Exploring Widespread Deployment through Infrastructure-Mediated Sensing

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Ubiquitous computing research in the home has traditionally involved approximating the actual home environment with a "living laboratory," which is equipped with a rich set of sensors, network infrastructure, and computation resources. Living laboratories such as the Aware Home at Georgia Tech and the PlaceLab at MIT allow the deployment of a large variety of sensors to capture human activity inside the home. Sensor infrastructures deployed in a living laboratory can be experimental in nature and do not need to meet the cost, stability, robustness, scalability, aesthetics, or maintenance constraints that would confront a sensor system suitable for deployment by ordinary consumers in their own homes. This approach, while extremely valuable for developing applications in a controlled setting, does not provide high quality data about the real-world utility of the applications that are developed and does not scale to actual homes.

This position paper discusses a technique called "Infrastructure Mediated Sensing," or IMS. IMS refers to the use of existing home infrastructure to sense human activity through the detection and classification of human activity within a home. The electrical, plumbing, and HVAC systems, as well as natural gas piping and computer networks, are widely available, existing infrastructures that can be used to sense when the home occupants do activities that relate to those infrastructures. In addition, sensing systems can use those infrastructures to transduce custom signals through a home. This type of sensing has an advantage over the distributed direct sensing method by reducing the need for the installation of many sensors throughout a space. Some researchers have experimented with sensors that are built into (or built from) widely used digital devices, such as cameras or Bluetooth radios in cell phones or the accelerometers that are built into popular smart phones, such as the iPhone or Nexus One. The attractiveness of this approach is that millions of these consumer devices have been sold worldwide, and they are highly refined and well understood technologies that are accessible to a wide variety of people across a wide variety of demographics. IMS employs a similar strategy for home-based sensing.

We have preliminarily explored five different IMS systems that leverage electrical, plumbing, gas, and heating, ventilation, and air conditioning (HVAC) systems in a home. The first, known as PowerLine Positioning (PLP), is a technology that uses the powerline infrastructure in a home for localizing tracked objects down to 1-meter. PowerLine Positioning is the first example of an affordable, whole-house indoor localization system that works in the vast majority of households, scales cost-effectively to support the tracking of multiple objects simultaneously, and does not require the installation of any new infrastructure. The solution requires the installation of two small plug-in modules in a home. These modules actively transduce a signal throughout the electrical system of the home. Simple receivers, or positioning tags, listen for these signals being radiated from the power lines (which act as large antennas) and wirelessly transmit their positioning readings back to the environment. A fingerprinting approach allows for the assignment of a meaningful label to the corresponding signature in signal space.

In a recent advancement of this concept, 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 in order to obtain whole-home range. 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.

Using a more passive approach, we have developed PowerLine Event Detection, which uses human-initiated electrical events as a proxy for determining location and activity within a home by sensing at a single point in the home. It consists of a single plug-in sensor that can classify electrical events, such as turning on or off a particular light, through the analysis of noise transduced along the power line from the switching and operation of electrical devices. Unlike past power consumption-based approaches, this solution is able to differentiate between the actuation of similar electrical devices, such as distinguishing both the on and off transitions between two similar light switches in a bedroom. Other electrical events like opening a garage door, opening a refrigerator door, turning on the stove, or using a hair dryer are also possible to detect and distinguish. To date, the power line event detection approach has shown average classification accuracies of over 88% in 25 different homes of varying sizes when classifying 60-70 different electrical events through controlled experimentation. This technique uses a learning approach on the spectrographic signal to determine the unique switching of electrical devices (both the transient noise from momentary switches and the continuous electrical noise produced by switch-mode power supplies), resulting from its location along the power line and the characteristics of the appliance itself.

We have looked at another IMS-based approach for the plumbing system that requires only a single sensor installed at any water outlet, such as a hose faucet, called HydroSense. This system analyzes and learns the water hammer phenomenon that occurs during the operation of valves in water fixtures. The average accuracy of classifying a specific fixture is nearly 90%. Not only can each fixture be detected, it can also identify the flow rates for cold and hot water events.

We have also explored human movement by sensing at single point in the home. This approach leverages the residential HVAC system. By measuring pressure differentials across an air handler unit, we were able to develop a system that is capable of identifying movements through doorways in a home, including the opening and closing of doors and the movement of people through doorways. This information is useful in determining the general movement and motion of people throughout a home. The latest version of this system involves a single sensor pack that is attached to the air filter, making it a very easy-to-install solution. Preliminary results from movement detection using pressure changes in the HVAC system have shown that it is possible to classify the opening and closing of specific doors with up to 80% accuracy with the HVAC in operation and 68% with the HVAC not in operation.

Infrastructure-Mediated Sensing (IMS) leverages the existing home infrastructure, such as the plumbing or electrical systems, to sense events in the home and also serve as a proxy for human activity. The primary goals of this new sensing approach are to reduce the economic, installation, aesthetic, and maintenance barriers to adoption of practical wide-scale sensing. This white paper introduces this concept as a means for potentially enabling large-scale explorations of ubiquitous computing technology in the home.