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My research spans the areas of ubiquitous computing, human-computer interaction, and sensor-enabled embedded systems. My group has largely focused on building new types of sensors and sensing systems that support a wide range of applications with an eye toward reducing deployment barriers. We have made significant progress on applications that cross a broad spectrum, ranging from energy and resource monitoring in the home, to home elder care, to mobile health monitoring, to new user interface systems. The primary theme of my group's research has been to discover and build sensors and sensory systems that solve hard problems by leveraging existing infrastructures and resources. This includes exploring the phenomena to be sensed in new ways, creating and understanding the appropriate theoretical models of the phenomena, building the actual systems to deploy at scale, and then working to apply these systems to real applications.

As part of our research vision, we have identified and developed many cost effective and deployable sensing systems that can easily be added to any ordinary home. For example, we have developed a new sensing approached call *Infrastructure Mediated Sensing (IMS)* that uses existing home infrastructure, such as electrical, plumbing, and gas, to detect human activity and other phenomenon. This technique greatly reduces the installation burden of home sensors and thus enables large-scale applications research. We have worked on building a new wireless sensing approach that uses the power lines as a receiving antenna, which allows us to dramatically reduce the power consumption of wireless sensors while still offering whole-home or building range in a goal to develop practical wireless sensing solutions. In addition, we have expanded this notion of practical sensing to pursue strategies that leverage common mobile phones for health monitoring (chronic asthma, cough sensing, etc.). We have been working very closely with Microsoft Research on new off-the-desktop user interface techniques that require little to no instrumentation to the environment itself.

In summary, our research for the last couple years falls within four broad themes:

1) **Sustainability Sensing**: Creating practical sensing systems and feedback interfaces for energy and water use
2) **Wireless sensing**: Developing new low-power sensor platforms
3) **Health sensing**: Creating new approaches for unobtrusive health sensing
4) **User interface technology**: Creating new, off-the-desktop, gesture-based input and haptic feedback output systems

Sustainability Sensing: Today's households are aware of how much total energy they consume through monthly bills, but not where and why. If we could report detailed energy use, it would create an enormous opportunity for households to understand their consumption practices better, to determine actionable measures to increase their energy efficiency, and ultimately to reduce their overall consumption. Even a 10-15% reduction in electricity use across US homes represents nearly 200 billion kWh of electricity per year. The value of itemized or disaggregated energy data also extends beyond residents to scientists, policy makers, manufacturers, and utilities. However, a sensing solution that provides this information typically requires the deployment of many sensors, which does not scale easily. My group has developed new sensing techniques that use the existing electrical, plumbing, and gas infrastructure in the home to detect human activity and resource use [10]. The novelty of this approach is its use of the side effects (often thought of as "noise") of devices already attached to the existing infrastructure. The approach uses this noise as a signal to provide relatively precise indications of the use of home appliances or devices, which transforms the need for a fully distributed sensor network into just a few sensors. Past work in non-intrusive load monitoring (NILM) has largely focused on using features related to power and current consumption, whereas we have expanded this idea to include high frequency EMI noise now inherently being generated by more modern electronics devices as an additional source of information. In addition, we are one of the first to explore accurate water and gas disaggregation using a single attachment point that is easy to install (see Figure 1).

Figure 1: Example real-time interface of electricity usage and appliance-level breakdown in the home using the ElectriSense technology. Video Figure Link

Figure 2: ElectriSense uses EMI generated by electronic devices to infer appliance usage events. This method requires the powerline to be sampled only using a DSP at a single location.

For electricity, we have developed a system called ElectriSense, which consists of a *single plug-in* device for the entire house that monitors the household power line [10, 12]. The system can identify electrical events, such as turning on or off a specific light or TV, entirely through the analysis of noise transduced over the power line from the switching of these electrical loads (see Figure 2). By understanding and creating a theoretical model of the complex switching characteristics and the resulting electrical noise of different devices (e.g., switch mode power supply, triacs, etc), we can predict the use of those devices in the home, such as electrical kitchen appliances, TVs, CFL lights, etc. Using slight electronic component tolerances and the transfer function of the powerline, we can start to differentiate between devices that are of the same brand and model within a home. Through a training process, a user can label exact appliances (e.g., assigning names to multiple TVs in a home). As a result, the system can provide precise, high-level activity and individual device usage information. To associate power (in Watts) to each event, we developed an easy-to-install power meter for the home that simply attaches to the outside of the breaker panel [17]. The advantage of this solution is that any homeowner can install it without the need of an electrician (see Figure 3). The sensor infers the whole-home current draw through the magnetic field induced by the bus bars in the breaker panel, even through the galvanized metal cover. With the single plug-in sensor and the single “stick on” power meter, we can disaggregate usage down to each appliance and estimate its power use.

Figure 3: Easy-to-install power meter that a user can stick-on on the outside of a breaker panel.

In the water space, we have also built a system called HydroSense for monitoring water consumption and fixture-level use. HydroSense consists of an easy-to-install, screw-on pressure sensor attached at *a single location* on the plumbing infrastructure, such as an exterior water spigot [8, 11, 18]. The system analyzes characteristics of the pressure impulse generated when water fixtures are operated, inferring usage down to an individual water fixture, such as a sink, toilet, or dishwasher (see Figure 4). This is the first system to provide detailed water consumption analysis for residential feedback and water planning systems that does not require modifying the pipes. Past solutions in this space have relied on using flow data from in-line flow sensors to infer water use. However, flow-based approaches have trouble disaggregating compound events or fixtures with similar flow ratings. Our approach, on the other hand, can infer flow using a model of the pressure drop in the house as well as using the high frequency resonances generated from the use of water fixtures in the home. These resonances provide additional information about the valve characteristic of the water fixture and its uniqueness in the homes based on the propagation characteristics in the home. Initially, our approach focused on training the system by providing examples. Our most recent work has used the large dataset we have gathered through our deployments to create a CRF model for classification of water use events without explicit training. We have also applied similar signal processing principles used in HydroSense to gas sensing, which uses a simple microphone installed at the gas regulator of the home [15].

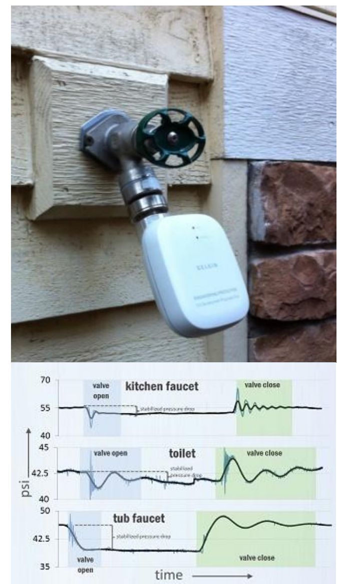

Figure 4: Top: HydroSense sensor installed on a hose spigot (from Belkin pilot). Bottom: HydroSense uses water pressure resonances to infer what fixtures are being used.

In addition to developing the sensing systems, we have also explored new feedback interfaces that can leverage this highly granular use data [2]. Through surveys, interviews, and deployments, we have developed a number of new water feedback interfaces for the home. Much of this work is now being carried out by Jon Froehlich as an Assistant Professor at the University of Maryland after recently graduating from our group (co-advised with James Landay).

Your Energy Efficiency Report

ComEd

CHAD SINGER
2216 S. BENTLEY AVE #9
LOS ANGELES, CA 90064

Your billing period	Total Cost	Compared to last bill	Compared to Similar neighbors*
Sep 1 - Sep 28, 2011	$161.68	$56.98 less (26%)	Similar

You reduced the amount of power used for air conditioning by 76% last month!

- That's 33% lower than that of similar neighbors!*
- If you maintain this level of usage, you'll save an estimated $271 this year.

Your dishwasher used 53% more energy this month than your neighbors'.

- You could save up to $180 a year by upgrading to an efficient dishwasher.
- If you find you often want to run the dishwasher before it is full, try the rinse-only feature common on newer models.

Your top energy consumers	Estimated Cost**	Compared to last bill	Compared to similar neighbors*
Electric Water Heater	$31.50	$8.12 (26%)	similar
Air Conditioner	$29.82	$48.23 (76%)	33% lower
Refrigerator	$22.66	similar	11% higher
Lighting	$13.90	$14.06 (53%)	21% lower
Dishwasher	$11.55	similar	53% higher
Stove	$10.01	$0.61 (5%)	6% lower
Dryer	$7.56	$0.63 (11%)	similar
Clothes Washer	$3.66	$0.09 (4%)	similar

THINGS YOU CAN DO RIGHT NOW TO IMPROVE YOUR EFFICIENCY

Target 68°
Save more on heating costs this winter. Setting your thermostat a few degrees lower will really add to your savings.

Insulate your water heater
Adding an insulating blanket to your water heater can reduce standby heat losses and save water heating costs.

Figure 5: Example ComEd utility bill that provides an itemized report on energy use, which uses our technology.

In an effort to make significant strides in the dissemination of our sustainability sensing work, I formed a company (Zensi, Inc.) to commercialize the energy and water monitoring technology. Through a successful exit, the company was acquired by Belkin International, Inc., who is now marketing, manufacturing, and selling this technology. By working with Belkin, local and national utilities, state and the national governments, and others in industry, we have access to new datasets that can be fed back into the research effort to refine and further develop the sensing solutions and machine learning algorithms; more importantly, we can use this information to develop new user interfaces and techniques that will promote behavior change by empowering consumers to reduce their personal consumption. ElectriSense is now part of pilots in the U.S., and customers are already getting itemized energy bills that provide detailed breakdowns of their energy use (see Figure 5). HydroSense is in the midst of late stage piloting and will be available through water municipalities and direct to consumers in late 2012 (see Figure 4).

Low-Power Wireless Sensing: Although IMS provides a method to gather rich activity information in a home by monitoring the home’s utility infrastructure, it is still inherently limited in the kind of information we can ultimately sense. There will still be a desire to deploy a rich set of sensors in an environment. However, a persistent concern of wireless sensors is the power consumption required for communication, which presents a significant adoption hurdle for practical applications. While battery-powered wireless sensor nodes are typically easy to deploy, to date they have not been easy to maintain due to the need to frequently change the batteries. Having truly long-lived (~25 years) and small wireless sensor nodes enables a breadth of applications in the home and other settings. These wireless sensors can be sealed and embedded in rigid devices with no requirement for wired connections to the outside environment, installed behind walls or hard-to-reach areas, such as crawl spaces and attics, or even inside the wall cavities of piping and ductwork.

We have developed an approach for wireless sensor nodes, which dramatically reduces the power consumption of each node while continuing to offer whole-home range. SNUPI (Sensor Nodes Utilizing Powerline Infrastructure) nodes contain an ultra-low-power transmitter that extends its range by coupling its wirelessly transmitted signal to the existing powerlines to obtain whole-home range [13] (see Figure 6). In the SNUPI system, only the base station receiver is wired directly to the powerline (*i.e*, plugged into an outlet). Each node in the sensor network transmits wireless signals that couple to nearby powerlines, creating signals that travel through the infrastructure to the base station receiver. In this way, the sensor nodes can transmit at much lower power because signals do not need to propagate over-the-air for the entire path to the receiver, they only need to propagate to the nearest powerline. By using this approach, we have been able to dramatically reduce the power consumption (less 70 µW peak) of the sensor's radio while still offering whole-house range and 10 kbps data rates. Interestingly, the transmitter consumes significantly less power than the low-power TI-MS430-based microcontroller, a role reversal in what dominates power use. My group is continuing to explore new modulation and communication schemes using this approach and is planning to eventually build a custom IC with an integrated radio and micro.

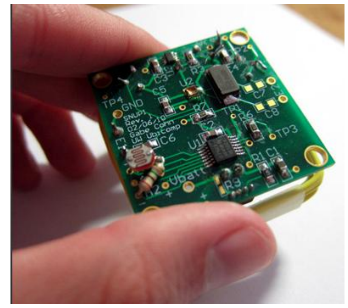

Figure 6: SNUPI nodes communicate with a single basestation by using the powerlines in a home or building as a receiving antenna.

SNUPI has generated significant interest, and we have started a new company out of UW that is now commercializing this technology.

Health Sensing: In the health space, we have explored both the applications of IMS for investigating indoor mobility patterns for rehabilitation as well as exploring new mobile health sensing approaches that leverage existing sensors already found on a phone. Indoor location tracking systems have been a major focus of ubiquitous computing research, and they have much promise to help in collecting objective data for home health and rehabilitation research. However, due to their typically difficult and time consuming installation process, we developed a technology called PowerLine Positioning (PLP) to enable practical residential location tracking for home health and rehabilitation research that would enable medical practitioners and researchers to collect more accurate and objective *in-situ* data in the home [16]. PLP is localization system that can track the location of tagged objects in a building to less than 1-meter. The installation involves a small number of simple, plug-in devices that use the physical electrical wiring in the building as the signaling antenna (opposite of SNUPI). Our custom tags are able to use the signals radiating from the power line to localize its position. Unlike RFID-based solutions, this system simply requires the installation of two plug-in modules for every 10,000 ft^2 of space, which allows a new class of applications to be explored. A number of researchers in nursing and rehabilitation have been using this indoor location sensing technology to automatically infer movement and activity patterns and correlate them to clinical outcomes. The gold standard has typically been an accelerometer-based solution called actigraphy, but PLP has allowed them to couple rich location information to data gather by an actigraph device.

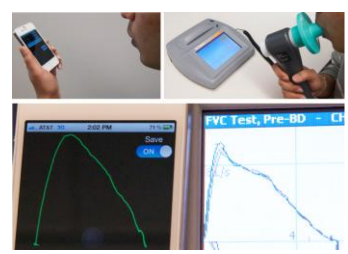

Figure 7: SpiroSmart (left) measures lung function (spirometry) using the mobile phone's built-in microphone and produces accurate results similar to a traditional clinical spirometer (right).

In the mobile health space, we are building a suite of pulmonary assessment tools. One is an objective cough monitoring tool that uses audio data from a mobile phone to classify the number of cough events in a day for individual with chronic pulmonary diseases [4]. This objective measure provides more accurate results than traditional self-reporting methods employed in the medical community. We are also building the first mobile phone spirometer (a device for measure lung volume and function) that does not require any additional hardware and still provides accurate lung function data (see Figure 7). The application works by holding the phone at arm's reach away and blowing at the screen [9]. Home spirometry is gaining acceptance in the medical community because of its ability to detect pulmonary exacerbations and improve outcomes of chronic lung ailments. However, cost and usability are preventing its widespread adoption. My group has developed a method of analyzing radiant sound from the lips and the resonances generated in the vocal tract via a simple microphone as a way of measuring airflow and flow-volume from the lungs. The goal of this project is to develop signal processing techniques using only the microphone for providing spirometric measurements and monitoring pulmonary ailments such as asthma, chronic obstructive pulmonary disease, and cystic fibrosis. One endemic problem in current lung monitoring systems is patient usage compliance and lack of objective trend data. This is largely due to system portability, cost, and lack of real-time feedback, which is something a mobile phone can provide. We are leveraging the mobile phone—an increasingly ubiquitous device that has substantial computing power. In addition, because of wireless network capabilities, our system can upload results and trends directly to the healthcare professionals, replacing expensive visits to the pulmonologist. Our application has already been evaluated with 52 patients and the initial results indicate that doctors can potential just use the data from our tool in making a diagnosis. We have just recently received funding to put SpiroSmart in practice in two large clinical trials and to apply for FDA 510(k) approval. Through a Coulter Foundation Grant, we are spinning out a small startup company called SpiroSmart that will continue the application development for the iPhone and Android platforms as well as create a self-management web portal for patients and doctors.

User Interface Technology: In the trend for developing new off-the-desktop user interfaces, computer vision and inertial measurement have made it possible for people to interact with computers using whole-body gestures. Although there has been rapid growth in the uses and applications of these systems, their ubiquity has been limited by the high cost of instrumenting environments for interaction. In collaboration with Desney Tan and Dan Morris at Microsoft Research, my group has been looking at new ways to sense whole-body gestures for user interfaces, called Humantenna. Our approach uses the human body as an antenna that receives existing electromagnetic (EM) noise from the power lines and electronic devices in a building [1, 7]. Specifically, we use changes in the observed signal that occur as the body changes pose (see Figure 8). We have shown that not only can we recognize various whole-body gestures in real-time, but also interactions with the physical environment (e.g., wall touches). This approach to sensing mobile whole-body interaction requires no instrumentation to the environment and only minimal instrumentation to the user using a single wearable device placed anywhere on the body.

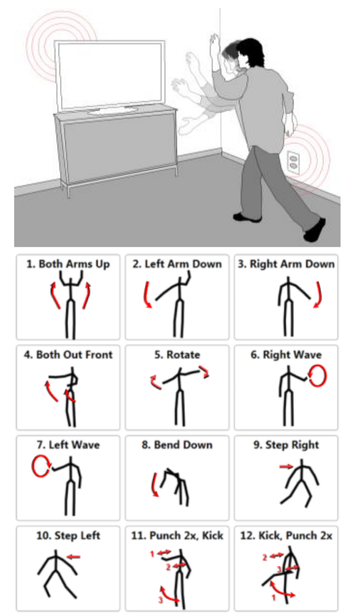

Figure 8: Humantenna detects in-air gestures by using the human body as an antenna. We can detect 12 different poses (bottom) in real-time. [Video Figure Link]

Haptic feedback or the sense of touch is a critical component of our interactions with the physical world. However, with the advent of on-screen keyboards, mobile devices, and at-a-distance interaction technology, there is a growing desire to replicate the physical stimulation loss with these digital devices. My group has been working on a number of haptic feedback systems for both mobile devices and for remote haptic feedback systems. For mobile devices, we have developed techniques for building virtual springs into mobile devices using a single motor, self-powered rotational haptic feedback devices, and ungrounded gyroscopic feedback systems for tablets [3, 5, 6, 14]. In our latest work, we have been exploring two techniques for an at-a-distance haptic feedback system that requires no physical contact or instrumentation of the human body. Imagine being able to provide haptic feedback to a person using a Microsoft Kinect, without having to put anything on the body. In one approach, we have used digitally controlled and generated vortex rings, which can be focused in a particular direction, can travel several meters without losing this focus, and can impart perceptible feedback. In a second approach, we are devloping an in-air haptic feedback system using high-intensity, beam-formed ultrasonic waves to generate acoustic radiation pressure at distance of up to 2-3 meters. Although promising, we are still investigating new beam forming strategies to increase efficiency for longer ranges.

Teaching: At the graduate and undergraduate level, I have tried to create an exciting learning environment for students interested in the applications of hardware and software. Most significantly, I created a new graduate course in Ubiquitous Computing, which is a course that incorporates a combination of topics covering a wide variety of disciplines that impact ubiquitous computing, human-computer interaction, distributed systems, embedded systems, software engineering, networking, and electrical engineering. The aim of the class is to explore the area of ubicomp and allow students to work on a variety of small technology projects by exposing them to the basics of building ubicomp systems, emerging new research topics, and advanced prototyping techniques.

For our undergraduate embedded systems class, I decided to revamp the class by introducing the AR Drone platform into the class as a way to directly apply the important concepts in embedded systems. Having a fun and engaging platform made it much easier to teach the theoretical concepts. I have been using the AR Drone for three years now and it has been a huge hit with an overload list of 25-30 students (for a 40-50 person class) each offering. The students ended up getting into much more advanced topics than I would not normally have had time to go into because they were so motivated, which also helped them in subsequent classes in their sequence. Some students said "*472 [this class] was the reason why I decided to specialize in embedded systems"* and *"I'm glad I deiced to learn I2C and TWI for the final project, because it helped out in 478 [the second embedded class]."* Other schools, including high schools, are also replicating what we did with the class, and we are sharing class notes, code, and course content. The students even independently created their own commemorative website about their experience in the class, which includes videos of students reflecting on their experience in the class and what they learned with this new approach. (http://www.filikagroup.com/ee472/).

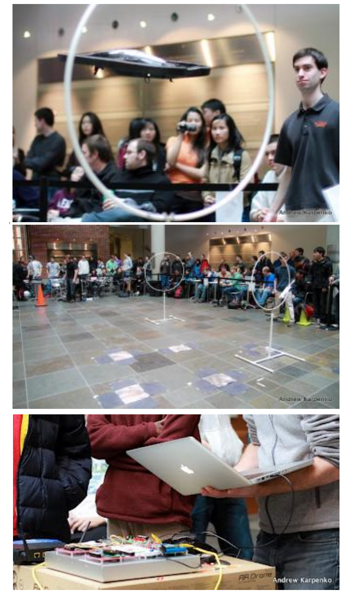

Figure 9: Students built embedded wireless controllers to communicate with the AR Drone's embedded sensor system to autonomously navigate it through an obstacle course.

In terms of graduate student mentorship, I advise a wide range of students in Computer Science & Engineering and Electrical Engineering. Their expertise ranges from circuits and embedded systems, to signal processing and machine learning, to human-computer interaction. We have been able to create an exciting lab environment where we can truly work on interdisciplinary research projects, while still giving each student the ability drill deeper in their respective areas.

Finally, I have been actively working on a number of K-12 outreach programs. This is something that is a personal interest of mine, since I was actually first exposed to research while in high school. That experience really made a difference for me in my career choice. Thus, I want to be able to share that experience with others. I created the *"Start Early"* program in 2009, which allows high school students to work on actual research projects for a 3-4 month period during the summer in our lab. The goal of this program is give them firsthand exposure to what it means to be a researcher and have them work on an active project. We have had great high school students go through this program, but in 2011 I had the most successful student thus far. The high school student was a first author on a CHI paper, which also received the best paper award. The CHI organizing committee informed me that was not only the first award winner, but he was also the first high school student to present at CHI at a paper session. I continue to be active in various other outreach programs such as the College of Engineering's Engineering Discovery Days. My lab usually hosts hundreds of high school students each year through these programs.

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