RGC Ref. No.:
UGC/FDS14/P01/17
(please insert ref. above)

RESEARCH GRANTS COUNCIL
COMPETITIVE RESEARCH FUNDING SCHEMES FOR
THE LOCAL SELF-FINANCING DEGREE SECTOR

FACULTY DEVELOPMENT SCHEME (FDS)

Completion Report
(for completed projects only)

Submission Deadlines:
1. *Auditor's report with unspent balance, if any: within **six** months of the approved project completion date.*
2. *Completion report: within **12** months of the approved project completion date.*

Part A: The Project and Investigator(s)

1. Project Title

Fuzzy Bit-plane-dependence Multi-domain Region Competition: Mathematical Modelling and Applications

2. Investigator(s) and Academic Department(s) / Unit(s) Involved

Research Team	Name / Post	Unit / Department / Institution
Principal Investigator	CHOY Siu-kai/ Associate Professor	Department of Mathematics, Statistics and Insurance / The Hang Seng University of Hong Kong
Co-Investigator(s)	YU Kwok-wai/ Associate Professor	Department of Mathematics, Statistics and Insurance / The Hang Seng University of Hong Kong

3. Project Duration

	Original	Revised	Date of RGC / Institution Approval *(must be quoted)*
Project Start Date	01 January 2018	NA	NA
Project Completion Date	31 December 2020	NA	NA
Duration *(in month)*	36	NA	NA
Deadline for Submission of Completion Report	31 December 2021	NA	NA

Part B: The Final Report

5. Project Objectives

5.1 Objectives as per original application

1. To study a mathematical optimization framework that integrates the bit-plane-dependence probability models in various image domains with the fuzzy region competition, and its related mathematical theory.
2. To conduct extensive and comparative experiments on the proposed method in various image segmentation applications.

5.2 Revised objectives

Date of approval from the RGC: NA

Reasons for the change: NA

5.3 Realisation of the objectives
(Maximum 1 page; please state how and to what extent the project objectives have been achieved; give reasons for under-achievements and outline attempts to overcome problems, if any)

All two project objectives have been achieved.

Objective 1: To study a mathematical optimization framework that integrates the bit-plane-dependence probability models in various image domains with the fuzzy region competition, and its related mathematical theory.

- We have developed a mathematical optimization framework that integrates the bit-plane-dependence probability model with the agglomerative fuzzy *k*-means clustering algorithm for image segmentation applications. Statistical analysis (e.g., parameter estimation, sufficient statistics) for the model parameters have been performed. In addition, the objective function of the fuzzy bit-plane-dependence multi-domain region competition segmentation model has been formulated. Based on the objective function, the update rules of the fuzzy bit-plane-dependence multi-domain region competition segmentation algorithm has been developed.

Objectives 2: To conduct extensive and comparative experiments on the proposed method in various image segmentation applications.

- We have developed the fuzzy bit-plane-dependence agglomerative clustering algorithm and the fuzzy bit-plane-dependence region competition algorithm, and conducted extensive experiments on different kinds of images using public databases. Comparative experimental results with existing approaches show that our methods achieve remarkable success in image segmentation applications.

5.4 Summary of objectives addressed to date

Objectives *(as per 5.1/5.2 above)*	**Addressed** *(please tick)*	**Percentage Achieved** *(please estimate)*
1. To study a mathematical optimization framework that integrates the bit-plane-dependence probability models in various image domains with the fuzzy region competition, and its related mathematical theory.	✓	100%
2. To conduct extensive and comparative experiments on the proposed method in various image segmentation applications.	✓	100%

6. Research Outcome

6.1 Major findings and research outcome
(Maximum 1 page; please make reference to Part C where necessary)

1. We have presented a novel fuzzy bit-plane-dependence image segmentation methodology. We propose a probability model for characterizing the distributions of image variations based on bit-plane probabilities and dependencies between bit-planes. Compared with the current state-of-the-art image variation models which assume the distributions have specific structures (e.g., symmetry, monotone and periodicity), the proposed model provides a universal parametric representation that can be used to model random distributions without enforcing any specific restrictions on the distributions. In addition, we show that the maximum likelihood estimators of model parameters are joint sufficient statistics, which, in turn, justify the theoretical basis for their use. To effectively segment images with various textures, we propose a fuzzy bit-plane-dependence image segmentation algorithm. The proposed algorithm integrates the bit-plane-dependence probability model into the agglomerative fuzzy algorithm, and incorporates neighboring information and boundary

correction for image segmentation applications. Experiments demonstrate the superior performance of the proposed method.

2. We have proposed a novel variational model based on fuzzy region competition and statistical image variation modeling for image segmentation. In the energy functional of the proposed model, each region is characterized by the pixel-level color feature and region-level spatial/frequency information extracted from various image domains, which are modeled by the windowed bit-plane-dependence probability models. To efficiently minimize the energy functional, we apply an alternating minimization procedure with the use of Chambolle's fast duality projection algorithm, where the closed-form solutions of the energy functional are obtained. Our method gives soft segmentation result via the fuzzy membership function, and moreover, the use of multi-domain statistical region characterization provides additional information that can enhance the segmentation accuracy. Experimental results indicate that the proposed method has a superior performance and outperforms the current state-of-the-art superpixel-based and deep-learning-based approaches.

6.2 Potential for further development of the research and the proposed course of action *(Maximum half a page)*

The project can be further developed by studying the following aspects:

1. Statistical analysis on the intrinsic structures of bit-planes should be performed in order to have a comprehensive understanding of the dependencies between bit-planes. The results are expected to provide statistical justification on the existence of bit-plane dependencies and the selection of the order of bit-plane dependencies.
2. The relationship between model parameters and real-world instance should be studied. Specifically, we would like to study the physical meaning of model parameters and "how do the model parameters relate to the objects that are present in the image".
3. A few parameters in the algorithm need to be selected appropriately so as to achieve satisfactory results. An automate parameter selection methodologies should be investigated.
4. The wavelet and Hilbert transforms are used to construct the transformed images in the experiments. However, various image domains are available in the literature and can be adopted in our case. Thus, the selection of image domains and their advantages for image segmentation (or in a specific application domains) should be investigated.

7. Layman's Summary

(Describe in layman's language the nature, significance and value of the research project, in no more than 200 words)

Image segmentation is a critical problem in computer vision for a wide variety of applications. Among the existing approaches, partial differential equations and variational methods have been extensively studied in the literature. Although most variational approaches use boundary and region information to segment natural and textural images with remarkable success, we note that most of the existing methods only consider simple information/features extracted from a particular image domain (e.g., grey level features in the spatial domain) to characterise image regions. However, such information/features are not informative enough to segment complex images. In the proposed project, we will investigate a robust and effective variational segmentation algorithm to remedy the aforementioned difficulties for a wide range of applications. In particular, we will study a mathematical optimisation framework that integrates the bit-plane-dependence probability models,

which are used to characterise local region information extracted from various image domains, with the fuzzy region competition for image segmentation. The proposed segmentation method will be assessed by extensive and comparative experiments using complex natural and textural images. Our proposed method is expected to assist researchers in the field of machine learning by providing a new model-based unsupervised learning algorithm with practical computer vision applications.

Part C: Research Output

8. Peer-Reviewed Journal Publication(s) Arising Directly From This Research Project

(Please attach a copy of the publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.)

The Latest Status of Publications				Author(s) *(denote the corresponding author with an asterisk*)*	Title and Journal / Book *(with the volume, pages and other necessary publishing details specified)*	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this Report *(Yes or No)*	Acknowledged the Support of RGC *(Yes or No)*	Accessible from the Institutional Repository *(Yes or No)*
Year of Publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*						
2019				S. K. Choy*, Kevin Yuen and Carisa Yu	Fuzzy bit-plane-dependence image segmentation (Vol. 154, 2019, P. 30 – P. 34, *Signal Processing*) https://doi.org/10.1016/j.sigpro.2018.08.010	2019	No	Yes	Yes
2021				S. K. Choy*, T. C. Ng, Carisa Yu and Benson Lam	Fuzzy Bit-Plane-Dependence Region Competition (Vol. 9, 2021, 2392, *Mathematics*) https://doi.org/10.3390/math9192392	No	Yes (Annex I)	Yes	Yes

9. Recognized International Conference(s) In Which Paper(s) Related To This Research Project Was / Were Delivered

(Please attach a copy of each conference abstract)

Month / Year / Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this Report *(Yes or No)*	Acknowledged the Support of RGC *(Yes or No)*	Accessible from the Institutional Repository *(Yes or No)*
NA	NA	NA	NA	NA	NA	NA

10. Whether Research Experience And New Knowledge Has Been Transferred / Has Contributed To Teaching And Learning

(Please elaborate)

The proposed algorithm can be used as examples in some courses related to data mining and machine learning.

11. Student(s) Trained

(Please attach a copy of the title page of the thesis)

Name	Degree Registered for	Date of Registration	Date of Thesis Submission / Graduation
NA	NA	NA	NA

12. Other Impact

(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, teaching enhancement, etc.)

NA

13. Statistics on Research Outputs

	Peer-reviewed Journal Publications	Conference Papers	Scholarly Books, Monographs and Chapters	Patents Awarded	Other Research Outputs (please specify)	
No. of outputs arising directly from this research project	2	0	0	0	Type	No.
					NA	NA

14. Public Access Of Completion Report

(Please specify the information, if any, that cannot be provided for public access and give the reasons.)

Information that Cannot Be Provided for Public Access	Reasons
NA	NA