



UNIVERSITI PUTRA MALAYSIA

***AUTOMATIC CONTROL OF FLOTATION PROCESS USING COMPUTER
VISION***

ALI JAHED SARAVANI

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**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

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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

AUTOMATIC CONTROL OF FLOTATION PROCESS USING COMPUTER VISION

By

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August 2015

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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 menghubungkan antara pemboleh ubah gambar dan pemboleh ubah proses, dan sistem ramalan yang menganggarkan parameter pelogaman berdasarkan pemboleh ubah 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.

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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.

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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_1	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).

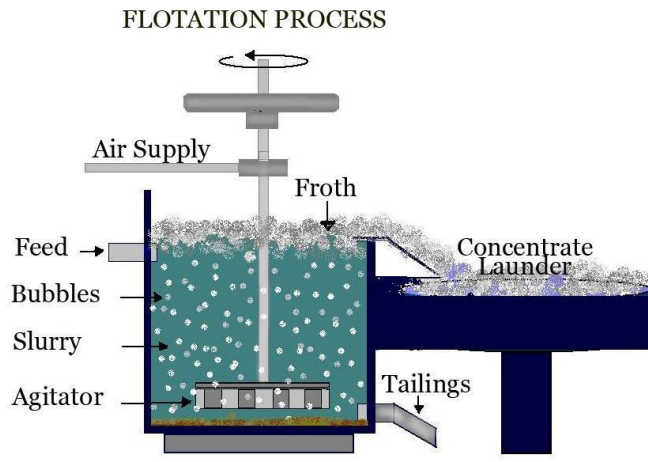


Figure 1.1. Flotation cell

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.

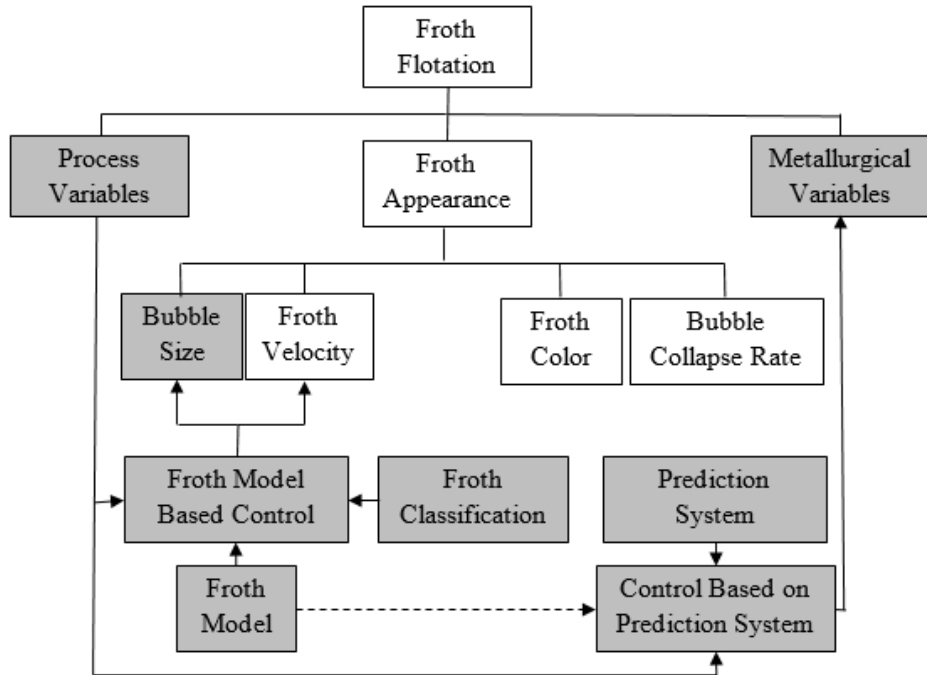


Figure 1.2. Schematic of using computer vision system in flotation process

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.

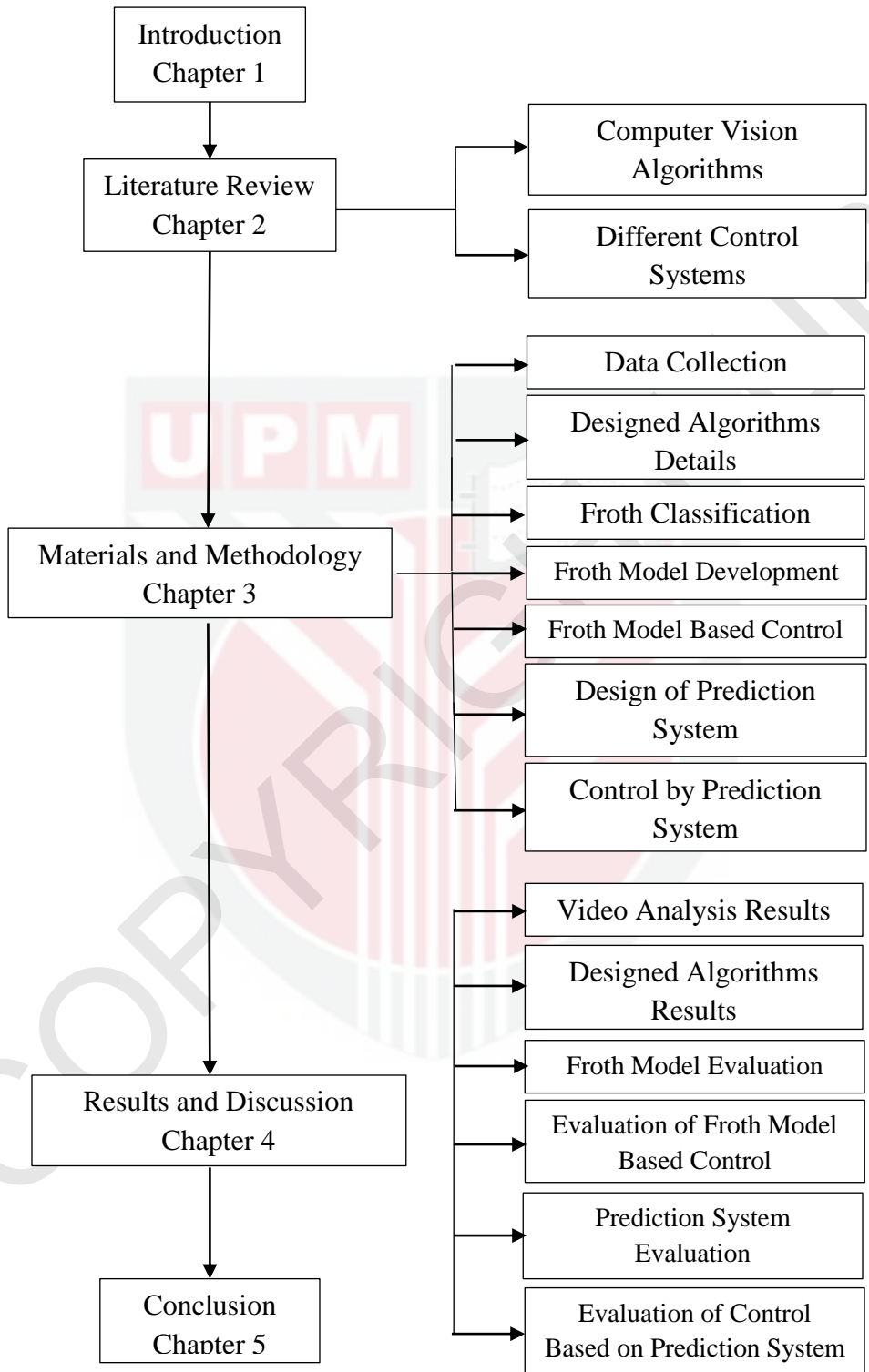


Figure 1.3. Thesis layout

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