Memorial University of Newfoundland

Faculty of Engineering and Applied Science

ENGI 6861: Computer Architecture

Computer Architecture of Wearable Technology

Author:

Matthew Hickey

Term VI Computer Engineering

November 29, 2019

Executive Summary

Wearable technology, which is technology worn on the body that processes information, is a rapidly expanding industry. With thanks to the meteoric improvement in low-footprint, energy-efficient processors, wearables are becoming more powerful, and more attractive to consumers. Two major classes of wearable technology are analyzed throughout this report: smartwatches; and virtual reality headsets.

Smartwatches are wearables worn on the wrist, like a normal watch, and are normally used to record health and fitness data. Two different smartwatches are analyzed for their architectures: the Apple Watch Series 5; and the Garmin Forerunner 235. These two watches employ different architectures, with the Apple Watch being more powerful from a compute power standpoint, and the Forerunner being a much more energy efficient smartwatch.

Virtual reality headsets are wearables that allow the user to be immersed within a virtual environment with a device worn on the head that covers the eyes with displays. The headset takes in user's movement data, and processes this data to update the virtual environment with movements that make the user feel like they are part of that virtual world. The Oculus Quest all-in-one headset was analyzed for its architecture. After inspection, it is shown that the Quest uses the same system on a chip, and storage and memory specifications as the Google Pixel 2 smartphone. This shows that the architecture decisions made for the headset were to mimic those of a smartphone, with the main difference being more intense processing and a shorter battery life.

After analyzing the case studies of the smartwatch and the virtual reality headset, it is clear that the main architecture decision of wearables is the trade-off between performance and power consumption. The exact place where this trade-off is made depends entirely on the final use case of the wearable being designed.

Table of Contents

1 Introduction

Wearables as defined by Technopedia are technologies that are worn on the body that contain various sensors that can record health and fitness information, or take movement input data in real-time [1]. The market for this technology has expanded rapidly in recent years, with the wearable market being worth $19 billion in 2015, and expected to expand to $57 billion by 2022 [2]. This growth rate can be attributed to the fact that it is a novel technology just getting past the early adoption phase, but this technology is also improving at an impressive pace each year. The 2010s have seen advances in lower-powered processors with a smaller footprint that allow wearable devices to become much more powerful. With improvements in small, powerful processors, it allows wearables to have more functionality, and focus less on designing the wearable around the electronics inside [3]. Clearly, this demonstrates the design requirement for low-power and small components to architects of wearable technology.

While there are many types of wearables on the market in present-day 2019, this report will focus on two types of wearable technology: smartwatches, which record movement data for health and fitness purposes; and virtual reality (VR) headsets, which process movement data in real time for providing immersive digital experiences to the user.

2 Smartwatches

2.1 Background

The most popular type of wearable in 2019 is the smartwatch [4]. Smartwatches are devices worn on one's wrist, equipped with sensors, and in some cases wireless communication capability for syncing data to a smartphone. They have rich operating systems (OS), on-board processors and memory, and come in a wide range of varieties from basic to high-end, with different specialized models in between [5].

2.2 Typical Specifications

Modern smartwatches typically have similar components to computers, albeit at a much smaller scale. They have an OS, which is most cases is proprietary to the manufacturer (i.e. watchOS for Apple); a single- or dual-core processor ranging from 80MHz to over 1.2GHz depending on the type of watch; up to a gigabyte of memory; battery life ranging between 18 hours to over a week; and depending on the watch - sensors to measure heart rate, fitness statistics, and atmospheric pressure [5].

It is simple to build a system that can accommodate all the required features of a smartwatch using normal computing components, however the challenge with a smartwatch is weight, size, and power consumption, as it needs to fit comfortably on the wrist, and be able to record data for at least an entire day on a single charge. This means all components must be lightweight, and energy efficient. According to ARM, the most necessary optimizations are using small data memories, using slower clock speeds, and choosing a silicon process technology that will offer the lowest possible power consumption, meaning the biggest design trade-off when designing smartwatches is between performance and power consumption [6]. To examine these trade-offs, two popular smartwatches will be analyzed for the architecture decisions that went into their design and manufacturing.

2.3 Analysis of Examples

Two popular examples of smartwatches are the Apple Watch Series 5, and the Garmin Forerunner 235, both shown below in Figure 1. These devices are priced quite differently, carry different levels of functionality, and are therefore targeted towards different market segments. Shown below in Table 1 are prices for the watches listed above [7] [8].

(a) Apple Watch Series 5 [7]

(b) Garmin Forerunner 235 [8]

Figure 1: Smartwatches discussed in this report.

Table 1: Smartwatch Prices

Watch	Price (CAD)
Apple Watch Series 5	529.00
Garmin Foreruner 235	319.99

Clearly, these watches come at different price points, target different segments of the market, and of course come with different architectures for accommodating the necessary features in each model. This section will cover each of the watches shown above in greater detail.

2.3.1 Apple Watch Series 5

2.3.1.1 Background

The Apple Watch Series 5 is the newest iteration of smartwatch from Apple Inc., released in September 2019. Priced at $529, clearly this is considered a higher-end smartwatch, fitting in with Apple's other product lines (iPhone, iPad, and Mac). This watch weighs between 30-40g depending the case, it has all-day battery life, a touch screen (324x394), voice call, GPS, compass, and music streaming capabilities, as well as the ability to run thousands of apps from the Apple App Store made specifically for the Apple Watch [9]. This device is made for Apple users, as it requires an iPhone to make use of all its features. Its operating system is the Apple-designed watchOS.

Much of what makes the Apple Watch quite appealing is the variety of sensor technology that can track much of your health and fitness data. This sensor technology will be discussed, along with other computer architecture components in this section.

2.3.1.2 Hardware and Functionality

An innovation brought on by the Series 5 is the always-on display, a first for Apple Watch. An always-on display is not ideal for a device wanting low-power consumption, especially a high-resolution screen with a high refresh rate like the one on the Apple Watch. However, this new model incorporates a low temperature poly-silicon and oxide (LTPO) display which reduces the refresh rate of the watch's screen from 60Hz to 1Hz, the minimum frequency for the always-on display to accurately display the time [9]. This is a clever way to reduce power consumption by reducing frame rate when the watch is not being used interactively.

The processor and System in Package (SiP) at the core of the Apple Watch Series 5 is Apple's S5 64-bit chip, shown below in Figure 2. This is the fifth generation of their custom-designed smartwatch chip where the entire system is fabricated into a single component with a footprint of about 40mm. This SiP includes 32GB of storage, the memory, as well some the sensors that come with the Series 5, including its GPS component and magnetometer (compass) [9].

Figure 2: Apple S5 Processor [10]

Due to the novelty of the S5 SiP, its predecessor the S4 will be inspected. The S4 and S5 SiPs are identical except for the S5's addition of the magnetometer and different storage options [11]. The S4 is powered by two 64-bit ARMv8 cores known as Tempest cores, which are Apple-designed energy-efficient (vs. the high-performance Vortex cores) cores that are used in other Apple products such as the iPhone [12]. The maximum clock speed of the Tempest cores is 1587 MHz, and they offer 32kB instruction and data caches, along with a unified 2MB L2 cache [13]. These cores rely on the ARM A64 instruction set, which is a variant of a pipelined RISC architecture, which implement out-of-order execution, making them more efficient than previous generation in-order designs [14]. The S4 SiP also includes a neural engine, which third party developers can take advantage of to run Apple's machine learning framework, CoreML, on the Apple Watch itself [15]. Its custom GPU is able to use Apple's graphics API, Metal, much like Apple's other products from computers to mobile phones, allowing for rich hardware-accelerated graphics content on the Apple Watch [16].

The Series 5 incorporates other sensors whose data is processed. These sensors are an electric heart rate sensor, which constantly monitors heart rate, and can perform an electrocardiogram (ECG/EKG) almost as accurate as a single-lead EKG [17]. Data from this sensor can be monitored and programmed to alert the wearer if there is any abnormal heart activity. The watch also uses its microphone to monitor noise levels, and alerts the user when current noise exposure could pose a risk for long-term hearing damage.

Arguably the most important sensors on a smartwatch with fitness tracking capabilities are the accelerometer, which actually tracks the motion patterns of the watch itself based on acceleration forces [18], and the gyroscope. Data from GPS, accelerometer, gyroscope, heart rate monitor, and your own personal health data (height, weight, age) are used together to give you valuable insights into your workouts. The Series 5 comes with pre-programmed sports like cycling, running, swimming, and yoga, amongst others. In running activities, the watch tracks and can display your calories burnt, your pace, your heart rate, your distance, cadence, and elapsed time [19]. Having this data displayed in real time on your wrist, and available for analysis after the run is something that makes this device so valuable, as it helps people stay motivated and quantitatively monitor their improvements.

2.3.1.3 Apple Watch Summary

After analyzing the price-point, features, and specifications of the Apple Watch Series 5, it is clear this is a high-end wearable device that values performance highly for a wearable device. It has a battery that needs to be recharged each night, and while it carries valuable stats for many different workouts, this app is targeted at individuals who want to exercise to remain healthy, and not so much professional athletes or athletes who need high-performance functionality for hours at a time (ultra-marathoners and Iron-man Triathletes), as the battery would exhaust itself before the workout finishes, as using all sensors (especially GPS) for extended periods depletes battery life rapidly

[20]. Therefore, this wearable device's main purpose is to allow for smartphone-like functionality on your wrist. This design for smartphone-like functionality is echoed when analyzing its hardware, as the Apple Watch uses the same energy-efficient CPU cores as iPhones.

2.3.2 Garmin Forerunner 235

2.3.2.1 Background

If its name wasn't obvious enough, the Garmin Forerunner 235 is first and foremost a runner's watch. It weighs 42g, and has a slightly larger footprint than the Apple Watch, fitting in a 45mm square. It costs $319.99, which is significantly less expensive than the Apple Watch Series 5. Battery life using it without GPS functionality is 9 days, whereas one charge gives 11 hours of GPS usage. The display (215x180) is not touch screen, navigation is done with buttons on the side. It can connect and sync data to a smartphone, but it can also be used independent of any other device. The sensors in this device include GPS, heart rate monitor, and an accelerometer [8]. It run's Garmin's own proprietary smartwatch OS [21].

What makes the Forerunner appealing is the trade-offs it makes in comparison with the Apple Watch for specializing the device to be a pure running wearable. These specializations and optimizations will be discussed in this section.

2.3.2.2 Hardware and Functionality

Please note due to the lack of resources about the Forerunner 235's internal hardware, the information provided here is for the Forerunner 230, which is the same as the 235 but with the absence of a heart rate monitor [22].

According to Rich Nass' teardown of the Garmin Forerunner 230, the core microprocessor is the Atmel Smart SAMG53 (ATSAMG53), as shown below in Figure 3 [23].

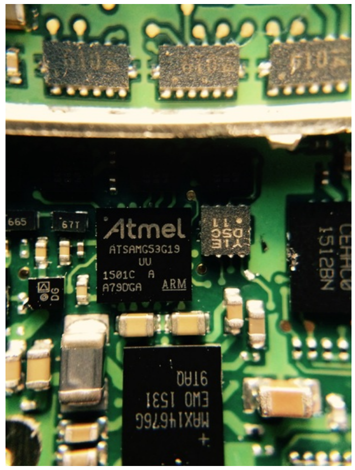

Figure 3: The Atmel microprocessor at the core of the Forerunner [23].

The ATSAMG53 chip is built with the ARM Cortex-M4 core with a three-stage pipeline, with 96kB of SRAM on the instruction/data (I/D) bus (for I/D cache), up to 512kB of embedded Flash memory, includes a floating point unit (FPU), and a maximum CPU speed of 48 MHz [24].

Like the Apple Watch, the Forerunner comes pre-loaded with activities, but is primarily focused on running and cycling [8]. It takes many of the same running metrics as the Apple Watch, like cadence, pace, heart rate, and distance, as shown in Figure 4. However, the Forerunner can do so for longer periods due to a lower power consumption. An interesting feature built into the Forerunner is the ability to load "courses" onto the watch and have the GPS guide you through turn-by-turn [25]. The Apple Watch does not offer this without downloading a third-party application, which likely uses more power than built-in functionality.

Figure 4: Mid-run display on Forerunner displaying distance, time, and current pace.

2.3.2.3 Garmin Forerunner 235 Summary

It is clear that the Garmin Forerunner does not attempt to be the ”smartphone on your wrist” that the Apple Watch offers. The Forerunner is a 32-bit, energy efficient wearable that is specialized for tracking running activities. It is not meant for people who want lots of functionality in their smartwatch, but for people looking for a reliable, efficient watch they can use for their fitness tracking and not have to charge every single day. Therefore, the Garmin Forerunner 235 is an example of how power consumption is prioritized over performance in the power-performance trade-off of wearables, as functionality is optimized to only have the necessities.

2.4 Smartwatch Summary

Comparing as contrasting the Apple Watch Series 5 and Garmin Forerunner 235 is an insightful case study for different varieties of smartwatches. The Apple Watch offers functionality and compute power that can normally only be found on smartphones, such as rich graphics and a 64-bit architecture, while the Forerunner offers less in terms of rich graphics rendering, and employs a 32-bit architecture. This illustrates different trade-offs between performance and power consumption between the two wearables, and shows how regardless of the type of wearable, the footprint of the hardware, and power consumption are the two most important design criteria and constraints.

3 Virtual Reality

3.1 Background

Virtual Reality (VR) technology is an area of wearables that have been on the rise as computer hardware capabilities improve. The Virtual Reality Society defines VR as a 3D environment generated by a computer that a person can interact with, and be immersed in such a way that the person can manipulate and interact with the environment much like they would in *actual* reality [26]. High-quality technology and intelligent architectures are required to realize VR due to the compute-intensive task of processing many inputs and rendering a virtual world/environment in real time, and depending on the level of detail (LoD), is an intensive task on its own [27]. Therefore, it is necessary to make intelligent architecture design decisions to ensure the VR wearable operates as intended, and with the correct performance specifications.

The most common type of VR wearable is the VR headset, and example is shown below in Figure 5. As illustrated, the headset is worn on the head (making it a wearable), and its screen takes up the user's entire field of view - thereby immersing them in a virtual environment. Some headsets include audio capabilities and movement sensors, but this will be discussed later in this section.

Figure 5: Example of a typical VR headset [28]

3.2 Typical Use Cases

Due to the immersive and potentially high-fidelity rendering that VR can accomplish, there are several key applications where this technology can be applied. For example, VR has the potential for entertainment, business, and medical applications.

3.2.1 Entertainment

For entertainment applications, VR has the potential to revolutionize video games. VR offers the ultimate level of immersion, and allows players to feel as if they are a part of the world in which they are playing, as shown below in Figure 6. Different VR technologies offer additional peripherals, which can include treadmill-like surfaces to track players' movements in-game without a controller, and controllers shaped like gloves that offer haptic feedback when players interact with objects in-game, thereby taking away elements that limit the immersion of video games [29].

Figure 6: Playing a video game in VR [30]

3.2.2 Business

For business applications, VR can be used for modelling buildings before they break ground, but also for completing expensive and dangerous training exercises at a lower cost, and with zero risk - like ExxonMobil has started doing recently. Exxon's VR simulator is quite advanced, letting users manipulate the virtual world by tracking their head, arm, and leg movements to allow them to complete virtual practice work on a model of one of Exxon's real assets [31]. An example of Exxon's setup is shown in Figure 7. This allows extensive training to be completed with zero consequence of failure and without having the need to actually send trainees to the platform.

Figure 7: An ExxonMobil employee trains using VR [31]

3.2.3 Medical

For medical applications, VR can be used as both a training tool (shown in Figure 8), and can allow the opportunity for telepresence surgery, where a surgeon can operate on a patient through virtual reality from a remote site, while complex machines follow the surgeon's actions with acute precision [32]. This will allow for doctors to receive life-like training without having patients going under the knife, and will allow patients requiring surgery in remote locations to have specialized surgery without the presence of a specialized surgeon.

Figure 8: A surgeon trains using VR [33]

3.3 Analysis of a Standalone Headset: Oculus Quest

A standalone VR headset means that the VR headset is capable of storing games and content on the device itself, and does all of its own processing without being connected to a computer [34]. The Oculus Quest, one of the most popular standalone VR headsets is shown below in Figure 9, along with its controllers. This headset has a retail value of $549.00 CAD [35].

Figure 9: Oculus Quest VR Headset [36]

Games and content are loaded onto the device via a mobile phone app, and the headset can then be used anywhere to experience VR gameplay [37]. This device is meant for consumers who want to experience VR gaming, but do not already have an expensive gaming computer, or do not want to make that large investment.

3.3.1 Hardware and Functionality

The Oculus Quest runs on the Qualcomm Snapdragon 835 mobile system on chip (SoC) [38]. This SoC is responsible for all processing and wireless connectivity on the headset. Some of the technical specifications of the Snapdragon 835 are shown below in Table 2. In addition to the specifications listed in Table 2, the Snapdragon 835 has hardware and sensors to support cellular, Wi-Fi, Bluetooth, Near Field Communication (NFC), and location services [39]. The Snapdragon 835 is designed to offer powerful graphics processing power in a low-power and low-footprint design, making it an appropriate choice for a standalone VR headset.

Table 2: Snapdragon 835 Technical Specifications

Hardware	Specification
CPU	8-core Qualcomm Kryo 280
CPU Clock Speed	Up to 2.45 GHz
CPU Architecture	64-bit
GPU	Qualcomm Adreno 540
Memory Speed	1866 MHz
Memory Type	LPDDR4x Dual-Channel

The Kryo 280 CPU implements the ARMv8-A 64-bit pipelined instruction set architecture [40]. It has eight cores, four of which can run up to the maximum of 2.45 GHz and have a 2MB L2 cache, while the four slower cores have a 1MB L2 cache, and the L1 caches are 64kB + 64kB [41]. The Adreno 540 GPU supports all of the most common graphics APIs, such as OpenGL, Vulkan, OpenCL, and DirectX 12, allowing a wide support set for the visuals it can render [39]. The Snapdragon 835 chip offers all of this functionality in a low-power, low-footprint design. In Figure 10 the SoC is pictured next to an American penny for scale.

The sensors onboard the Quest allow for six degrees of freedom (6DOF) in both the headset and its controllers. This means that accurate tracking is provided for all three

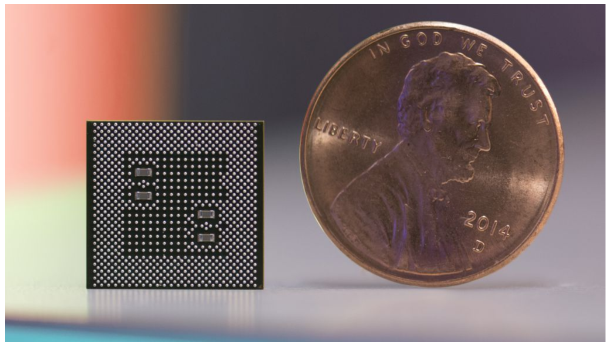

Figure 10: Snapdragon 835 footprint compared to a penny [42]

dimensions, and orientation along those axes [43]. The 6DOF tracking allows the player's inputs to be as accurate as possible in the virtual world. The model of the Quest listed above for $549 CAD comes with 64GB of internal storage, and 4GB of memory [44]. The Snapdragon 835 SoC and these memory specifications are very similar to that of a mobile phone. In fact, the Google Pixel 2 smartphone uses the Snapdragon 835 chip, and comes with the same storage and memory specifications [45]. The only difference is the Quest is specialized to be a powerful graphics processing machine, while the Pixel 2 is meant to be a more general-purpose device, being a smartphone.

3.3.2 Oculus Quest Summary

Given the fact that the Oculus Quest is a standalone VR headset, and it contains near identical specifications to a smartphone, it is appropriately priced close to smartphone prices. This price allows the headset to be a good choice for an entry-level headset for consumers that want to experience VR without the large up-front cost of a high-performance computer being a barrier to entry. Obviously, the VR experience will not be as clean on the Oculus Quest when compared to VR headsets that connect to a computer (such as the Oculus Rift S), because processing and rendering power of a desktop computer compared to that of smartphones is enormous, but this is why the Quest is meant for entry-level consumers without these powerful computers.

4 Conclusion

This report has offered an overview of two distinct types of wearables, smartwatches and virtual reality headsets. These two wearable families cover two different purposes for wearable technology: data collection from your body's movement and health statistics; and using data collected by monitoring movement, processing it in real time to provide the user with an immersive virtual experience.

Analysis of the Apple Watch and Garmin Forerunner, which were released in a similar time period, show that choice for computer architecture design is impacted by the desired use case for that product. The Apple Watch has impressive hardware, and offers a rich user experience with a faster clock speed, and a 64-bit architecture versus the Forerunner's slower clock speed and 32-bit architecture. In fact, the maximum clock speed of the Apple Watch's processor is over 33 times faster than the maximum clock speed of the Forerunner, illustrating the performance difference between these two devices. Despite the Apple Watch's superior performance, the Forerunner's battery lasts about 9 times longer than the Apple Watch battery (ignoring GPS usage on both devices). This shows how Apple chose a performance-focused architecture, while Garmin chose an efficiency-focused architecture, which target users with different needs.

The Oculus Quest is a wearable, just like both smartwatches analyzed in this report, however instead of being used as a device worn at all times to monitor health and fitness statistics, it is a device worn when the user wants to experience virtual reality. This wearable tracks user's movements and uses them as inputs to update the virtual environment that the user is currently experiencing. The Oculus Quest, being an all-in-one, or standalone headset needs to have a well-designed architecture to offer powerful graphics rendering after taking inputs from the user's movements, all while being as efficient as possible due to the device running on battery power. Therefore, the architecture reflects a device that must possess powerful processing ability, but must be efficient on battery power - a smartphone. The SoC and storage/memory specification used in the Oculus Quest are identical to those used in the Google Pixel 2 smartphone. The main difference is the Oculus Quest is executing more compute-heavy tasks, so its battery life is shorter than that of the Pixel 2.

As was shown through case studies of various wearable devices, wearable architectures must make trade-offs between performance and power, and how much an architecture leans one way or the other depends on the use case for the device employing that architecture.

References

[1] Technopedia, “Wearable device.” https://www.techopedia.com/definition/31206/wearable-device.

[2] K. Mamtani, “Wearable technology market by device global opportunity analysis and industry forecast, 2014-2022,” April 2017.

[3] L. Avila and M. Bailey, “The wearable revolution,” *IEEE Computer Graphics and Applications*, vol. 35, Mar.-Apr. 2015.

[4] J. Peckham, “Best smartwatch 2019: the top wearables you can buy today.” https://www.techradar.com/news/wearables/best-smart-watches-what-s-the-best-wearable-tech-for-you-1154074, October 2019.

[5] J. Bempong, “Smartwatch architecture.” http://meseec.ce.rit.edu/551-projects/spring2016/1-2.pdf, 2016.

[6] D. Maidment, “Advanced architectures and technologies for the development of wearable devies,” tech. rep., ARM, August 2014.

[7] Apple, “Apple watch series 5.” https://www.apple.com/ca/shop/buy-watch/apple-watch.

[8] Garmin, “Garmin forerunner 235.” https://buy.garmin.com/en-CA/CA/p/529988.

[9] Apple, “Apple watch series 5 design.” https://www.apple.com/ca/apple-watch-series-5/design/, September 2019.

[10] A. Guyot, “Apple watch s5 chip.” https://www.macstories.net/news/apple-watch-series-5-the-macstories-overview/, September 2019.

[11] MacDailyNews, “S5 chip powering apple watch series 5 is identical to s4 in apple watch series 4.” https://macdailynews.com/2019/09/18/s5-chip-powering-apple-watch-series-5-is-identical-to-s4-in-apple-watch-series-4/, September 2019.

[12] wintercharm, “Cores in apple s4 sip.” https://news.ycombinator.com/item?id=18152415, October 2018.

[13] A. Frumusanu, “The a12 tempest cpu uarch: A fierce small core.” https://www.anandtech.com/show/13392/the-iphone-xs-xs-max-review-unveiling-the-silicon-secrets/5, October 2018.

[14] ARM, “Cortex-a32.” https://developer.arm.com/ip-products/processors/cortex-a/cortex-a32.

[15] A. Inc., “Get ready for watchos 6.” https://developer.apple.com/watchos/.

[16] S. Troughton-Smith, “S4 60fps physically-based metal rendering.” https://twitter.com/stroughtonsmith/status/1047188165369495552, October 2018.

[17] Apple, “Apple watch series 5 health.” https://www.apple.com/ca/apple-watch-series-5/health/, September 2019.

[18] R. Goodrich, “Accelerometers: What they are and how they work.” https://www.livescience.com/40102-accelerometers.html, October 2013.

[19] Apple, “Apple watch series 5 fitness.” https://www.apple.com/ca/apple-watch-series-5/workout/, September 2019.

[20] Apple, “Apple watch battery.” https://www.apple.com/ca/watch/battery/.

[21] S. Specifications, “Garmin forerunner 235 specifications.” https://www.smartwatchspecifications.com/Device/garmin-forerunner-235/.

[22] W. Irvin, “Garmin forerunner 230 vs. 235: Comparison and verdict.” https://reviewposition.com/fitness-wearables/garmin-forerunner-230-vs-235/, August 27 2018.

[23] R. Nass, “Tear down: Garmin forerunner 230 gps running watch.” https://www.embedded-computing.com/embedded-computing-design/tear-down-garmin-forerunner-230-gps-running-watch, March 2016.

[24] M. T. inc., “Atsamg53.” https://www.microchip.com/wwwproducts/en/ATSAMG53.

[25] Garmin, “Creating a course using garmin connect web.” https://support.garmin.com/en-CA/?faq=tWx3JQyjlU474jqa91EJs8.

[26] V. R. Society, “What is virtual reality?.” https://www.vrs.org.uk/virtual-reality/what-is-virtual-reality.html.

[27] M. Hickey, “Real time ray tracing,” September 2019.

[28] Amazon, “Oculus rift windows pc headset.” https://www.amazon.ca/Oculus-Rift-Windows-VR-Headset/dp/B00VF0IXEY.

[29] L. Brown, “Top 10 popular virtual reality peripherals.” https://filmora.wondershare.com/virtual-reality/top-10-popular-virtual-reality-peripherals.html, November 2017.

[30] S. Dent, “’beat saber’ players were so fast that they broke steam vr.” https://www.engadget.com/2019/02/12/beat-saber-players-too-fast-for-steam-

vr/, February 2019.

[31] ExxonMobil, “Safety training gets a dose of virtual reality.” https://energyfactor.exxonmobil.com/science-technology/digital-garage-safety-training/, April 2019.

[32] R. M. Satava, “Emerging medical applications of virtual reality: A surgeon’s perspective,” *Artificial Intelligence in Medicine*, vol. 6, pp. 281–288, August 1994.

[33] A. Virtual, “Virtual reality medical and healthcare training.” https://archvirtual.com/virtual-reality-medical/.

[34] A. Hart, “Best standalone vr headsets in 2019: Black friday 2019 - deals and buyer’s guide.” https://www.androidcentral.com/best-standalone-vr-headsets, November 2019.

[35] Oculus, “Oculus quest.” https://www.oculus.com/quest/.

[36] “Oculus quest headset.” https://www.bestbuy.com/site/oculus-quest-all-in-one-vr-gaming-headset-64gb-black/6342914.p?skuId=6342914.

[37] Oculus, “Oculus quest features.” https://www.oculus.com/quest/features/.

[38] O. VR, “Introducing oculus quest, our first 6dof all-in-one vr system.” https://developer.oculus.com/blog/introducing-oculus-quest-our-first-6dof-all-in-one-vr-system/, September 2018.

[39] Q. T. Inc, “Snapdragon 835 mobile platform.” https://www.qualcomm.com/products/snapdragon-835-mobile-platform.

[40] R. Triggs, “Qualcomm’s kyro 280 and ’built on arm cortex tehnology’ explained.” https://www.androidauthority.com/kryo-280-and-semi-custom-arm-cpu-cores-740584/, January 2017.

[41] H. Hagedoorn, “Snapdragon 835 has kryo 280 cores at 2.45ghz max.” https://www.guru3d.com/news-story/snapdragon-835-has-kryo-280-cores-at-2-45ghz-max.html, January 2017.

[42] J. Peckham, “Snapdragon 835: 4 things it will bring to your next flagship android phone.” https://www.techradar.com/news/snapdragon-835-4-things-it-will-bring-to-your-next-flagship-android-phone, March 2017.

[43] Technopedia, “Six degrees of freedom (6dof).” https://www.techopedia.com/definition/12702/six-degrees-of-freedom-6dof.

[44] P. L. Austin, “Review: The oculus quest is virtual reality’s best bet yet.” https://time.com/5584275/oculus-quest-review/, May 2019.

[45] B. Kuchera, “The best part of the oculus quest: It makes the hard stuff look easy.” https://time.com/5584275/oculus-quest-review/, April 2019.