Beyond Visualization – Vivid Frameworks for Ubiquitous Sensor Data

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ABSTRACT

We have already witnessed profound and often unanticipated developments as IoT is built out and the world is mediated via mainly graphical wireless devices held at arm's length. But what will happen once the world is precognitively interpreted by what we term 'sensory prosthetics' that change what and how humans physically perceive, a world where your own intelligence is split ever more seamlessly between your brain and the cloud? In this article, I describe research initiatives in my group that anticipate the broad theme of interfacing humans to the ubiquitous electronic "nervous system" that sensor networks will soon extend across things, places, and people, going well beyond the 'Internet of Things' to challenging the notion of physical presence.

Keywords: wearable sensing, sensor networks, embedded sensing, augmented reality, Internet of Things

1 A SENSATE PLANET

I was a child growing up in the urban sprawl of Boston during the mid 1960's – as this was the dawn of widespread consumer electronics driven by the introduction of semiconductors, technically-minded kids like me were building things like electronic music machines [1] and sensor projects (Fig. 1) – indeed, the 'smart home' was well before then an established, albeit stillborn, concept [2]. Already at that time, I was fascinated by the concept of distributed sensors and what they could do to the human sense of presence, as I'd string wires across my neighborhood and attach sensors to them, building what was effectively a hardwired sensor network.

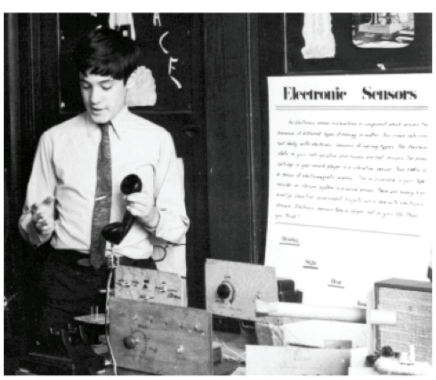

Figure 1: My first electronic sensors project in 1969

In many ways, this anticipated the central theme of my research group at the MIT Media Lab - how sensor networks augment and mediate human experience, interaction and perception [3]. The integration of computation, sensing, networking, and wireless technologies have enabled sensor information to diffuse into cognitive networks at different scales across the planet, from wearable computing (presently driven by mobile and quantified-self applications) to smart homes and smart cities, and ultimately to a connected planet as remote sensing and embedded sensors for agriculture and even environmental/oceanic studies [4] are subsumed. This has sparked relevant concerns about individual and collective privacy that begins to reach sharp focus now, as we come to grips with the consequences of leaky information gleaned from social media, never mind exploitable contextual information that will soon be derived from omnipresent sensing. But, hopefully with these factors in mind, the world will be properly wired as the emerging Internet of Things marches on with great promises of revolutionary benefit to important needs like transportation, agriculture and food production, healthcare, energy consumption, etc.

As illustrated by the projects outlined in this paper, my research team and I are fascinated by what happens to the human post IoT's ubiquitous connectivity transformation, as our perception, actuation, cognition, and even identity begin to diffuse beyond the physical boundary of self [5].

2 THE DOPPELLAB PROJECT

Our initial projects in connecting distributed embedded sensors to people were animations of sensors distributed throughout our building complex. We began in the mid 2000's with simple 2D Flash animations of real-time sensor data atop a map of our lab area (Fig. 2 left), then displayed more complex phenomena using 3D environments in the shared-reality environment of SecondLife [6] (Fig. 2 right).

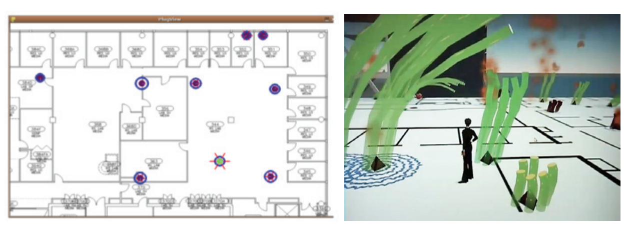

Figure 2: Our early ubiquitous sensor visualizations, using Flash (2006, left) and SecondLife (2008, right).

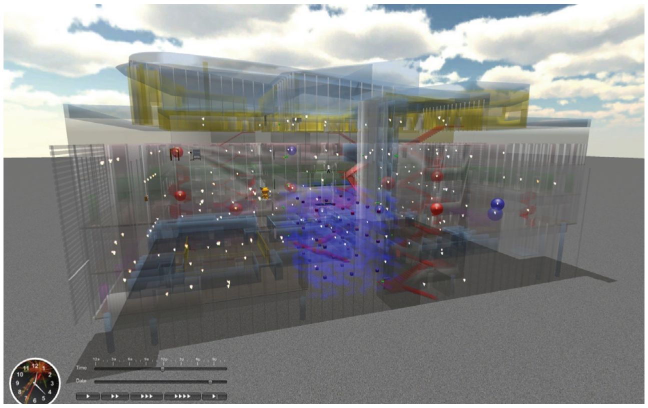

Figure 3: A view from 'DoppelLab' – an immersive 3D view of our building through which diverse sensors are visualized and sonified.

Our subsequent efforts in this area then evolved to encompass real-time feeds from all over our building, incorporating not only sparsely-updating sensors like temperature/humidity and motion, but also streaming feeds like audio and video as well as data posted on social media, which is itself a 'sensor' of sorts. We moved to game engines for this work, which enabled more flexibility than SecondLife, ending up with Unity3D. This evolved into our DoppelLab platform [5,9], which stabilized circa 2013. Although 3D visualization environments have begun to establish in niche industries like operation of large factories/refineries and disaster planning (e.g., where real-time radiation readings are superimposed over models of a ruined reactor [8]), environments like this that agnostically and agilely blend diverse data atop immersive models of buildings and complexes will play an important role in the 'control panel' for the Internet of Things, where data of all sorts will be used to control any manner of facility operation – systems will no longer use only their own 'Balkanized' vertical sensor infrastructure.

There are many emerging IoT protocols that aspire to blend data between different devices, sensors, and systems (e.g., [9]) – as none are yet properly established, a few years ago we built our own JSON-based sensor posting framework called 'CHAIN-API' [10], a RESTful protocol that allows sensors to post descriptive updates as well as link to other relevant sensor feeds. All sensor information for the projects described here are provided via this service.

3 THE TIDMARSH PROJECT

Our subsequent work along these themes [11] has expanded into a heterogeneous outdoor environment – a 600-acre retired Cranberry bog called 'Tidmarsh Farms' that has recently undergone a restoration into a natural wetland. Wetlands are garnering wide interest in environmental circles as effective natural sinks for man-made pollutants like groundwater-borne nitrates and CO_2 (although many emit significant methane, and what distinguishes a carbon-sinking vs carbon-emitting wetland isn't currently well understood) [12]. To capture data during the restoration process, we have instrumented the Tidmarsh site with many different sensors. The ubiquitous 'pawns' of this deployment are versatile micro-powered wireless sensor nodes that we have developed [11]. The latest version of this node is shown in Fig. 4. It communicates with a base station across up to several hundred open-air meters utilizing a modified ZigBee protocol that we have developed. Each sensor node sports an array of micro-climate sensors (temperature/humidity, barometric pressure, light intensity and spectral quality, accelerometer for wind, etc.), plus a suite of others, such as a microphone for extracting simple acoustic features and a PIR motion sensor for detecting sizable wildlife. It is easily expandable via a water-resistant plug at the bottom of the enclosure – we are utilizing this port on most of our installed nodes to add sensors to analyze soil moisture, temperature, and conductivity, as well as accommodate air and water quality sensors. A small solar cell atop the sensor package is able to power this device indefinitely with moderate sunlight, while transmitting typically at a few updates per minute.

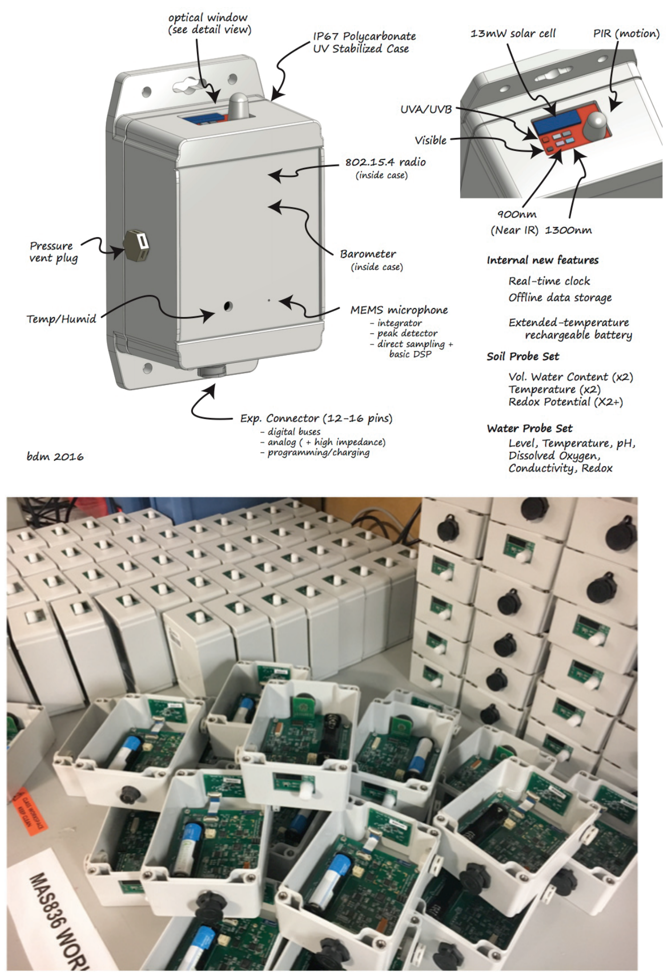

Figure 4: The latest version of our Tidmarsh Micropower Wireless Sensor Node, designed by Brian Mayton.

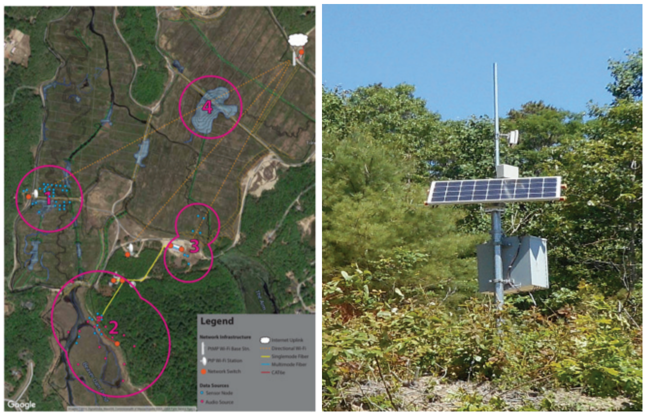

Figure 4: Wireless network sites (left) & base station (right)

Figure 5: DoppelMarsh – data manifesting in an avatar landscape (top) and the appearance of fictitious virtual animals representing integrated sensor data (bottom)

We have instrumented 4 large regions of the Tidmarsh complex with over 100 sensor nodes, soon to grow to roughly 300 nodes this spring. Each group of nodes are serviced by a base-station that relays the data to a wired head-end up to a kilometer or more away via a directional WiFi link. If electrical power isn't available, these base-stations are powered by solar arrays. Each basestation also hosts an embedded camera, a weather station, and at least one microphone (some can host many – we stream up to 32 channels of CD-quality audio from the Tidmarsh site).

We have provided many applications with which to interact with and plot the data real-time streaming and cached from Tidmarsh (see http://tidmarsh.media.mit.edu), including manifestation in a virtual world, taking inspiration from our DoppelLab project. We have incorporated terrain scans and the restoration plans into a 3D environment we call 'DoppelMarsh' (Fig. 5) that we likewise render via Unity3D. Plants and ground cover are generated as seasonally appropriate, grounded by data coming from the embedded cameras [13], and locally-sensed weather conditions (e.g., rain, snow, fog, etc.) also correspondingly appear in our virtual 'avatar' landscape. Sensor values and updates are given by a variety of animations driven by the actual data, and averages of particular sensor measurements over a period of time are represented through the appearance of virtual animals (Fig. 5) [13]. We have also built a framework to represent sensor data via composed music [14] – when visiting the virtual Tidmarsh, you can hear spatialized real-time audio from our distributed microphones as well as listen to the sensor data via music mapped currently into 3 different compositions that observers can easily select and change. In general, our eyes and ears are good at evaluating different phenomena – my team has explored different ways of moving sensor data fluidly across aural and visual modalities to best leverage different modes of human perception [15].

Through this effort, we have provided a very different way to visit and experience the Tidmarsh site. If you physically visit the real place, now that it is an actual wetland, it takes considerable time and effort to only walk a few meters – getting into the marsh requires tall wading boots, and the voracious tick population entails significant risk of disease. But in the virtual Tidmarsh, you can ignore physical constraint, and fly, float, or glide across the wetland, seeing/hearing streams and data from sensors embedded in the marsh that manifest in different ways.

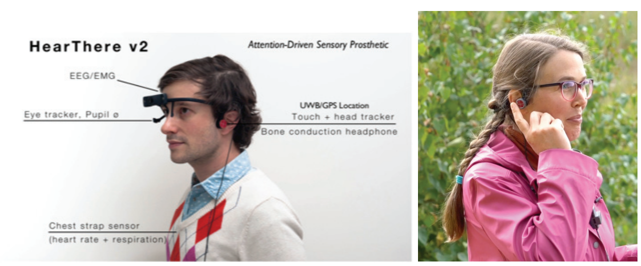

Figure 6: Attention-Driven Auditory Prosthetic – early research prototype (left) and subsequent Tidmarsh-fielded version (right)

But that said, we aren't yet completely virtual constructs, and VR experiences still hugely lack the richness of the real world. Accordingly, we've been exploring ways to naturally augment the perception of visitors to such sensor-laden premises with the transduced information in natural ways [11] – much as how people can focus their natural senses onto phenomena of interest, we have asked whether we can do that with embedded electronic sensors – e.g., detect users 'focusing' onto particular stimuli, then feed audio/video from relevant sensors gracefully into the users' sight or hearing. Our initial efforts in this area have concentrated on audio, using bone-conduction headphones augmented with various sensors to detect head direction and motion and user state. By localizing the user and using the sensor information to determine what sensor information to present (and how to present it), we have built and successfully tested what we call a 'Sensory Prosthetic' [16] (Fig. 6) – a device to 'amplify' human perception by naturally and dynamically tapping into external embedded environmental sensors.

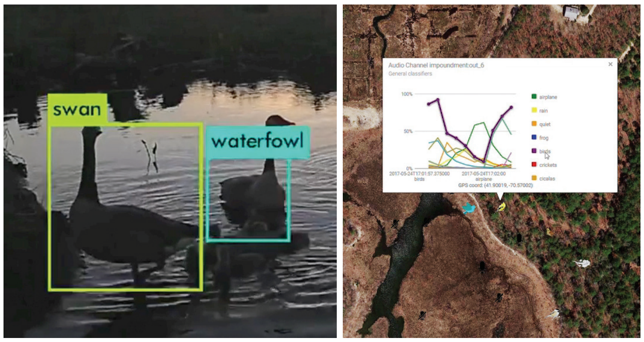

Figure 7: Recognizing wildlife from video streams (left) and audio (right) using our Tidzam framework

Once sensor data reaches the internet, it will be processed by AI algorithms. We have leveraged machine learning in our Tidmarsh project to dynamically identify and locate wildlife through the embedded audio and video streams (Fig. 7), posting detected phenomena as virtual sensors using our CHAIN-API standard, all realized in deep-learning application framework we call 'Tidzam' [17]. Tidzam identifies several bird species with reasonable accuracy and detects different kinds of insects and natural phenomena in the audio stream - we expect this to improve as training set grows.

In general, machine learning will leverage all sensor data on the net, regardless of quality – sensor data will be dynamically 'calibrated' or weighed according to how it correlates with that from other sensors, some of which will be more accurate than others. We have built a machine-learning-based estimator called 'LearnAir' [18] that does this for atmospheric sensing – it crawls the web looking for data relevant to air quality and learns relevant correlations and calibrations. In the future, data leveraged from sensors will prove more valuable than individual sensor data itself.

We are now looking at exploiting such machine learning at the microorganism level, leveraging image recognition with low-cost embedded microscopy [19], then going a level deeper by incorporating low-cost nanopore DNA sequencing into some of our environmental sensing nodes.

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