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Photo, John Coleman, Great Lakes Indian Fish and Wildlife Commission

Researcher Eric Greenlee highlighting the cause of failure of a custom sensor developed by the Great Lakes Indian Fish and Wildlife Commission on the Sandy River. The sensor malfunctioned because a beaver chewed through the wire!

COMMUNITY-DRIVEN MOBILE AND UBIQUITOUS COMPUTING

This article calls for careful, calculated, community-driven co-design of mobile and ubiquitous solutions to bridge the gap in financing and capacity of marginalized communities as they battle for the safety and health of their members. Communities across the globe face incredible challenges to preserve their environment, lifestyle, prosperity, equality, and even democracy. In the past five years, the urgency of multiple global crises, including climate degradation that causes extreme weather and shatters ecosystems and the COVID-19 pandemic that caused a global health crisis and economic upheaval, has threatened an already delicate balance. However, the impacts of these events are uneven – vulnerable, low-income, and marginalized communities have borne the brunt of many of these crises, not having the infrastructure or capacity to address every single gap.

Vulnerable coastal communities, for example, have faced significant challenges due to extreme weather and rising sea levels. Coastal zones provide key services to local communities but also carry significant risks from the land and ocean including threats from waves, storm surges, floods, and sea level rise, all of which are increasing with climate degradation. Protecting and restoring coastal ecosystems, such as coral reefs and mangroves can help mitigate these threats while also supporting local economies and societal resilience. These communities have recently turned to mobile and ubiquitous technology to bridge the capacity and resources divide. Communities in Chatham County, Georgia, have deployed smart sea level sensors to provide early warnings for evacuations, as well as baseline data to address long term effects of sea level rise [1,2]. Native American tribes in the Western Great Lakes of North America constantly battle with accelerating climate degradation of coastal wetlands which destroys Manoomin (wild rice), and the ecosystems supported by it. Rice has sustained the body and spirit of tribal members for generations, making this loss devastating for identity and sustenance [3]. These tribes have deployed local sensor networks coupled with remote sensing to understand the changing ecosystems and initiate short- and long-term interventions. Targeted sensor deployments can enable lower-burden, data-driven interventions by providing a lower-cost and lower-latency alternative to manually collected data. Other researchers have worked with tribes in the Southwest USA to build Internet measurement tools to ease the process to dispute coverage data maintained by Internet service providers, to fight for better connectivity and Internet access [4]. Finally, projects such as the Array-of-Things [5] have deployed large scale sensing infrastructure to collect data on everything from traffic problems, urban heat, air quality, and wild animal interactions, giving a wealth of data to city/community leaders to make informed management decisions.

While many promising solutions have been engineered to support communities, so much work remains and problems are exceedingly complex, including notions around data privacy, ecological footprint, poor design, and local politics/economics. Local communities in Hawaii are priced out of their homes by tourism and development, while not allowed access to clean drinking water due to multiple contamination events and ecological crises [6]. Boroughs where incomes are lower – in urban cities like Atlanta and Chicago – continue to lack the resources and infrastructure to stave off the effects of deadly heat waves and heat islands, leading to preventable deaths [7]. There has never been a more critical moment for collective action leveraging the sensor and IoT revolution, but how can it be facilitated? What are the barriers and facilitators? How can SIGMOBILE members help?

In this viewpoint, we propose that the development of mobile and ubiquitous computing devices and technologies should be intricately linked to community needs as opposed to isolated innovations. The present and future of SIGMOBILE demand a paradigm shift towards community-integrated solutions. Slowly, technology design is shifting from user-centered design methodologies (i.e., designing for hypothetical average users, generally motivated by profit) to community and asset-based design approaches, where the capacity, constraints, and needs of a community of users are considered in the process from design concept to deployment. This shift anchors the design, development, and deployment of computational devices to the context of real-world community aspirations. This viewpoint spotlights the critical role that these technologies could play in community-asset building if designed in the proper context – specifically with embedded and mobile applications in environmental conservation, sustainability, and mobile health, which are areas with a long history in SIGMOBILE conferences. We also highlight the often ignored challenges on the periphery: social dynamics, relationships, privacy, and data sovereignty. The hope is that researchers will understand the potential impact of co-design and partnering with vulnerable communities in a long-term and reciprocal process to empower each other for collective action to ensure a bright future and healthy planet.

(Left) Researcher Eric Greenlee spreading Manoomin (wild rice) seed on the Lac du Flambeau Reservation with the tribal natural resource department. (Right) The root system of Manoomin (wild rice) taken during field research on Aurora Lake in Wisconsin.

Photos, (left) William (Joe) Graveen, Lac du Flambeau Tribal Natural Resource Department; (right) Eric Greenlee, Georgia Institute of Technology

COMPUTING HAS NEVER BEEN MORE ACCESSIBLE. BUT…

Mobile and embedded development has never been more accessible. Inexpensive components, widespread availability of educational resources, and open-source software and hardware have significantly reduced the barriers to entry in the past decade. However, this accessibility is in many ways superficial, as actual deployment-ready, long-term, and impactful devices are rarely seen except when engineered by professionals at significant cost. Well-intentioned researchers will make short-term partnerships and deploy buggy or incomplete research devices they designed

alone, which often fail to deliver a significant sustained beneficial impact to a community. Unfortunately, this damages relationships between researchers and communities, wastes the time and resources of all parties, and sours community attitude to any future researchers.

Guiding Principles. This potential for waste and damage calls for redirecting efforts toward community-integrated initiatives that consider a few key principles. First, research initiatives must align goals with the need to deliver meaningful and tailored technology that directly addresses specific community priorities. Second, they must foster a greater sense of community ownership and engagement. Finally, these focused initiatives must consider community assets, not just deficits, to unlock opportunities for expanding the capacity of a community, thereby making a real impact where it is needed most. Embracing these principles could generate more effective, sustainable, and widely accepted solutions in ubiquitous computing for communities. The two application areas of environmental conservation/sustainability and health offer a lens to examine the benefit of these principles, the open research problems, and the challenges inherent in engaging with communities for technology development, which we explore below.

APPLICATIONS

Environmental Conservation and Sustainability. Extreme weather events, warming waters, and rapid habitat loss reduce the ability of communities to access, maintain, and use natural resources, especially coastal resources from oceans, lakes, rivers, and wetlands. Native American/First peoples, and other marginalized communities are disproportionately affected by the twin threats of resource extraction (e.g., mining, logging, oil/gas pipelines) and climate change, as they cannot mount legal defense nor can they muster significant resources to mitigate effects of environmental degradation. Decades of work in the wireless sensor networks community has focused on environmental conservation (and recently, computational sustainability) – including seminal works on systems for animal monitoring [8] and ecosystem monitoring [9]. Concurrently, global crowdsourcing and citizen science initiatives [10,11] have accelerated our understanding of ecosystem change. However, most research has focused on individual users with high technical literacy and means, making it difficult to translate these sensing networks to readily usable tools for communities with limited resources. Additionally, these tools tend to focus on longer-term purely scientific efforts, like modeling climate processes, which can be challenging to translate to immediate needs communities have identified such as flood warnings, resource management, safety, etc. Extending and reimagining prior work with community-driven design will not only lead to a more useful set of systems that communities actually benefit from but will also build partnerships that enable researchers to leverage local assets and knowledge to develop purely scientific frameworks and knowledge.

University Researchers, K12 teachers, and members of a non-profit convene around an ancient Native Hawaiian fishpond, Waikalua Loko I'a in Kaneohe, Hawaii, to discuss ecological restoration efforts and computer science education using embedded systems.

Photo, Josiah Hester

Health. The COVID-19 pandemic affected billions of people across the globe, exposing the many cracks in health infrastructure, especially for marginalized and low-income communities and populations [12]. Additionally, the opioid and obesity crisis, coupled with increased poverty, malnutrition, and lack of access to healthcare/insurance in many low-income communities, have compounded with the pandemic and led to many preventable deaths. The SIGMOBILE conferences have had a long history of leading the way on health-based technology solutions to critical issues from eating and obesity to opioid abuse and mental health [13]. A recent example includes promoting health equality of California's Hispanic/Latino population by using technology and community engagement via a specific community engagement role to include the underrepresented community in diabetes research [14]. The SIGMOBILE research community's approach of building relevant, situated platforms for the many aspects of health can be further enhanced by a deep integration with specific community needs.

CHALLENGES

The shift from making devices for communities to collaborating with them presents unique challenges that disrupt traditional development cycles. Here we list a set of challenges, which researchers will face when engaging in community driven co-design that must be taken into consideration when approaching community integrated development.

Alignment of Goals. The disparity in motivations and mindsets between technology creators and real-world application users often hamper solutions' effective implementation. On the surface, both parties may appear to share the same overarching objectives; however, the rewards for each can significantly differ. A graduate student may find value in publishing a paper on a small deployment of novel sensors, while a tribal elder may view this as an unproductive diversion or even an invasion of privacy. To effectively collaborate, goals must align with milestones and timescales common to both researchers and com-

munities, meanwhile shifting the focus to the technology's impact rather than its implementation. Research in this space should not be evaluated by the novelty of its components but by the integration and design for adoption and sustained impact.

Community Capacity. In tandem with aligning goals, engaging with a community likely imposes additional responsibilities on its members. Not all commitments are technical, but could involve input from domain experts or training required to conduct field research. The process of creating technology necessitates a commitment to the solution, but the responsibility must be reciprocally beneficial. It's essential to be aware of the realistic capacity of community members. Especially problematic is the process, whether intentional or not, of using a community's scarce time to solicit design ideas and later ignoring them. One common scenario is when the design is already set and the community feedback is sought to acknowledge its hypothetical usefulness. Embarking on community-driven research implies a responsibility to actually use the insight provided by the community in the creation of new technology.

Building long-term relationships. Establishing trust between all involved parties is paramount to justifying the increased effort in developing new solutions. Long-term relationships require continuous and consistent communication, understanding, and collaboration. Building these relationships ensures that all parties feel valued, heard, and dedicated to the shared goals. This most likely requires taking the effort to involve oneself in the community outside of the direct needs of any particular project, for example volunteering, or engaging in a community effort which you are already a member of. Community members may be acting in their professional or personal capacity, which can result in an obfuscation of the lines between a researcher's professional and personal life.

Technical Literacy. An effective sensing system is composed not only of its hardware and software but also the communication and documentation of its use. For a research system to attain long-term adoption and usefulness, it is typically beneficial to design interfaces similar to what community members are familiar with and to host workshops that communicate how to take full advantage of the system. This is similar to a software team choosing a framework solely based on team experience to promote easy integration and maintenance. While some design philosophies emphasize meeting people where they are, in many cases it is reasonable to trust the ability and motivation of engaged community members to learn how to do something new. Building technical literacy is especially important during the initial brainstorming and co-design phase, where one of the researcher's primary responsibilities is to communicate what technology can feasibly do and the tradeoffs (cost, usability, battery life, etc.) between pursuing different design ideas. This communication must be an ongoing process because by nature of conducting research, the understanding of tradeoffs and limitations will change over time.

Privacy and Data Sovereignty. Maintaining control and ownership of data is an urgent problem for any field collecting vast amounts of data [15]. However when dealing with underrepresented communities, like tribal nations seeking to protect the privacy of their enrolled members, locations of sacred places, and even stories, data sovereignty becomes an increasingly important issue. Developing for sovereignty can pose additional administrative and technical complexity or even directly clash with principles such as data accessibility and other FAIR principles [15]. For example, some Anishinaabe conservationists are rightfully reluctant to share their population data of a specific species with the Wisconsin Department of Natural Resources because the state could use the data to justify increasing the number of hunting permits for this species, which most Anishinaabe people strongly oppose. Data sovereignty for Anishinaabe communities means they decide who to share data with.

Acknowledging and addressing these challenges does not always ensure success, and there may be situations where integration fails. This highlights the need for prudence when proposing solutions to problems outside your active involvement. Merely possessing the technical skills and motivation to construct an environmental sensor does not inherently make it useful for ecologists and field researchers. The most reliable way to ensure the effectiveness of a solution is to have a vested interest in the problem space being designed for. This shared stake serves as a cornerstone for engagement, leading to the development of solutions that are both thoughtful and driven by genuine need.

OPEN QUESTIONS & RESEARCH CHALLENGES

Toolkits, Testbeds, and Platforms. The SIGMOBILE research community has had a long term goal of building useful hardware/software platforms to supercharge important areas of research. What are the foundational platforms for community co-design? An essential direction for research is the creation of open-source toolkits that facilitate the planning, engagement, development, deployment, and education related to embedded services. While numerous proprietary solutions are available for specific sensing tasks, these often fall short when addressing the previously discussed challenges, such as prohibitive costs, data ownership, sustainability, and flexible connectivity. Toolkits, testbeds and platforms that support community integration should enhance the end-to-end experience of co-design, not only reduce engineering efforts. Examples include ways to collaborate on requirements gathering, multidirectional sharing of knowledge, and prototyping, in addition to building devices with dynamic programming interfaces and accessible data collection and analysis, and, finally, to promote long-lasting support, collaborative documentation and training tools along with channels of ongoing communication. Evaluation of such systems is another challenge and opportunity for co-design, but bridging this gap between purely technical stakeholders and domain experts will foster genuinely impactful and sustainable ubiquitous computing.

COMMUNITY-DRIVEN RESEARCH IS NOT A CHECKLIST OF RESPONSIBILITIES AND PITFALLS TO AVOID

Deployments. It seems the exception that research products actually make it to the field and are celebrated by the community. Often, if a device is mature enough to be deployed for an actual application, it is no longer considered "novel" or interesting enough to be published. "Experience" track papers have sought to bridge this gap, and represent (potentially) a shift in thinking of the SIGMOBILE community, where we celebrate the effort and thoughtfulness, as well as the iteration and co-design practice, and lessons learned, to inform our own work. Celebrating and highlighting these experiential papers, even making them on the same level as regular papers, is a necessary first step to elevating community centered co-design of mobile and ubicomp technology.

Co-design and Development *Methodology*. Despite the abundance of technical resources available to learn how to develop devices, the ability to utilize these skills effectively to address genuine needs is a much more complex task and is difficult to quantify. Hence, cultivating a methodology which includes education, collaboration, and technical proficiency is a significant challenge. Frameworks should engage and incorporate stakeholders in all steps of the design and development workflow. Such a process ensures that resulting technologies authentically represent and respond to their needs. This effort also includes educating about sustainability and teaching how to design systems for long-lasting real-world deployments, including technical factors, e.g., scalability and maintenance, and social considerations, e.g., ensuring the technology is beneficial, usable, and acceptable. Fleshing out these methodologies is crucial for democratizing applicable technology and empowering the creation of effective and sustainable devices.

CONCLUDING THOUGHTS AND CALL TO ACTION

Community-driven research is not a checklist of responsibilities and pitfalls to avoid. The only way to authentically do this work is to genuinely engage with the community for a prolonged period of time and to befriend community members. Participating in community events that do not directly achieve research goals, learning about a people's history, and living within the community are necessary. The SIGMOBILE research community is extraordinarily well situated to make a positive impact working with marginalized communities, due to the very nature of our work and the devices we build and use. This viewpoint article asks the reader to consider the communities they live and work in, and how to best be a responsible collaborative citizen researcher building for a more sustainable future. ■

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