RGC Ref. No.:
UGC/FDS11/E04/15
(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

OREO: Cross-Layer **O**ptimization for Powe**r** **E**fficient **O**LED Display

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

Research Team	**Name / Post**	**Unit / Department / Institution**
Principal Investigator	Dr. ZHAO Yingchao / Associate Professor	School of Computing and Information Sciences, Caritas Institute of Higher Education
Co-Investigator(s)	Dr. XUE Chun Jason / Associate Professor	Department of Computer Science, City University of Hong Kong
Others		

3. Project Duration

	Original	**Revised**	**Date of RGC / Institution Approval** *(must be quoted)*
Project Start Date	01/01/2016		
Project Completion Date	31/12/2018	30/06/2019	Institution Approval granted on 11/05/2018
Duration *(in month)*	36	42	Institution Approval granted on 11/05/2018
Deadline for Submission of Completion Report	31/12/2019	30/06/2020	

Part B: The Final Report

5. Project Objectives

5.1 Objectives as per original application

1. Propose a unified power model for OLED display based on related work on static power modeling, and develop a tool suite with the unified power model, which will calculate display power consumption when display content and OLED display setting are given;
2. Develop an online video classification method and develop category-specific dynamic tone mapping (DTM) approaches of power saving with OLED displays for videos with category-specific visual quality requirements;
3. Explore visual-quality aware dynamic voltage scaling (DVS) strategies for online video streaming that meet runtime requirements with high-efficiency;
4. Propose classification techniques for games, and develop OLED display power-reduction techniques for games according to classification and visual attention;
5. Enhance skills and capabilities of teachers and students studying scheduling algorithms and power saving technologies applied in software development, which is part of the programmes offered by the institute, so that the research experiences and new knowledge generated from the project can benefit both teaching and learning.

5.2 Revised objectives

Date of approval from the RGC: N/A

Reasons for the change: N/A

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 the five objectives are realized. The extent of each objective is explained as follows:

1. Propose a unified power model for OLED display based on related work on static power modeling, and develop a tool suite with the unified power model, which will calculate display power consumption when display content and OLED display setting are given.

We proposed a unified dynamic OLED power model as follows:

$$P^{i,j}(C_n)=R\times|C_n-C_{n-1}|+(\alpha\times C_n^2+\beta\times C_n^2+\delta\times C_n+D) \quad (1)$$

Here C_n and C_{n-1} are the color values of the current and the previous frames, respectively. R is a constant related to the frame rate. α, β, δ and D are characterized coefficients, which vary in the specific RGB color channel.

By leveraging the power model in (1), we developed a tool suite and quantitatively measured the dynamic power consumption of OLED screen on smartphones in [J2] and found that the approximation error of this dynamic power consumption model was below 5.3%, while the approximation error of the original static power model was 10%.

2. Develop an online video classification method and develop category-specific dynamic tone mapping (DTM) approaches of power saving with OLED displays for videos with category-specific visual quality requirements.

We analyzed the power consumption features of four video categories (movie trailers, cartoon clips, video games, news reports) and established a power feature based Hidden Markov Model (HMM) video classifier, which was depicted in Algorithm 1 of [J2]. The HMM classifier could classify videos to correct categories with a reasonably high accuracy.

Using this HMM classifier, we developed an interactive content-aware dynamic tone mapping (ICA-DTM) scheme, which is summarized in Algorithm 2 of [J2]. Besides common ICA-DTAM policies, we proposed two category-specific policies to enhance the efficacy: one was the color remap policy for cartoon clips and news report, the other was the opening/ending dim policy for movie trailers. Experiments showed that the ICA-DTM could achieve 17.8% OLED power saving on average.

3. Explore visual-quality aware dynamic voltage scaling (DVS) strategies for online video streaming that meet runtime requirements with high-efficiency.

On one hand, we made a set of hardware modifications on the OLED display circuit, and proposed a Dynamic Voltage Scaling (DVS)-friendly OLED pixel driver circuit design in [J1]. Experiments showed that the DVS-friendly OLED pixel driver could maintain high visual quality with SSIM greater than 0.94. However, the conventional driver had very poor quality when the supply voltage decreased.

On the other hand, we proposed a Fine-grained DVS (FDVS) OLED display panel design in [J1], which partitioned an OLED display panel into multiple areas with independent voltage supplies. FDVS offers a more adaptive control on the voltage scaling at smaller granularities for local display contents, which is more practical and efficient.

4. Propose classification techniques for games, and develop OLED display power-reduction techniques for games according to classification and visual attention.

We analyzed display characteristics of games along with other display content categories and found that games had the most frequent transitions among the four categories. Based on these characteristics, we designed a set of effective temporal optimization methods in [J1] including video category based dynamic voltage scaling prediction, real-time voltage regulation adjustment. Experiments showed that the proposed technique saved 15.3%~34.26% OLED power on average while maintaining a high display quality (SSIM>0.98).

5. Enhance skills and capabilities of teachers and students studying scheduling algorithms and power saving technologies applied in software development, which is part of the programmes offered by the institute, so that the research experiences and new knowledge generated from the project can benefit both teaching and learning.

Scheduling algorithms have been introduced to teachers in the research seminars. The idea of power saving was introduced to students in the lecture. Students could learn how OLED works and why it is better than other types of displays from the aspect of energy saving. Some power saving technologies for OLED were introduced to students to enhance their learning interests.

5.4 Summary of objectives addressed to date

Objectives *(as per 5.1/5.2 above)*	**Addressed** *(please tick)*	**Percentage Achieved** *(please estimate)*
1. Propose a unified power model for OLED display based on related work on static power modeling, and develop a tool suite with the unified power model, which will calculate display power consumption when display content and OLED display setting are given	✓	100%
2. Develop an online video classification method and develop category-specific dynamic tone mapping (DTM) approaches of power saving with OLED displays for videos with category-specific visual quality requirements	✓	100%
3. Explore visual-quality aware dynamic voltage scaling (DVS) strategies for online video streaming that meet runtime requirements with high-efficiency	✓	100%
4. Propose classification techniques for games, and develop OLED display power-reduction techniques for games according to classification and visual attention	✓	100%
5. Enhance skills and capabilities of teachers and students studying scheduling algorithms and power saving technologies applied in software development, which is part of the programmes offered by the institute, so that the research experiences and new knowledge generated from the project can benefit both teaching and learning	✓	100%

6. Research Outcome

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

In the study of Objective 1, we found that, different from conventional static power model, the practical power estimation and optimization varied significantly with hardware specification, display content, and application scenarios. Using conventional static power modeling to estimate power consumption could cause 10% errors. Therefore, we proposed a unified OLED power model, which could measure both static and dynamic power consumption with approximation error below 5.3% in [J2].

In the study of Objective 2, we found that OLED display had particular color-specific power consumption, which was closely related to the human visual perception system and the graphic characteristic of the displayed content. For example, we found that video streams from the same video category shared many common power consumption features on OLED screens. Therefore, we were able to build a Hidden Markov Model (HMM) classifier to categorize videos based on OLED screen power characteristics. Using this HMM classifier, we proposed an interactive content-aware dynamic tone mapping scheme, namely, ICA-DTM, to remap output color range and minimize the power inefficient color composition on OLED screens for power saving in [J2].

In the study of Objective 3, we delivered a set of hardware-level innovations in the designs of OLED driver circuit to retain the HVP-quality under the application of dynamic voltage scaling (DVS), and the peripheral circuits to actively compensate the process variations and aging effects. Specifically, we investigated a novel DVS-friendly OLED driver design that can minimize the display color distortions under supply voltage variations, offering better power saving ratio of OLED panels under the same HVP-quality constraint. Novel peripheral circuit designs for reliability enhancements, i.e. process variation and aging effect tolerance, were also proposed. Eventually we proposed a new hardware optimization approach to the OLED display, which met the runtime requirements with high-efficiency in [J1].

In the study of Objective 4, we realized that OLED display's characteristics could further benefit particular display content, such as video games, which had relatively constant composition, gradual scene change, and mild brightness and color tone. Therefore, we proposed a set of dedicated spatial and temporal optimization algorithms in [J1].

Regarding Objective 5, we used the OLED display technology as teaching materials, which could help students understand the importance of scheduling algorithms in power management. Other scheduling methods [C1] were introduced in a research conference. The extension of the developed power management techniques of mobile phones could also be used to achieve power saving of other components of the phones, such as sensors and GPUs, etc.. Students could apply these techniques in the software engineering projects or their final year projects.

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

This research project achieves substantial reduction in the power consumption of OLED display panel in mobile devices while assuring viewer experience.

One potential direction for future development is to apply the technology proposed in this project to new display applications such as virtual reality (VR) and augmented reality (AR) devices, since VR/AR also faces the problem of limited power resources of mobile hardware. The course of action is as follows:

1. Apply the human visual system awareness oriented display optimization from OLED display technique into the near-eye VR display scenario;
2. Develop focus-oriented dynamic local rendering and brightness adjustment techniques to further reduce power consumption.

Another potential direction for future development is to develop a new video player with ICA-DTM capability. The course of actions is as follows:

1. Extract features while decoding the video file to decide its video category;
2. Use DTM to tune pixel explosion and color effect based on its video category.

7. Layman's Summary

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

The research project investigated an interdisciplinary OLED panel power management scheme by integrating the interactive innovation at hardware, system and application levels. The techniques reported in this project can efficiently relieve the OLED display panels' power consumption and also preserve optimal visual quality. Since display is usually the biggest power consumer in mobile devices and OLED is gradually dominating the consumer market, the improvement of OLED display power management will greatly prolong battery life and enhance the system performance by allocating saved energy to other energy-starving operations. The novel techniques developed in this project may also be applied to other OLED displays, for example VR and AR wearable displays. Reducing power consumption of these OLED displays could ultimately reduce the environmental pollution from waste batteries.

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)*						
	2020	**Yes**		**[J1]. *Xiang Chen, Zirui Xu, Wei Zhang, Jason Xue, Yingchao Zhao, Yiran Chen**	**DiViSi: Quality-retaining Dynamic Driver Voltage Scaling for Organic Light Emitting Diode Displays IEEE Transactions on Computer-Aided Design Of Integrated Circuits And Systems**	**No**	**Yes**	**Yes**	**Yes**
		Yes		**[J2]. *Zhuwei Qin, Yingchao Zhao, Jason Chun Xue, Xiang Chen**	**ICA-DTM: Interactive Content-Aware OLED Screen Power Optimization by Dynamic Tone Mapping Pervasive and Mobile Computing**	**No**	**Yes**	**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)*
07/2017/ Bern, Switzerland	Scheduling Tasks to Minimize Active Time on a Processor with Unlimited Capacity	[C1]. 14th Annual Conference on Theory and Applications of Models of Computation	No	Yes	Yes	Yes

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

(Please elaborate)

The proposed project extended the conventional teaching practice. The intensive usage of lab instruments such as power monitor, sensors, etc., requires PI to understand the utilization of instruments and creatively use these instruments in the performed research. The research on software design and implementation, hacking the hardware design of the mobile phone, and power and performance measurement also offers the research team the first-hand experience on the corresponding hardware design and testing.

The proposed project also makes great efforts to create novel teaching topics and make the students well prepared for the design challenges of embedded and mobile systems. The developed research outcomes, including the power management scheme of mobile systems and the relevant power model and circuit designs, have been seamlessly integrated into the course offered by the PI. The corresponding course materials and project information become available to the students to encourage the students to conduct the design of smartphone software and hardware designs and testing.

Moreover, the proposed research has found impact on the cross-domain learning experience. This project offers great training opportunities to the involved researchers by immersing them in the research on mobile systems, circuit design, and machine human interface, as well as prototyping our research outcomes and sharing the results on the interactive forums like online video and social networks. The integrated research tasks comprehensively train the students with the research and development skills that are desired by the rapidly growing industry.

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
N/A	N/A	N/A	N/A

12. Other Impact

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

This research is conducted in close collaboration with our research partners from different universities, for example, University of Pittsburgh, George Mason University, and Southeast University.

We envision potential direct transfer of our proposed techniques to industry during our research process. The outcomes of this research have direct impacts on display panel design and usage in mobile devices by making the research outcomes publicly accessible to those partners.

The internship or other opportunities provided by our collaborators also offer versatile training for undergraduate and graduate students as well as the ideal initial step of technology transferring.

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	1	N/A	N/A	Type	No.

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
N/A	N/A