision control. *International journal of mineral processing, 48*(3): 135-158.

Morar, S., Forbes, G., Heinrich, G., Bradshaw, D., King, D., Adair, B., & Esdaile, L. (2005). Centenary of Flotation Symposium: *The use of a colour parameter in a machine vision system, Smart-Froth, to evaluate copper flotation performance at Rio Tinto's Kennecott Utah Copper Concentrator.*

Morar, S. H. (2010). *The use of machine vision to describe and evaluate froth phase behaviour and performance in mineral flotation systems.* (PhD Thesis), University of Cape Town.

Morar, S. H., Bradshaw, D. J., & Harris, M. C. (2012a). The use of the froth surface lamellae burst rate as a flotation froth stability measurement. *Minerals Engineering, 36*: 152-159.

Morar, S. H., Harris, M. C., & Bradshaw, D. J. (2012b). The use of machine vision to predict flotation performance. *Minerals Engineering, 36*: 31-36.

Nakhaei, F., Mosavi, M., Sam, A., & Vaghei, Y. (2012). Recovery and grade accurate prediction of pilot plant flotation column concentrate: Neural network and statistical techniques. *International journal of mineral processing, 110*: 140-154.

Napier-Munn, T., & Wills, B. A. (2011). *Wills' mineral processing technology: an introduction to the practical aspects of ore treatment and mineral recovery*: Butterworth-Heinemann.

Nguyen, K., & Thornton, A. (1995). Proceedings of the DICTA-95, the 3rd Conference on Digital Imaging Computing Techniques and Applications: *The application of texture based image analysis techniques in froth flotation.*

Nguyen, K. K., & Holtham, P. (1997). Proceedings of the first joint Australian and New Zealand biennial conference on Digital Imaging and Vision Computing and Applications: *The application of pixel tracing techniques in the flotation process.*

Nunez, F., & Cipriano, A. (2008). Control Conference, CCC 2008: *Hybrid modeling of froth flotation superficial appearance applying dynamic textures analysis.* Chinese.

Núñez, F., & Cipriano, A. (2009). Visual information model based predictor for froth speed control in flotation process. *Minerals Engineering, 22*(4): 366-371.

Outotec. (2013). Outotec Sustainable use of Earths natural resources. Retrieved 8 Aug, 2014, from WWW.OUTOTEC.COM

Perry, R. H., Green, D. W., & Maloney, J. O. (1984). Perry's chemical engineer's handbook, *Perry's chemical engineer's handbook*: McGraw-Hill Book.

Reddick, J., Hesketh, A., Morar, S., & Bradshaw, D. (2009). An evaluation of factors affecting the robustness of colour measurement and its potential to predict the grade of flotation concentrate. *Minerals Engineering, 22*(1): 64-69.

Roesch, M., Ragot, J., & Degoul, P. (1976). Modeling and control in the mineral processing industries. *International journal of mineral processing, 3*(3): 219-246.

Runge, K., McMaster, J., Wortley, M., La Rosa, D., & Guyot, O. (2007). Ninth Mill Operators' Conference: *A correlation between Visiofroth™ measurements and the performance of a flotation cell.*

Sadr-Kazemi, N., & Cilliers, J. (1997). An image processing algorithm for measurement of flotation froth bubble size and shape distributions. *Minerals Engineering, 10*(10): 1075-1083.

Sbárbaro, D., & Del Villar, R. (2010). *Advanced Control and Supervision of Mineral Processing Plants*: Springer.

Shean, B., & Cilliers, J. (2011). A review of froth flotation control. *International journal of mineral processing, 100*(3): 57-71.

Supomo, A., Yap, E., Zheng, X., Banini, G., Mosher, J., & Partanen, A. (2008). PT Freeport Indonesia's mass-pull control strategy for rougher flotation. *Minerals Engineering, 21*(12): 808-816.

Takagi, T., & Sugeno, M. (1985). Fuzzy identification of systems and its applications to modeling and control. *Systems, Man and Cybernetics, IEEE Transactions on*(1): 116-132.

Tucker, J. P., Deglon, D.A., Franzidis, J.P., Harris, M.G. and O'Connor, C.T. (1994). An evolution of a direct method of bubble size distribution measurement in a laboratory batch flotation cell. *Minerals Engineering, 7*: 667–680.

Van Deventer, J. S., Moolman, D. W., & Aldrich, C. (1996). Visualisation of plant disturbances using self-organising maps. *Computers & chemical engineering, 20*: 1095-1100.

Vieira, S., Sousa, J., & Durao, F. (2005). Fuzzy modelling strategies applied to a column flotation process. *Minerals Engineering, 18*(7): 725-729.

Wang, W., Bergholm, F., & Yang, B. (2003). Froth delineation based on image classification. *Minerals Engineering, 16*(11): 1183-1192.

Wang, W., Hu, Y., Liu, W., & Ye, Z. (2009). Intelligent Systems and Applications, 2009. ISA 2009. International Workshop on: *Online Vision System and Measuring Parameters for Bubbles in Mineral Flotation.*

Wang, W., & Stephansson, O. (1999). Intelligent Processing and Manufacturing of Materials, IPMM'99. Proceedings of the Second International Conference on: *A robust bubble delineation algorithm for froth images.*

Wang, W., & Wang, L. (2000). Signal Processing Proceedings, WCCC-ICSP 2000. 5th International Conference on: *Froth image segmentation algorithms and their validation.*

Whelan, P., & Brown, D. (1956). Particle-bubble attachment in froth flotation. *Transactions of the Institute of Mining and Metallurgy, 65*: 181-192.

Wills, B. A. (2011). *Wills' mineral processing technology: an introduction to the practical aspects of ore treatment and mineral recovery*: Butterworth-Heinemann.

Wright, B. A. (1999). *The development of a vision-based flotation froth analysis system.* (MSc Thesis), University of Cape Town.

Xu, C., Gui, W., Yang, C., Zhu, H., Lin, Y., & Shi, C. (2012). Flotation process fault detection using output PDF of bubble size distribution. *Minerals Engineering, 26*: 5-12.

Xu, S., Liu, H., & Song, E. (2011). Marker-controlled watershed for lesion segmentation in mammograms. *Journal of digital imaging, 24*(5): 754-763.

Yang, C.-h., XU, C.-h., Mu, X.-m., & ZHOU, K.-j. (2009a). Bubble size estimation using interfacial morphological information for mineral flotation process monitoring. *Transactions of Nonferrous Metals Society of China, 19*(3): 694-699.

Yang, C., Xu, C., Gui, W., & Zhou, K. (2009b). Application of highlight removal and multivariate image analysis to color measurement of flotation bubble images. *International Journal of Imaging Systems and Technology, 19*(4): 316-322.

Yong, Z., Kejun, J., & Yukun, W. (2012). Control Conference (CCC) *Flotation concentrate grade prediction model based on RBF neural network & immune evolution algorithm.* Chinese.

Zanin, M., Wightman, E., Grano, S. R., & Franzidis, J.-P. (2009). Quantifying contributions to froth stability in porphyry copper plants. *International journal of mineral processing, 91*(1): 19-27.

Zheng, X., Franzidis, J., & Johnson, N. (2006). An evaluation of different models of water recovery in flotation. *Minerals Engineering*, *19*(9): 871-882.

Zhou, H., Wu, X., & Li, X. (2011). Power and Energy Society General Meeting, 2011 IEEE: *An ANFIS model of electricity price forecasting based on subtractive clustering.*

Zhu, J., & Wang, Y. K. (2008). Intelligent Control and Automation, WCICA 2008. 7th World Congress on: *Application of image recognition system in flotation process.*