Amulet: an open-source wrist-worn platform for mHealth research and education

David Kotz Department of Computer Science Dartmouth College Hanover, NH, USA

Abstract—The advent of mobile and wearable computing technology has opened up tremendous opportunities for health and wellness applications. It is increasingly possible for individuals to wear devices that can sense their physiology or health-related behaviors, collecting valuable data in support of diagnosis, treatment, public health, or other applications. From a researcher's point of view, the commercial availability of these "mHealth" devices has made it feasible to conduct scientific studies of health conditions and to explore health-related interventions. It remains difficult, however, to conduct systems work or other experimental research involving the hardware, software, security, and networking aspects of mobile and wearable technology. In this paper we describe the Amulet platform, an open-hardware, open-software wrist-worn computing device designed specifically for mHealth applications. Our position is that the Amulet is an inexpensive platform for research and education, and we encourage the mHealth community to explore its potential.

Index Terms—mHealth, wearable computing, mobile computing, health, research, education

I. INTRODUCTION

In the decade since the NetHealth workshop was first founded, the field of mobile health (mHealth) has exploded – with research exploring topics from sensor technology to data analytics, and from patient monitoring to behavioral intervention. Disciplines from computer engineering to computer science, from medical informatics to health economics, from behavioral health to mental health, have explored the scientific foundations of the field. Applications for mHealth include individual wellness, remote patient monitoring, behavioral intervention, clinical information management, elder care, athletic competition, public health, rural healthcare, and more.

Indeed, mHealth technology now makes it possible for individuals to wear devices that can sense their physiology or health-related behaviors, collecting valuable data in support of diagnosis, treatment, research, or public health. Other devices and apps enable health management or intervention, often through motivational technology that provide the user justin-time feedback or encouragement.

From a researcher's point of view, the commercial availability of these "mHealth" devices has made it more feasible to conduct scientific studies of health conditions and to explore health-related interventions. It remains difficult, however, to conduct systems work or other experimental research involving the hardware, software, security, and networking aspects of mobile and wearable technology. In this paper we describe



Fig. 1: Amulet, with wristband

the **Amulet** platform (Figure 1), an open-hardware, opensoftware wrist-worn computing device designed specifically for mHealth research [1], [2]. The purpose of this paper is to present the Amulet to the broader research community, to encourage others to explore its potential as an inexpensive platform for research and education.

II. THE AMULET PLATFORM

We developed the Amulet as a platform for experimental mHealth research, with several fundamental goals: first, that it be an open-source design, available to all researchers; second, that it be ultra-low-power, recognizing that mHealth applications need to run reliably for days or weeks between charges; and third, that it be secure by design, recognizing the need for data confidentiality and integrity in sensitive healthrelated applications.

In the process, we developed a custom printed-circuit board (PCB), custom 3d-printed case, custom operating system, custom compiler, custom run-time system, custom developer tools, and a selection of custom applications. By developing this platform from the ground up, we were able to design the system for secure, ultra-low-power operation; indeed, in some configurations, an Amulet can run for weeks without recharging. We describe the hardware and software, including the development tools, in a 2016 SenSys paper [3]. Since that time we have refined the design, improving the user interface, the operating system, and the underlying hardware, adding new

capabilities and increasing energy efficiency. The latest model, known as "Kite.d", is shown in Figures 1 and 2 and is available from GitHub: https://github.com/AmuletGroup/amulet-project.

The Amulet is a wrist-worn computational platform, somewhat like a smart-watch (with the ability to run multiple thirdparty apps) and somewhat like a fitness band (with extremely long battery life). Amulet's hardware includes a generalpurpose low-power microcontroller (the MSP430) for running apps, a simple microcontroller (M0) for Bluetooth BLE connectivity, an accelerometer and gyroscope, two light sensors, two buttons, three capacitive-touch sensors, a temperature sensor, a microphone, and a microSD card for data logging. We built the Amulet-OS operating system to run multiple applications, produced by independent developers, with strong memory isolation through language limitations (a subset of C known as Amulet-C), compile-time restrictions and instrumentation, and clever use of the "memory protection unit" (MPU) in the MSP430 [3], [4]. Amulet-OS provides an API for application developers to access sensors, the user interface, the SD storage and the network. The developer toolkit includes a graphical tool called ARP-View that helps developers predict Amulet battery lifetimes and understand how their decisions affect those lifetimes. A complete overview of the platform can be found in two recent papers [3], [4].

III. AMULET-BASED RESEARCH

The Amulet has already been used for several research projects, and has the potential to be used for much more. Here, we summarize some of that research.

a) Stress detection: Stress is the root cause of many diseases. The ability to monitor when and why a person is stressed could provide feedback for personal stress management, and form the foundation for stress-reduction interventions. We developed StressAware, an Amulet application to measure the stress levels of individuals continuously and in real time [5], [6]. The app implements a stress-detection model, continuously streams heart-rate data over BLE from a commercial heart-rate monitor (such as a Zephyr or Polar H7 chest strap), classifies the wearer's stress level, logs the stress level on the microSD card, and then displays it as a graph on the screen. We found the StressAware app to be reasonably accurate (63%), with a projected battery life of up to 12 days between charges, and with good usability ratings by our test subjects. The results were promising, indicating that the Amulet may eventually be useful for the development of stress-related interventions that could improve the health of individuals [5], [6].

In the literature, the most accurate methods for stresslevel monitoring rely on clinical-grade sensors strapped to the user. These sensors measure physiological signals of a person and are often bulky, custom-made, expensive, and/or in limited supply, hence limiting their large-scale adoption by researchers and the general public. In our study, we explored the viability of commercially available off-the-shelf sensors for stress monitoring. The idea was to use cheap, non-clinical sensors to capture physiological signals, and make inferences about the wearer's stress level based on that data. Specifically, we used a Polar H7 chest-strap sensor (to measure heart rate) along with the Amulet wristband (for collecting data). We evaluated this system in a lab setting with three well-validated stress-inducing stimuli with 26 participants. Our analysis showed that – using the off-the-shelf sensor alone – we were able to detect stressful events with an F1 score of 0.81, on par with clinical-grade sensors [7].

We are about to conduct a new, larger study about stress, using the Amulet, the Polar H10 heart-rate chest-strap sensor, a custom wrist-band sensor for electrodermal activity (EDA) [8]. Results will be available soon.

b) Activity tracking: It is well known that physical activity helps reduce the risk of cardiovascular disease, hypertension and obesity. The ability to monitor a person's daily activity level can inform self-management of physical activity and related interventions. Indeed, for older adults with obesity, the importance of regular, physical activity is critical to reduce the risk of long-term disability. In this work, we developed ActivityAware, an Amulet application that measured individuals' daily activity levels (sedentary, moderate and vigorous), continuously and in real-time. The app implements an activitylevel detection model, continuously collects acceleration data on the Amulet, classifies the current activity level, updates the day's accumulated time spent at that activity level, logs the data for later analysis, and displays the results on the screen. We developed an activity-level classifier and trained it using data from a user study, where subjects performed the several physical activities; in evaluating this classifier, we obtained preliminary results that suggest accuracies up to 98%, for n=14 subjects. Furthermore, we projected battery life of up to 4 weeks before needing to recharge. These results were promising, indicating that the app may eventually be useful for the development of interventions that could improve the health of individuals [9], [10].

For older adults, the importance of regular physical activity is critical to reduce the risk of long-term disability. In recent work, we presented GeriActive, an Amulet application that monitored in real-time older adults' daily activity levels (low, moderate and vigorous) [11]. The app implemented an activity-level detection model we developed and trained using data from volunteer subjects (n=29) who performed common physical activities (sit, stand, lay down, walk and run) and obtained an accuracy of 94.3% with leave-one-subject-out (LOSO) cross-validation. We ran a week-long field study to evaluate the usability and battery life of the GeriActive system, wherein 5 older adults wore the Amulet as it monitored their activity level. We found our system has the potential to be usable and useful, with a battery life of at least 1 week. The results are promising, indicating that the app may be useful for activity-level monitoring by individuals or researchers for health-delivery interventions that could improve the health of older adults [11].

c) Ecological momentary assessment (EMA): Although the Amulet was designed as a 'hub' for the collection of sensor data from body-worn and body-area sensors, including







Hardware specs:

Processing:

- Texas Instruments MSP430FR5989,
- with internal 2 KB SRAM and 128 KB FRAM
- Sensing:
 - Analog Devices ADMP510 microphone
 - Everlight ALS-PT19 light sensor
 - Texas Instruments TMP20 temperature sensor
 - STMicroelectronics LSM6DSL gyroscope
 - Analog Devices ADXL362 accelerometer
 - Lapis Semi ML8511 UVA/B sensor
- Communication:
 - Nordic nRF51822 used as a modem for communicating with BLE peripheral devices
- User Interface:
 - Sharp LS013B7DH03 display; 128x128 resolution
 - Two buttons
 - Three capacitive touch sensors with low power MPR121 touch controller
 - Haptic buzzer, and two LEDs
- Storage:
 - Daughter board with a microSD card slot
- Misc:
 - Battery charger (MCP73831)
 - 110mAh battery

Software architecture:



The name 'Amulet':

We selected the name because the word 'amulet' can be defined as a "small piece of jewelry thought to give protection against evil, danger, or disease." [Apple dictionary] those on the Amulet itself as well as those connected via Bluetooth BLE, it also has huge potential as a means for collecting self-report information. Self-report information, that is, data contributed by the person who is the subject of health monitoring, is often collected by a mechanism called Ecological Momentary Assessment (EMA), that is, prompts for information "in the moment" while the person is conducting normal activities of daily life. These prompts – which may be delivered to the subject at regular times, or at random times, or at times triggered by sensor data indicating particular activity or physiological state - are presented to the subject and request a short response from the subject. For example, the prompt might be "how stressed do you feel right now, on a scale from 1 to 5?" Traditionally, EMA studies were conducted using paper diaries; in recent years, EMA studies are conducted via smartphone apps. A wristband interface, such as that on the Amulet, may be even more effective than a smartphone, because it offers a quick, easily accessible interface for the subject to respond. We used the Amulet as an EMA platform in several of the above-mentioned studies. We have also explored the "receptivity" of subjects to EMA prompts, and how receptivity is related to subject context, in recent papers [12]-[14].

d) Usability: To be effective for mHealth applications, both those above and others, the Amulet (and its apps) must be usable by the relevant population of subjects. As many of our intended applications are for older adults, we have specifically sought to understand the degree to which the Amulet is usable by older adults. Our early results look promising, though provide further insight into the characteristics that are important to older-adult populations [15].

In earlier work we explored some of the important design considerations for wearable devices [16], presenting and defining a list of 20 human-centered design principles. We explain how each principle can be incorporated during the design phase of the wearable device creation process. By adopting these principles, we expect practitioners to achieve better wearable solutions, improving user acceptance, satisfaction and engagement. We further explored users' feedback about existing wearable bands, and analyzed the most critical issues currently faced in the interacting interaction with such devices [17]. We also investigated users' privacy concerns regarding wearable devices [18], [19]; in some instances, users were not aware of the risks associated with wearable devices, while in other cases, users seemed to be aware of the privacyrelated risks, but were perhaps unable to negotiate complicated privacy settings to meet their needs and preferences.

e) Secure data sensing: One of the long-standing challenges of mobile data sensing is the potential for the adversary to attack the sensor unit itself – in effect, to cause the sensor itself to 'lie' about the physical property it is sensing. The challenge, then, is to develop a system that can detect such attacks, or ameliorate their impact, perhaps by using redundant sensors or multi-modal sensors. Some of our collaborators used the Amulet to explore these so-called sensor-hijacking attacks, which may prevent medical devices from accurately

reporting the user's health state (e.g., by reporting incorrect or outdated physiological measurements) [20]. They outline their experiences in implementing a "data-driven security solution" for detecting these sensor-hijacking attacks on the Amulet. Their paper addresses the limited capabilities (computation, memory, battery power) of the Amulet platform, requiring several trade-offs related to detection accuracy and resource requirements. They conclude the paper with a list of insights about the capabilities such platforms should provide developers to enable the inclusion of "data-driven security primitives" in such systems [20].

f) Secure data sharing: Owners of mobile-health apps and devices often want to share their mHealth data with others, such as physicians, therapists, coaches, and caregivers. For privacy reasons, however, they typically want to share a limited subset of their information with each recipient according to their preferences. We introduced ShareHealth, a scalable, usable, and practical system that allows mHealth-data owners to specify access-control policies and to cryptographically enforce those policies so that only parties with the proper corresponding permissions are able to decrypt data. The design and prototype implementation of this system make three contributions: (1) they apply cryptographically-enforced accesscontrol measures to stream-based (specifically mHealth) data, (2) they recognize the temporal nature of mHealth data streams and support revocation of access to part or all of a data stream, and (3) they depart from the vendor- and device-specific silos of mHealth data by implementing a secure end-to-end system that can be applied to data collected from a variety of mHealth apps and devices [21], [22].

The above system was designed with Amulet in mind, but depended on the secure transfer of sensitive data from the Amulet to a smartphone, and thence to the cloud. Although existing network protocols leverage encryption for confidentiality and integrity, network-level encryption does not provide end-to-end security from the device, through the smartphone and database, to downstream data consumers. We provided a new open protocol that provides end-to-end authentication, confidentiality, and integrity for healthcare data in such a pipeline. We presented and evaluated a prototype implementation to demonstrate this protocol's feasibility on the Amulet, and presented a case for the system's ability to meet critical security properties under a specific adversary model and trust assumptions [23].

g) Secure memory protection: The proliferation of applications that handle sensitive user data on wearable platforms generates a critical need for embedded systems that offer strong security without sacrificing flexibility and long battery life. To secure sensitive information, such as health data, ultralow-power wearables must isolate applications from each other and protect the underlying system. The Amulet platform, as described above, provides strong memory-protection guarantees to isolate apps from each other, and from the system, so an errant app cannot read or tamper with the memory of the system or of another app. These properties were accomplished via a combination of hardware support, runtime support, compiler support, and language limitations [3]. Amulet, like many other embedded platforms, use microcontrollers that lack sophisticated Memory Management Units (MMU). Some, like the Amulet, include a Memory Protection Unit (MPU), but current MPUs are inadequate to the task, leading platform developers to software-based memory-protection solutions. We recently presented a novel memory-isolation technique that leverages compiler-inserted code and MPU-hardware support to achieve better runtime performance than software-only counterparts [4].

h) Peripheral integration: The Amulet is equipped with a Bluetooth BLE radio so it can receive data from BLEenabled sensors and transmit data to smartphones, but the full implementation of BLE communication on the Amulet is still a work in progress. After our early work we described architectural changes that improve the Amulet's ability to receive data from a variety of BLE-enabled sensors and make it easier for developers to integrate new BLE-enabled sensors with the Amulet by introducing support for connecting to multiple sensors at the same time, rewriting the radio code to be more generic, and exposing BLE functionality to the AmuletOS [24]. We discussed the relevant parts of the AmuletOS and the BLE protocol as background, described the structure of BLE communications on the Amulet, and documented the proposed changes to create a system for easily integrating new BLE-enabled sensors and handling connections to multiple sensors simultaneously.

In a more recent paper [25], we describe a custom BLEenabled mHealth measurement device that we intend to integrate with the Amulet. Specifically, we developed a Bluetoothconnected resistance band (essentially, a large-scale rubber band with a force sensor in the handles) that tests the ability to detect exercise repetitions. Using this novel resistance band, we feasibly detected repetition of exercises in older adults [25]. We are now working to integrate this novel sensing device with the Amulet over BLE.

IV. AMULET IN EDUCATION

In addition to its use in research projects, the Amulet could be an excellent platform for embedded-systems projects in computer science or engineering curricula. We envision it being useful in courses on mobile health, mobile computing, wearable sensing, embedded systems, or digital electronics. The Amulet source distribution includes the full development toolkit, including a preconfigured virtual machine, which should make it relatively easy for students to download and install. The Amulet is programmed in C, and is thus accessible to any undergraduate student with some experience developing on embedded systems. The Amulet could thus be the core platform for a course on wearable computing, with exercises in developing step counters or UV-exposure trackers. Students in an embedded-systems course could measure the power or computational efficiency of the device and explore low-level modifications to AmuletOS. Students in a digitalelectronics course could examine its design and develop modifications, fabricating their own custom variants with new or

different features. Engineering students in a cross-disciplinary mHealth course could develop novel health-monitoring or health-intervention applications in collaboration with students from public health or behavioral health programs. Students in a design course could critique its physical design and conduct studies of its user interface. In short, there are many possible opportunities; we encourage educators to try Amulet and to share their experience via the forum on its GitHub page.

At Dartmouth, we brought a set of Amulets to a student Hackathon, hoping to encourage one or more groups to use the Amulet for their project.

V. SUMMARY

The Amulet provides an outstanding opportunity for research and teaching in mobile health. It is open-hardware and open-source, making it possible for researchers to explore (or modify) any aspect of the system – from the underlying hardware architecture, to the operating system and runtime system, to the system API, to the developers' toolchain, to the applications themselves. Amulets can be inexpensively fabricated in small quantities (dozens or hundreds of Amulets), making it feasible for small research groups or large studies alike. As a result, we strongly encourage the community to adopt the Amulet for research projects, classroom projects, or even commercial developments.

VI. AVAILABILITY

The Amulet platform – both hardware and software – is open-source and available for download on GitHub: github. com/AmuletGroup/amulet-project. The Amulet may be freely reproduced or modified for research and education purposes (see the license on GitHub). In 2018 we manufactured 150 Amulets at an approximate cost of US\$175 per unit. Please contact the author if you are interested in exploring the use of Amulet in your research or curriculum. More information about the Amulet project can be found at the website amulet-project.org.

VII. ALTERNATIVES

We are unaware of any alternative platforms that are totally open-hardware, open-software. Early efforts like Open-Source Watch [26] faded several years ago. A recent effort, AsteroidOS [27] provides an Android-based smartwatch operating system suitable for installation on existing hardware; this approach may provide a richer experience, but battery life less than a day. Blocks recently announced Project Open-Watch [28], but only a portion of the software is open-source and it runs on a limited set of commercial hardware platforms. Finally, the mbed project [29] provides an open-source OS for IoT devices, but it cannot run multiple apps.

Many commercial smartwatches have emerged since the Amulet was designed; the most prominent examples are Apple Watch [30], the Samsung Galaxy series [31], and Fitbit smartwatches like Ionic [32]. These full-featured devices support third-party apps but with limited battery lifetime, and proprietary hardware and software.

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REFERENCES

- J. Sorber, M. Shin, R. Peterson, C. Cornelius, S. Mare, A. Prasad, Z. Marois, E. Smithayer, and D. Kotz, "An Amulet for trustworthy wearable mHealth," in *Workshop on Mobile Computing Systems* and Applications (HotMobile), February 2012, pp. 7:1–7:6. DOI 10.1145/2162081.2162092
- [2] D. Kotz, R. Halter, C. Cornelius, J. Sorber, M. Shin, R. Peterson, S. Mare, A. Prasad, J. Skinner, and A. Molina-Markham, "Wearable computing device for secure control of physiological sensors and medical devices, with secure storage of medical records, and bioimpedance biometric," U.S. Patent 9,936,877, April 2018, this patent adds claims to its predecessor. Available online: http: //www.cs.dartmouth.edu/~dfk/papers/kotz-patent9936877.pdf
- [3] J. Hester, T. Peters, T. Yun, R. Peterson, J. Skinner, B. Golla, K. Storer, S. Hearndon, K. Freeman, S. Lord, R. Halter, D. Kotz, and J. Sorber, "Amulet: An energy-efficient, multi-application wearable platform," in *Proceedings of the ACM Conference on Embedded Networked Sensor Systems (SenSys)*. ACM Press, November 2016, pp. 216–229. DOI 10.1145/2994551.2994554
- [4] T. Hardin, R. Scott, P. Proctor, J. Hester, J. Sorber, and D. Kotz, "Application memory isolation on ultra-low-power MCUs," in *Proceedings of the USENIX Annual Technical Conference (USENIX ATC)*. USENIX, July 2018, pp. 127–132. Available online: https://www.usenix.org/system/files/conference/atc18/atc18-hardin.pdf
- [5] G. Boateng and D. Kotz, "StressAware: An app for real-time stress monitoring on the Amulet wearable platform," in *Proceedings of the IEEE MIT Undergraduate Research Technology Conference (URTC)*. IEEE, January 2017. DOI 10.1109/URTC.2016.8284068
- [6] G. G. Boateng, "StressAware: App for continuously measuring and monitoring stress levels in real time on the amulet wearable device," Dartmouth Computer Science, Tech. Rep. TR2016-802, May 2016, senior Thesis. Available online: http://www.cs.dartmouth.edu/reports/ TR2016-802.pdf
- [7] V. Mishra, G. Pope, S. Lord, S. Lewia, B. Lowens, K. Caine, S. Sen, R. Halter, and D. Kotz, "The case for a commodity hardware solution for stress detection," in *Workshop on Mental Health: Sensing & Intervention.* ACM, October 2018, pp. 1717–1728. DOI 10.1145/3267305.3267538
- [8] G. C. Pope, V. Mishra, S. Lewia, B. Lowens, D. Kotz, S. Lord, and R. Halter, "An ultra-low resource wearable EDA sensor using wavelet compression," in *Proceedings of the IEEE Conference on Body Sensor Networks (BSN)*. IEEE, March 2018, pp. 193–196. DOI 10.1109/BSN.2018.8329691

- [9] G. Boateng, R. Halter, J. A. Batsis, and D. Kotz, "ActivityAware: An app for real-time daily activity level monitoring on the Amulet wrist-worn device," in *Proceedings of the IEEE PerCom Workshop on Pervasive Health Technologies (PerHealth)*. IEEE, March 2017, pp. 431–435. DOI 10.1109/PERCOMW.2017.7917601
- [10] G. G. Boateng, "ActivityAware: Wearable system for real-time physical activity monitoring among the elderly," Master's thesis, Dartmouth Computer Science, May 2017, available as Dartmouth Computer Science Technical Report TR2017-824. Available online: http://www.cs.dartmouth.edu/reports/TR2017-824.pdf
- [11] G. Boateng, J. A. Batsis, P. Proctor, R. Halter, and D. Kotz, "GeriActive: Wearable app for monitoring and encouraging physical activity among older adults," in *Proceedings of the IEEE Conference* on Body Sensor Networks (BSN). IEEE, March 2018, pp. 46–49. DOI 10.1109/BSN.2018.8329655
- [12] J.-N. Kramer, F. Künzler, V. Mishra, B. Presset, D. Kotz, S. Smith, U. Scholz, and T. Kowatsch, "Investigating intervention components and exploring states of receptivity for a smartphone app to promote physical activity: Study protocol of the ALLY micro-randomized trial," *JMIR Research Protocols*, 2018, accepted for publication.
- [13] V. Mishra, B. Lowens, S. Lord, K. Caine, and D. Kotz, "Investigating contextual cues as indicators for EMA delivery," Dartmouth Computer Science, Tech. Rep. TR2018-842, April 2018. Available online: http://www.cs.dartmouth.edu/~trdata/reports/TR2018-842.pdf
- [14] —, "Investigating contextual cues as indicators for EMA delivery," in *Proceedings of the International Workshop on Smart & Ambient Notification and Attention Management (UbiTtention)*. ACM, September 2017, pp. 935–940. DOI 10.1145/3123024.3124571
- [15] J. Batsis, A. Zagaria, D. Kotz, S. Bartels, G. Boateng, P. Proctor, R. Halter, and E. Carpenter-Song, "Usability evaluation for the Amulet wearable device in rural older adults with obesity," *Gerontechnology*, vol. 17, no. 3, pp. 150–158, 2018, accepted for publication. DOI 10.4017/gt.2018.17.3.003.00
- [16] V. G. Motti and K. Caine, "Human Factors Considerations in the Design of Wearable Devices," in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 58, no. 1. SAGE Publications, Sep. 2014, pp. 1820–1824. DOI 10.1177/1541931214581381
- [17] B. Lowens, V. Motti, and K. Caine, "Design recommendations to improve the user interaction with wrist worn devices," in *IEEE International Conference on Pervasive Computing and Communication Workshops (PerCom Workshops)*, Sch. of Comput., Clemson Univ., Clemson, SC, USA. IEEE, Mar. 2015, pp. 562–567. DOI 10.1109/ percomw.2015.7134099
- [18] V. G. Motti and K. Caine, "Users' Privacy Concerns About Wearables: impact of form factor, sensors and type of data collected," in *Workshop* on Wearable Security and Privacy, vol. 8976, no. ISBN 978-3-662-48050-2. Lecture Notes in Computer Science, 2015, pp. 1–14. Available online: http://fc15.ifca.ai/preproceedings/wearable/paper_2.pdf
- [19] B. Lowens, V. G. Motti, and K. Caine, "Wearable Privacy: Skeletons in The Data Closet," in *IEEE International Conference on Healthcare Informatics (ICHI)*. IEEE, Aug. 2017, pp. 295–304. DOI 10.1109/ichi.2017.29
- [20] H. Cai, T. Yun, J. Hester, and K. K. Venkatasubramanian, "Deploying Data-Driven Security Solutions on Resource-Constrained Wearable IoT Systems," in *IEEE International Workshop on Internet of Things Computing and Applications (IoTCA 2017)*. IEEE, Jun. 2017, pp. 199–204. DOI 10.1109/ICDCSW.2017.15
- [21] E. Greene, P. Proctor, and D. Kotz, "Secure sharing of mHealth data streams through cryptographically-enforced access control," *Journal of Smart Health*, April 2018, accepted for publication. DOI 10.1016/j.smhl.2018.01.003
- [22] E. Greene, "ShareABEL: Secure Sharing of mHealth Data through Cryptographically-Enforced Access Control," Dartmouth College, Computer Science, Hanover, NH, Tech. Rep. TR2017-827, July 2017. Available online: http://www.cs.dartmouth.edu/reports/TR2017-827.pdf
- [23] D. B. Harmon, "Cryptographic transfer of sensor data from the Amulet to a smartphone," Dartmouth College, Computer Science, Hanover, NH, Tech. Rep. TR2017-826, May 2017. Available online: http://www.cs.dartmouth.edu/reports/TR2017-826.pdf
- [24] A. J. Knowles, "Integrating bluetooth low energy peripherals with the amulet," Dartmouth Computer Science, Tech. Rep. TR2016-807, May 2016, senior Honors Thesis. Available online: http: //www.cs.dartmouth.edu/reports/TR2016-807.pdf

- [25] C. L. Petersen, E. V. Wechsler, R. J. Halter, G. G. Boateng, P. O. Proctor, D. F. Kotz, S. B. Cook, and J. A. Batsis, "Detection and monitoring of repetitions using an mHealth-enabled resistance band," in *IEEE/ACM International Conference on Connected Health: Applications, Systems and Engineering Technologies (CHASE)*. ACM, September 2018, pp. 21–23. DOI 10.1145/3278576.3278586
- [26] J. Cook. (2018, Dec.) Open-Source Watch. Available online: http: //oswatch.org
- [27] F. Revest. (2018, Dec.) AsteroidOS. Available online: https://asteroidos. org
- [28] Blocks. (2018, Dec.) Project OpenWatch. Available online: https: //github.com/OpenWatchProject
- [29] Mbed. (2018, Dec.) Mbed OS. Available online: https://www.mbed. com/en/platform/mbed-os/
- [30] (2018, Dec.) Apple Watch. Available online: https://www.apple.com/ watch/
- [31] (2018, Dec.) Samsung Galaxy and Gear. Available online: https: //www.samsung.com/us/mobile/wearables/
- [32] (2018, Dec.) Fitbit Ionic. Available online: https://www.fitbit.com/ionic