A Smartphone Thermal Temperature Analysis for Virtual and Augmented Reality

Xiaoyang Zhang, Harshit Vadodaria, Na Li, Kyoung-Don Kang, and Yao Liu
Department of Computer Science
State University of New York at Binghamton
{xzhan211, hvadoda1, nli19, kang, yaoliu}@binghamton.edu

***Abstract*—Emerging virtual and augmented reality applications are envisioned to significantly enhance user experiences. An important issue related to user experience is thermal management in smartphones widely adopted for virtual and augmented reality applications. Although smartphone overheating has been reported many times, a systematic measurement and analysis of their thermal behaviors is relatively scarce, especially for virtual and augmented reality applications. To address the issue, we build a temperature measurement and analysis framework for virtual and augmented reality applications using a robot, infrared cameras, and smartphones. Using the framework, we analyze a comprehensive set of data including the battery power consumption, smartphone surface temperature, and temperature of key hardware components, such as the battery, CPU, GPU, and WiFi module. When a 360° virtual reality video is streamed to a smartphone, the phone surface temperature reaches near 39°C. Also, the temperature of the phone surface and its main hardware components generally increases till the end of our 20-minute experiments despite thermal control undertaken by smartphones, such as CPU/GPU frequency scaling. Our thermal analysis results of a popular AR game are even more serious: the battery power consumption frequently exceeds the thermal design power by 20–80%, while the peak battery, CPU, GPU, and WiFi module temperature exceeds 45, 70, 70, and 65°C, respectively.**

I. Introduction

Virtual reality (VR) and augmented reality (AR) applications are fast emerging in several areas, such as education/training, entertainment, medicine, and manufacturing. In VR or AR applications, users often hold or wear smartphones, head mounted displays, or smart glasses for an extended period of time; therefore, thermal comfort and safety is a key issue. Prior studies showed that a person senses warmth when the temperature of an object is in the range between 33–35°C [1]. A user may feel discomfort and begin to feel pain in the temperature range of 42–45°C [2].

Although smartphone overheating has been reported many times, an in-depth measurement and analysis is relatively scarce. Kang et al. [3] claim their work is the first to perform a systematic analysis and user study of smartphone thermal behaviors for various mobile applications, such as video chats, games, video recording, video streaming, and voice calling. They observe serious thermal issues in smartphones. Their work, however, was performed using relatively old smartphones with a main focus on general mobile applications; they did not consider thermal impacts of VR or AR applications expected to significantly increase data transmissions and computations to support more immersive user experiences using state-of-the-art smartphones or wearable VR/AR devices (that often have similar hardware architectures/specifications to smartphones).

To shed light on this issue, in this paper, we perform an initial work on measuring, analyzing, and predicting the smartphone thermal temperature and present preliminary results to promote further work on thermal analysis and management in mobile devices for VR and AR applications. More specifically, we build an effective temperature measurement and analysis framework for VR/AR applications using a robot, infrared cameras, and a new generation of Android smartphones (Google Pixel 4 and Samsung Galaxy S10). Using the framework, we collect and analyze a comprehensive set of data including (but not limited to) the power consumption, phone's surface temperature, and temperature of various hardware components, such as the battery, CPU, GPU, and WiFi module. In our experiments, we consider two applications. In the first application, a 360° video [4] in VR mode is streamed to a smartphone for 20 minutes. In this experiment, the temperature of the phone surface reaches near 39°C that is higher than the thermal threshold for a sensation of warmth [1]. Also, we have built a prediction model more accurate than the one presented in [3] to predict the surface temperature of a smartphone with high accuracy. Our prediction errors are 0.34°C and 0.4°C in terms of the mean absolute error and root mean square error, respectively.

Furthermore, we use Minecraft Earth [5] that is a popular AR game for thermal analysis. The results indicate serious thermal concerns: the battery power consumption frequently exceeds the thermal design power (TDP) by approximately 20–80%. The peak battery, CPU, GPU, and WiFi module temperature exceeds 45, 70, 70, and 65 °C, respectively. The battery temperature continuously increases from approximately 26°C at the beginning to near 46°C at the end of our experiment. The temperature of the CPU, GPU, and WiFi module mostly range between 60–70°C. Such high temperatures may greatly diminish the long-term reliability and durability of hardware. Also, they may incur thermal safety risks when users run VR/AR applications for extended periods of time on their handheld or wearable devices.

The rest of the paper is organized as follows. In Section II, background for mobile thermal management is given. Section III describes the setup of the temperature measurement framework and the measurement methodology. In Section IV, we measure and analyze thermal dynamics of Android smartphones, while discussing key issues for further research on more effective mobile thermal management in the future. In Section V, related work is discussed. Finally, Section VI concludes the paper.

II. Background

Smartphone overheating often results in: 1) performance degradation, 2) impaired user experiences, and 3) potential health risks (e.g., skin damage) [3]. An application processor (AP) in a mobile device typically consists of the CPU, GPU, and multimedia codec. A mobile system-on-chip (SoC) usually supports frequency scaling for thermal control. When the CPU temperature exceeds the threshold set by the manufacturer, either the clock frequency is throttled or cores are turned off. In Android smartphones, the `thermal-engine` in the underlying Linux kernel begins thermal throttling when the CPU temperature is higher than the threshold. In addition, dynamic frequency scaling is performed when the GPU overheats in modern smartphones.

Smartphone users often complain about discomfort for overheating [6], [7] which degrades user experiences [3]. Extended exposure to heat may also result in accelerated skin aging [8] or toasted skin syndrome [9]. Thermal management in mobile devices, however, is challenging. In mobile devices, active cooling (e.g., forced air or liquid cooling) is infeasible due to the small form factor and weight constraints. A smartphone consists of thin multiple layers of integrated circuits and wires that have different degrees of conductivity. In addition, data communication and computation demands in emerging AR and VR applications are considerably higher than those in most existing mobile applications and are increasing. Thus, it is important to analyze thermal behaviors of smartphones in VR/AR settings.

III. Measurement Methodology

In this section, we discuss our measurement framework and methodology.

A. Experimental Framework

Component	Specification
CPU	Cortex-A76/A55 (Kryo 485)
Number of Cores	8
GPU	Qualcomm Adreno 640
Burst Frequency	600 MHz
TDP	5W

TABLE I: Hardware specifications of Qualcomm Snapdragon 855 with 1x2.84 GHz Kryo 485 Gold Prime, 3x2.42 GHz Kryo 485 Gold, and 4x1.78 GHz Kryo 485 Silver cores [10], [11]

1) Hardware setup: Figure 1 shows the hardware infrastructure of our experiments. It consists of several parts: 1) a target smartphone, 2) two FLIR ONE infrared cameras [12] for measuring the smartphone surface temperature (front and back), and 3) a robot. When a user plays a VR or AR application, she may keep moving her device, such as a smartphone or headset. In this work, we use a robot to simulate the movement of a VR/AR device without incurring thermal discomfort or skin damage to users. Specifically, we consider three patterns that simulate when a user 1) rotates, 2) walks in a circle, or 3) shakes her head repeatedly as illustrated in Figure 2. In our experiments, we used two advanced Android smartphones: Google Pixel 4 and Samsung Galaxy S10 rooted for experiments. Due to space limit, we mainly present our temperature measurement and analysis results acquired using the Pixel 4 phone that allows more open access to various temperature sensors and system performance statistics. (The results we have got using the Galaxy S10 phone were similar to those discussed in this paper.) Table I summarizes the key hardware specifications of the Qualcomm Snapdragon 855 SoC used in Pixel 4 smartphones (and many other smartphones) [10], [11]

2) VR and AR applications: In our experiments, we consider a 360° video streamed from YouTube in VR mode with

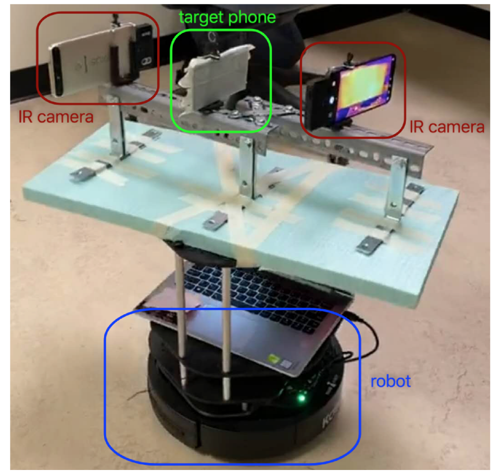

Fig. 1: Our experimental platform consists of one target smartphone, two infrared cameras, and one robot.

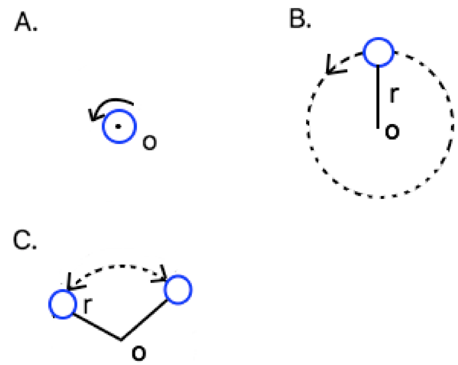

Fig. 2: We configured the robot to move in three patterns during our experiments to emulate human behaviors in VR/AR applications.

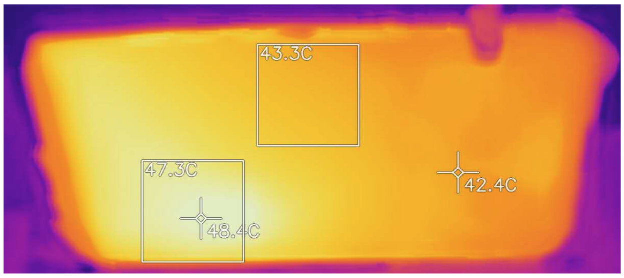

Fig. 3: A thermal image of the smartphone's front surface

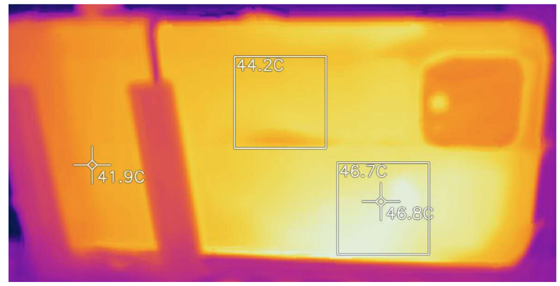

Fig. 4: A thermal image of the smartphone's back surface

2160s resolution [4] and a popular AR game, Minecraft Earth [5]. 360° video streaming provides immersive experience to a user where she can change her viewport by moving the device. For 360° VR video streaming, we used the rotate pattern in Figure 2.A to simulate user movements. For Minecraft Earth, we used the head shake pattern in Figure 2.C. Both applications require considerable data transmissions over the Internet and computations on the device. In addition, the data and computation requirements may change considerably over time depending on several factors inherent in VR/AR, such as the movements and real-world surroundings of users. In each experimental run, we execute one of the two applications on the smartphone for 20 minutes.

3) Measurement schemes: We run a separate lightweight application together with the VR or AR application on the target phone to collect system statistics, such as the CPU/GPU frequency, utilization, and temperature measurements. There are different approaches to develop a statistics collection application. One approach is to register broadcast receivers through the Android API. Although this approach is easy to implement, the update rate is low, typically one measurement every 5 seconds. Moreover, not all statistics necessary for thermal measurement and analysis can be retrieved using this approach. Instead, we take an alternative approach: we collect statistics directly from the Android system files used to monitor the hardware modules in the target smartphones. Using this approach, we analyze a much more comprehensive set of data summarized in Table II every 1 second.

In addition, we read the surface temperature of the smartphone using infrared cameras. As shown in Figures 3 and 4, the two IR cameras in Figure 1 take thermal images of the front and back surfaces of the phone every 5 seconds, respectively. (As the surface temperature of smartphone changes relatively slowly, the shooting rate is acceptable.) Our measurement application retrieves the surface temperature data produced by the infrared cameras for analysis.

The average room temperature of our laboratory where the experiments were performed was 25.8°C with negligibly small fluctuations.

IV. Temperature Measurement and Analysis

In this section, we measure and analyze the thermal characteristics of smartphones for the VR and AR applications

Feature name	Description
time	timestamp for each record
bat_voltage*	battery voltage (mV)
bat_current*	battery current (mA)
bat_power*	battery power (mW)
bat_capacity*	battery level (%)
bat_temp*	battery temperature (°C)
wifi_tx*	WiFi chip upload rate (KB/s)
wifi_rx*	WiFi chip download rate (KB/s)
f_cpu0 - 7*	CPU frequency, 8 cores (Hz)
cpu_user*	Time spent in user mode (ms)
cpu_nice	Time spent in low priority user mode(ms)
cpu_system	Time spent in system mode (ms)
cpu_idle*	Time spent in the idle task (ms)
cpu_iowait	Time waiting for I/O to complete (ms)
cpu_irq	Time servicing interrupts (ms)
cpu_softirq	Time servicing softirqs (ms)
cpu_temp0 - 7	CPU temperature, 8 cores (°C)
wifi_temp*	WiFi chip temperature (°C)
pm8150_temp*	Power management IC temperature (°C)
pa_therm*	Power amplifier temperature (°C)
xo_therm*	Temperature relates to oscillator (°C)
camera_temp	camera module temperature (°C)
mdm_core_temp	Mobile Data Modern temperature (°C)
charger_temp	Charger IC temperature (°C)
gpu_usage*	GPU usage (%)
gpu_temperature*	GPU temperature (°C)
gpu_frequency*	GPU frequency (Hz)
thread_number*	total number of thread
MemFree*	Free size of memory
MemAvailable*	Available size of memory

TABLE II: Features collected from the target smartphone include system statistics and device sensor data.

discussed in the previous section. Due to space limitations, we present the most important results only.

A. Temperature Measurements and Predictions for VR

1) Temperature Measurements: In Figure 5, the battery power consumption is well below the 5W TDP in Table I and varies around 2W for most of the time, slightly exceeding 4W only once. We have observed that the VR application consumes less than 8% of the battery in 20 minutes. The current is below 1A, and the voltage of the battery ranges between 4.1–4.6V. Thus, we observe that general energy management is acceptable for the tested VR application. The surface temperature of the smartphone shown in Figure 5, however, approaches near 39°C, possibly leading to thermal sensation or discomfort. The battery temperature shown in Figure 5 ranges between 34–36°C. This indicates that the bat-

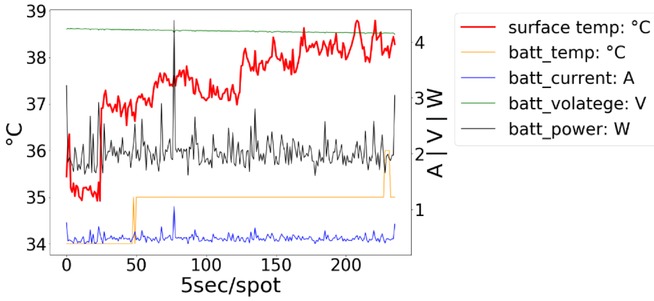

Fig. 5: VR: Surface temperature vs. battery temperature and power consumption

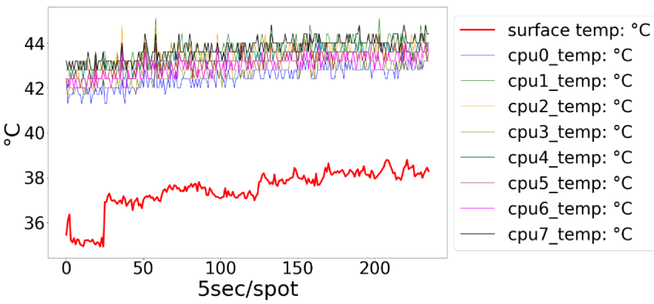

Fig. 6: VR: Surface temperature vs. CPU temperature

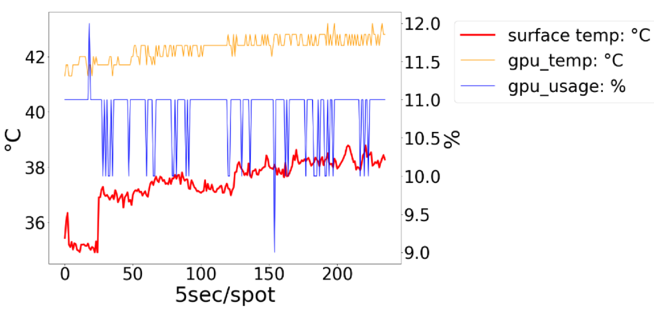

Fig. 7: VR: Surface temperature vs. GPU temperature and utilization

tery temperature does not solely determine the smartphone's surface temperature. Thus, we also analyze other components in the smartphone as follows.

Figure 6 shows that the CPU temperature ranges between 41–45°C. We have observed that the corresponding CPU core utilization ranges between 3-50%. The temperature of the CPU and surface, generally keeps increasing in Figure 6 despite continuous dynamic frequency scaling between 0.6–1.8GHz for thermal control (and power management).

Similarly, the GPU temperature exceeds 42°C and keeps increasing as shown in Figure 7, although the GPU utilization ranges only between 9–12% and dynamic frequency scaling is performed continuously between 0.245–0.27GHz. Figure 8 shows that the WiFi module temperature increases as well, exceeding 42°C at the end.

2) Smartphone Surface Temperature Predictions via Linear Regression: We have found that it is possible to accurately

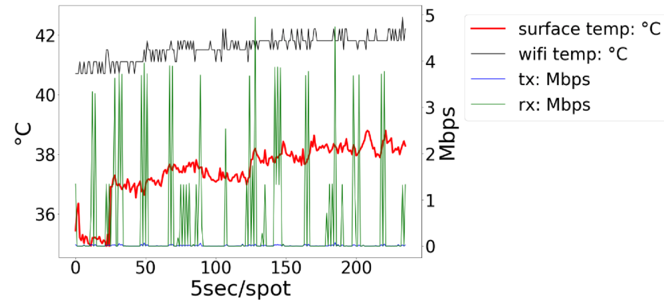

Fig. 8: VR: Surface temperature vs. WiFi

predict the phone surface temperature via linear regression using the *features available in the Android phones without requiring any external thermometer*. To construct a dataset for temperature predictions, we have placed the Google Pixel 4 smartphone on the robot that rotates as depicted in Figure 2.A to simulate a user's head movements while watching a 360° YouTube video streamed to the smartphone in VR mode. In addition, we have used FLIR infrared cameras to record thermal images of the devices during the 360° VR video streaming as described before. The input features used for surface temperature predictions are marked with "*" in Table II. Specifically, we use the input features collected at $t-1$ seconds to predict the phone surface temperature at t seconds.

To design and train the prediction model, we used the linear regression model from scikit-learn [13]. We split our dataset into two parts: 80% for training and 20% for testing. Infrared images taken every 5 seconds during our measurements serve as the ground truth. Especially, we use the maximum surface temperature extracted from each infrared image. Our thermal temperature prediction achieves a mean absolute error (MAE) of 0.34°C. The corresponding mean squared error (MSE) is 0.16°C, and the root mean squared error (RMSE) is 0.40°C.

B. Temperature Measurements for AR

Figure 9 shows the power consumption of Minecraft Earth. Unlike the VR application, the power consumption significantly exceeds the 5W TDP of Qualcomm Snapdragon 855 (Table I). Initially, the peak power consumption is over 8W, which is 60% above the 5W TDP. The power consumption decreases and ranges between approximately 4–6W from 400 seconds to the end of the experiment (1200 seconds), due to power management and thermal control, such as CPU/GPU frequency scaling. As depicted in the figure, however, the battery temperature keeps increasing: it is initially close to the room temperature (≈ 26°C) but exceeds 46°C at 1200 seconds, because heat, once accumulated, cannot be dissipated quickly in smartphones. In total, about 15% of the energy is consumed for running the AR application for 20 minutes.

The CPU temperature, shown in Figure 10, initially increases over 75°C and drops well below 70°C around 200 seconds partially due to CPU frequency scaling. However, it subsequently increases in a rather consistent fashion, exceeding 70°C at the end of the experiment.

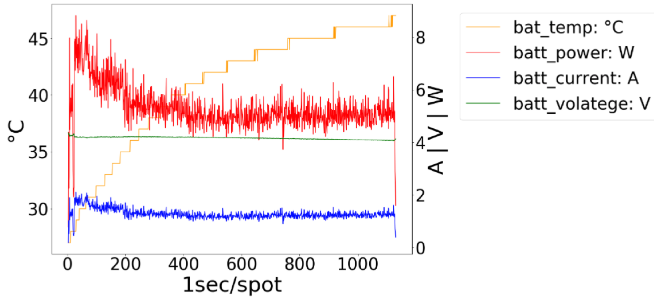

Fig. 9: AR: Battery power consumption and temperature

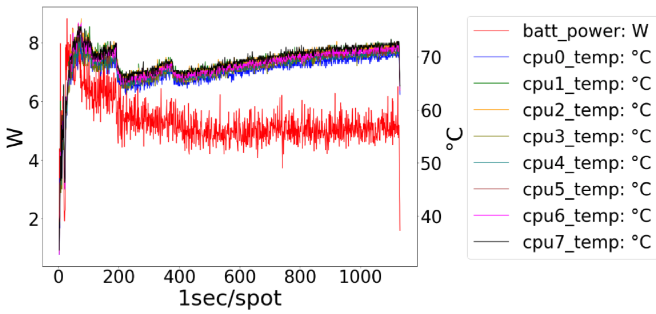

Fig. 10: AR: Power consumption vs. CPU temperature

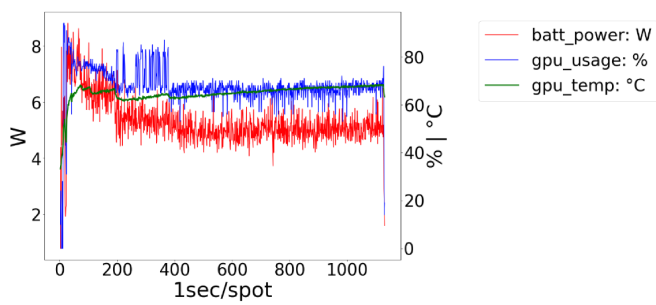

Fig. 11: AR: Power consumption vs. GPU temperature and utilization

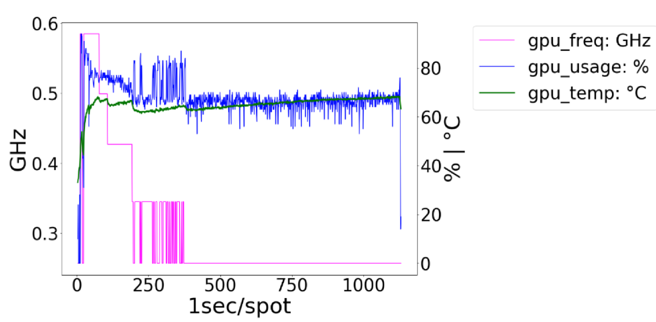

Fig. 12: AR: GPU temperature, frequency, and utilization

Figure 11 shows that the GPU utilization is higher than 60% for most of the time and often reaches or exceeds 80%. Consequently, the GPU temperature is higher than 60°C for most of the time and close to 70°C at the end despite aggressive GPU frequency scaling shown in Figure 12, which can degrade the image/video quality and overall user experience.

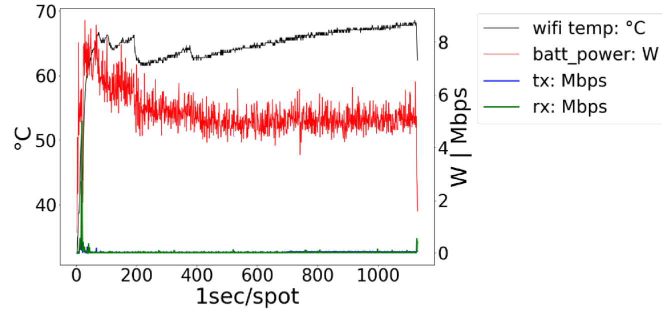

Fig. 13: AR: Power consumption and WiFi chip temperature

Figure 13 shows that the temperature of the WiFi component ranges between 60–70°C with a generally increasing trend, since AR applications often involve significant data streaming in addition to computations.

C. Discussions

In the tested VR application, the CPU, GPU, and WiFi module quickly heat up at the beginning of our experiments due to the heavy workload for video streaming, decoding, rendering, and continuous viewport changes created by the robot. Similarly, the hardware components become hot at the beginning of Minecraft Earth. Also, after running it only for a few seconds, we felt a thermal pain when we touched the camera of the phone due to heavy usage of the camera in the AR application. Notably, initial heat is not dissipated but more heat is accumulated due to the on-going streaming and computational workloads. Physical design constraints of smartphones, e.g., the small and thin form factor, passive cooling, and multiple layers of high-density electronic components, deter quick heat dissipation too. Overall, our results indicate that significantly more effective thermal management is required for AR and VR applications in mobile devices. There are many related research issues for future work including the following ones:

- Further thermal analysis using more VR/AR applications and different smartphones and head mounted displays is necessary.
- A user experience study is necessary in addition to using the robot.
- In-depth research on hardware/software support for more effective thermal management in mobile devices is needed to enhance user experiences in VR/AR applications sensitive to performance and thermal characteristics.

V. Related Work

Thermal management on mobile devices has previously been investigated. Xie et al. [14] propose a thermal simulator for mobile devices. Bhat et al. [15] propose a predictive dynamic thermal and power management scheme for throttling the frequency and number of cores used in the system. Focusing on the mobile device's thermal temperature, Egilmez et al. [16] developed a user-specific skin temperature-aware DVFS scheme. Park et al. [17] propose an app-oriented scheme to throttle background applications based on their contributions to heat generation. Researchers have also measured the thermal behavior of smart glasses. For example, the temperature of a Google Glass can rise to as high as 51.9°C by running a video chat application.

A work closely related to ours is [3] that measures the temperature of various smartphones running a variety of applications including video chatting, gaming, and video recording. They showed that certain applications can cause smartphones to overheat and cause a thermal pain. They also propose a smartphone surface thermal temperature prediction model using system-collected CPU usage statistics, CPU temperature, battery temperature, and data transmission and reception rates as inputs. However, the GPU, a very important component extensively used for view rendering in VR, AR, video, and gaming applications, was not considered in their model. Comparing to their work, we focus our study on emerging VR and AR applications on a new generation of smartphones. Our thermal temperature prediction model considers the device's GPU usage information as well as a comprehensive set of data collected from a number of temperature sensors available on Android smartphones. We achieve more accurate temperature predictions: our RMSE (the only accuracy metric used in [3]) is much smaller than that of [3].

Another line of research related to thermal control is mobile power consumption optimization. EVR [18] leverages semantic-aware streaming and hardware-accelerated rendering for energy saving. Sun et al. [19] propose a new 360° rendering algorithm with a co-designed hardware architecture. Strix [20] aims to minimize the display power consumption in VR applications via dynamic brightness scaling. MARLIN [21] leverages tracking to reduce the energy consumption for object detection via deep learning in AR applications. In addition, MARVEL [22] combines local tracking with selective cloud offloading for AR with low energy consumption.

VI. Conclusions and Future Work

An important factor that affects user experiences in VR/AR is the thermal characteristics of smartphones that serve as a basic platform for AR/VR applications. However, a systematic thermal analysis of smartphones for VR or AR application is relatively scarce. To address the issue, in this paper, we build a temperature measurement and analysis framework for VR/AR applications using a robot, infrared cameras, and smartphones. Using the framework, we have analyzed the thermal characteristics of two popular VR/AR applications. After streaming a 360° VR video from YouTube for 20 minutes, the smartphone surface temperature increases close to 39°C. In the tested AR game, the battery power consumption frequently exceeds the thermal design power by 20–80%. The peak temperature of the battery, CPU, GPU, and WiFi component exceeds 45, 70, 70, 65 °C, respectively. In our experiments, the smartphones overheat quickly at the beginning, and the thermal temperature generally keeps increasing despite aggressive dynamic CPU/GPU frequency scaling performed by the underlying OS and hardware. Overall, research on thermal analysis and management for emerging VR/AR applications is in an early stage with many open issues as outlined in §IV.

References

[1] L. Hagander, H. Midani, M. Kuskowski, and G. Parry, "Quantitative sensory testing: Effect of site and skin temperature on thermal thresholds," *Clinical Neurophysiology*, vol. 111, pp. 17–22, 02 2000.

[2] J. C. Lawrence and J. P. Bull, "Thermal conditions which cause skin burns," *Engineering in Medicine*, vol. 5, no. 3, pp. 61–63, 1976.

[3] S. Kang, H. Choi, S. Park, C. Park, J. Lee, U. Lee, and S.-J. Lee, "Fire in your hands: Understanding thermal behavior of smartphones," in *MobiCom*, 2019.

[4] Sound of the Sea, 1 Hour (Ocean Noises) - VR 360 Video. [Online]. Available: https://www.youtube.com/watch?v=S0lPLXp_i08

[5] Minecraft Earth. [Online]. Available: https://www.minecraft.net/

[6] Pixel xl overheating issue? [Online]. Available: https://forum.xda-developers.com/pixel-xl/help/pixel-xl-overheating-issue-t3621246/page4

[7] Google pixel won't stay on and keeps overheating [troubleshooting guide]. [Online]. Available: https://thedroidguy.com/google-pixel-wont-stay-keeps-overheating-troubleshooting-guide-1081040

[8] J. Seo and J. Chung, "Thermal aging: A new concept of skin aging," *Journal of Dermatological Science Supplement*, vol. 2, 12 2006.

[9] A.-G. Kibbi and Z. Tannous, "Skin diseases caused by heat and cold," *Clinics in dermatology*, vol. 16, no. 1, pp. 91–98, 1998.

[10] Snapdragon 855 - Qualcomm. [Online]. Available: https://en.wikichip.org/wiki/qualcomm/snapdragon_800/855

[11] Qualcomm Snapdragon 855. [Online]. Available: https://www.notebookcheck.net/Qualcomm-Snapdragon-855-SoC-Benchmarks-and-Specs.375436.0.html

[12] FLIR ONE Gen 3. [Online]. Available: https://www.flir.com/products/flir-one-gen-3/

[13] sklearn.linear_model.linearregression. [Online]. Available: https://scikit-learn.org/stable/modules/generated/sklearn.linear_model.LinearRegression.html

[14] Q. Xie, M. J. Dousti, and M. Pedram, "Therminator: a thermal simulator for smartphones producing accurate chip and skin temperature maps," in *Proceedings of the 2014 international symposium on Low power electronics and design*, 2014, pp. 117–122.

[15] G. Bhat, G. Singla, A. K. Unver, and U. Y. Ogras, "Algorithmic optimization of thermal and power management for heterogeneous mobile platforms," *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, vol. 26, no. 3, pp. 544–557, 2017.

[16] B. Egilmez, G. Memik, S. Ogrenci-Memik, and O. Ergin, "User-specific skin temperature-aware dvfs for smartphones," in *2015 Design, Automation & Test in Europe Conference & Exhibition (DATE)*. IEEE, 2015, pp. 1217–1220.

[17] J. Park, S. Lee, and H. Cha, "App-oriented thermal management of mobile devices," in *Proceedings of the International Symposium on Low Power Electronics and Design*, 2018, pp. 1–6.

[18] Y. Leng, C.-C. Chen, Q. Sun, J. Huang, and Y. Zhu, "Energy-efficient video processing for virtual reality," in *Proceedings of the 46th International Symposium on Computer Architecture*, 2019, pp. 91–103.

[19] Q. Sun, A. Taherin, Y. Siatitse, and Y. Zhu, "Energy-efficient 360-degree video rendering on fpga via algorithm-architecture co-design," in *The 2020 ACM/SIGDA International Symposium on Field-Programmable Gate Arrays*, 2020, pp. 97–103.

[20] Z. Yan, C. Song, F. Lin, and W. Xu, "Exploring eye adaptation in head-mounted display for energy efficient smartphone virtual reality," in *Proceedings of the 19th International Workshop on Mobile Computing Systems & Applications*, 2018, pp. 13–18.

[21] K. Apicharttrisorn, X. Ran, J. Chen, S. V. Krishnamurthy, and A. K. Roy-Chowdhury, "Frugal following: Power thrifty object detection and tracking for mobile augmented reality," in *Proceedings of the 17th Conference on Embedded Networked Sensor Systems*, 2019, pp. 96–109.

[22] K. Chen, T. Li, H.-S. Kim, D. E. Culler, and R. H. Katz, "Marvel: Enabling mobile augmented reality with low energy and low latency," in *Proceedings of the 16th ACM Conference on Embedded Networked Sensor Systems*, 2018, pp. 292–304.

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