RGC Ref. No.: UGC/FDS14/P02/19
(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

Unsupervised Fuzzy Superpixel-based Image Segmentation

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

Research Team	Name / Post	Unit / Department / Institution
Principal Investigator	Prof CHOY Siu-kai/ Professor	Department of Mathematics, Statistics and Insurance / The Hang Seng University of Hong Kong
Co-Investigator(s)	Dr YU Kwok-wai/ Associate Professor	Department of Mathematics, Statistics and Insurance / The Hang Seng University of Hong Kong
Others	Mr NG Tsz-ching/ Research Associate	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 2020	01 January 2020	NA
Project Completion Date	31 December 2022	30 June 2023	Approved by HSUHK on 27 January 2021
Duration *(in month)*	36	42	
Deadline for Submission of Completion Report	31 December 2023	30 June 2024	

4.4 Please attach photo(s) of acknowledgement of RGC-funded facilities / equipment.

NA

Part B: The Final Report

5. Project Objectives

5.1 Objectives as per original application

1. To investigate a fuzzy clustering-based superpixel generation algorithm and a fuzzy graph-theoretic superpixel partitioning algorithm, and their related mathematical theory; and
2. To conduct extensive 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 investigate a fuzzy clustering-based superpixel generation algorithm and a fuzzy graph-theoretic superpixel partitioning algorithm, and their related mathematical theory.

- We have developed a variational algorithm based on fuzzy clustering and total variation regularization for superpixel segmentation (superpixel generation). Mathematical analysis (parameter estimation, divergence of TV minimization) for the model parameters have been performed. To efficiently minimize the energy functional of the proposed model, we adopt an alternating direction method of multipliers with the modified Chambolle's fast duality projection algorithm. Our algorithm can generate regular and compact superpixels with high segmentation accuracy, satisfactory boundary adherence, and low computational cost. In addition, we have presented a multi-phase image segmentation methodology based on fuzzy superpixel decomposition, aggregation and merging. First, a collection of layers of dense fuzzy superpixels is generated by the variational fuzzy decomposition algorithm. Then a layer of refined superpixels is extracted by aggregating various layers of dense fuzzy superpixels using the hierarchical normalized cuts (graph-theoretic superpixel partitioning). Finally, the refined superpixels are projected into the low dimensional feature spaces by the

multidimensional scaling and the segmentation result is obtained via the mean-shift-based merging approach with the spatial band-width adjustment strategy.

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

- We have developed the variational fuzzy superpixel segmentation algorithm and fuzzy superpixel-based image segmentation 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 investigate a fuzzy clustering-based superpixel generation algorithm and a fuzzy graph-theoretic superpixel partitioning algorithm, and their related mathematical theory; and	✓	100%
2. To conduct extensive 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 variational model based on fuzzy clustering and total variation regularization for superpixel segmentation. Compared with the classical hard-labeled methodologies, our approach gives soft results via the fuzzy membership function, and moreover, the use of total variation provides additional information that can enhance the superpixel regularity, which in turn improves the segmentation performance. To efficiently minimize the energy functional of the proposed model, we adopt an alternating direction method of multipliers with the modified Chambolle's fast duality projection algorithm. Our algorithm can generate regular and compact superpixels with high segmentation accuracy, satisfactory boundary adherence, and low computational cost. Comparative experimental results with the current state-of-the-art approaches reveal the superior performance of the proposed method.
2. We have proposed a multi-phase image segmentation methodology based on fuzzy superpixel decomposition, aggregation and merging. First, a collection of layers of dense fuzzy superpixels is generated by the variational fuzzy decomposition algorithm. Then a layer of refined superpixels is extracted by aggregating various layers of dense fuzzy superpixels using the hierarchical normalized cuts. Finally, the refined superpixels are projected into the low dimensional feature spaces by the multidimensional scaling and the segmentation result is obtained via the mean-shift-based merging approach with the spatial bandwidth adjustment strategy. Our algorithm utilizes the superimposition of fuzzy superpixels to impose more accurate spatial constraints on the final segmentation through the fuzzy superpixel aggregation. The fuzziness of superpixels also provides spatial features to measure affinities between fuzzy superpixels and refined superpixels, and guide the merging process. Comparative experiments with the existing approaches reveal a superior performance of the proposed method.

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

While the proposed method yields promising superpixel and image segmentation performance, our approach is still facing a number of shortcomings. First, a few parameters in the algorithms need to be selected appropriately so as to achieve satisfactory results. Nevertheless, our experimental results reveal that selecting a value for each parameter in a certain range is good enough to provide similar performance. Second, the boundary recall (BR) and boundary displacement error (BDE) of the proposed algorithms are not the highest compared with that of the competing algorithms. This may be explained by the fact that the total variation regularization in our formulation depends only on the fuzzy membership function and does not apply directly on the image contents.

Although the proposed method brings satisfactory performance, we shall study the following as future work. First, as mentioned previously, some parameters in the algorithms need to be selected manually to achieve promising results. Thus, an automatic parameter selection approach is necessary so that these parameters can be adaptively adjusted during the optimization procedure, which would improve the segmentation performance. Second, while the proposed methodology yields satisfactory BR and BDE performance, the boundary adherence can be further improved by incorporating the PDE-based geometric flow into the energy functional. Third, a classical multidimensional scaling is adopted in the fuzzy superpixel merging procedure. It is expected that the computational cost can be further reduced by employing non-metric or generalized multidimensional scaling.

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 challenging problem in computer vision and has a wide variety of applications in various fields. One of the main approaches to this problem is to perform superpixel segmentation followed by a graph-based methodology to achieve image segmentation. Crucial to the successful image segmentation using this method is the superpixel generation and partitioning algorithms. Existing generation algorithms have various priorities and place emphasis on boundary adherence, superpixel regularity, computational complexity, etc, but normally do not perform well in all of the above simultaneously. Partitioning algorithms are typically based on graph-based approaches and could have high computational costs, which makes them inefficient in practical contexts. In the proposed project, we investigate an effective unsupervised fuzzy superpixel-based image segmentation algorithm to remedy the aforementioned difficulties for a wide range of applications. In particular, we study the combined use of a novel fuzzy clustering-based superpixel generation technique and fuzzy graph-theoretic superpixel partitioning approach for image segmentation applications. The proposed segmentation method is assessed by extensive comparative experiments using complex natural images. Our proposed method is expected to assist researchers in the field of machine learning by providing a new superpixel-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)*						
2022				T. C. Ng and S. K. Choy*	*Variational Fuzzy Superpixel Segmentation*, IEEE Transactions on Fuzzy Systems, vol. 30, no. 1, pp. 14-26, 2022.	2021	No	Yes	Yes https://researchdb.hsu.edu.hk/view/publication/202000219
2023				T. C. Ng, S. K. Choy*, S. Y. Lam and K. W. Yu	*Fuzzy Superpixel-based Image Segmentation*, Pattern Recognition, vol. 134, 109045, 2023.	No	Yes (Annex I)	Yes	Yes https://researchdb.hsu.edu.hk/view/publication/202200215

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