# Internet of Things: a review of literature and products

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**ABSTRACT**
This paper offers an HCI perspective on the emergent agenda of the Internet of Things (IoT). The purpose is to provide insights and resources for how HCI could engage productively with the IoT agenda while it is still evolving and being realised. We examined and reviewed HCI-related literature and commercial products of the IoT, categorising a final collection of 89 research papers and 93 commercial products into two tables. Through this, we are able to provide a snapshot of the types, extent and foci of both research and commercial efforts. It has also revealed trends, opportunities, as well as gaps for how HCI could proceed when engaging more deeply with the IoT. Finally, this review provides insights for HCI, suggesting tools, methods and potential approaches that can help ensure a human-centred IoT.

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Internet of Things (IoT); Commercial Products; Design; Survey;

**ACM Classification Keywords**
H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

## INTRODUCTION

The Internet of Things (IoT) refers to a broad vision whereby 'things' such as everyday objects, places and environments are interconnected with one another via the Internet. An example of a simple IoT object now available in some homes is a thermostat which can determine when people occupy certain rooms and alter levels of heating, lighting and other functions in the house accordingly. By widening the Internet from "a network of interconnected computers to a network of interconnected objects" (Commission of the European Communities 2009), the IoT will include a vast and intricate network of devices. These devices will include sensors to measure the environment around them, actuators which physically act back into their environment such as opening a door, processors to handle and store the vast data generated, nodes to relay the information and coordinators to help manage sets of these components. Through this, it has the potential to significantly extend, enrich and even shift the relationship between people and the world around them. In fact, many are hoping that the IoT will play a pivotal role in addressing many of today's societal challenges such as an ageing society, deforestation, traffic congestion and recyclability. This interconnection of physical objects is expected to amplify the profound effects that large-scale networked communications are having on our society, gradually resulting in a genuine paradigm shift (Botterman 2009).

Yet, there is still no stable definition for the IoT. This perhaps reflects the emergent nature of the IoT vision and that it encompasses a range of divergent research groups. Most definitions consist of highly technical terminologies identifying the IoT in terms of a network, services, infrastructure, protocol, and so on (EPOSS 2008, IoT-A http://www.iot-a.eu/public/terminology). Some research groups have highlighted human-related concerns such as privacy, security and trust but even so, they are approached from a very technical point of view (e.g. Chen 2012; Romana et al. 2013). HCI involvement could provide a human-centred contribution, ensuring that people become the central focus of the IoT vision (Koreshoff et al. 2013).

To date, HCI has engaged with technologies that bear some characteristics of those proposed for the IoT. In particular many efforts around ubiquitous and pervasive computing include Internet technologies for sensing, monitoring, tracking and actuating. The primary vision of ubiquitous and pervasive computing is similar to that of the IoT, in that they seek to design computers which are a "part of the environment, embedded in a variety of everyday objects, devices and displays" (Sharp et al. 2007 p218). We would argue that tangible and wearable computing (Ishii 2008; Reichl et al. 2007), which focus on embedding computing into everyday objects, also share many attributes of the IoT. However, the key distinction between these explorations of technology and the IoT is the notion of interconnectivity. What we mean by interconnectivity is the potential for multiple connections to be made, and data shared, between all objects of the IoT. Efforts within pervasive, ubiquitous, tangible and wearable computing to date often consist of only one device connecting to one data source, whereas the IoT promotes the concept of an ecosystem where one device is speaking to many things (Berzowska 2005).

In this paper, we review recent HCI-related literature as well as commercial products associated with the IoT vision. One aim is to provide a resource for the general HCI audience to understand the current state of research associated with the emergent IoT agenda. A second aim is to highlight ways whereby HCI can progress into engaging more productively with efforts of the IoT. This


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is achieved through enabling a dialogue between the findings of our literature review and the commercial offerings, revealing opportunities, directions, gaps, and future approaches for HCI as it engages more fully with the IoT. Next, we will describe how we conducted our review. Following this we will present the findings, including two tables that categorise recent research and commercial efforts related to the IoT. We then use these as the basis for discussing how the HCI community can engage with the developing vision of the IoT.

## METHOD

We explored both HCI-related literature as well as commercial offerings related to the IoT. With HCI-related literature, we used keyword searches (e.g., Internet of Things, sensors, connectivity, etc.), drawing from the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI) proceedings as this is the premier HCI conference. Considering the close relationship identified between efforts such as ubiquitous computing and the IoT, we also surveyed articles from the journal of Personal and Ubiquitous Computing (PUC). Given the fact that the IoT is still a relatively new research domain, we limited our search to the last four years. Another reason for this limitation was the sheer number of articles available annually from these publications (from CHI and PUC alone there was a combined 1,793 papers). We then expanded our search to yield articles from the ACM Ubicomp Conference, European IOT research clusters, and technical reports. We found that very few papers mentioned the term 'IoT' explicitly. Hence we expanded our search criteria to include papers which dealt with devices that could both monitor or track their environment through sensors, and had the capability to transmit that data – common elements of the IoT. This led to a total of 43 papers from CHI and 46 papers from PUC.

We then reviewed each of these papers, classifying them into different categories based on the main focus of their contribution(s). Using an iterative affinity sorting process, we reached a final set of three categories, sub-divided into domain-specific, activity-related, and system-centric pursuits. In all, we identified 17 main areas of focus within the literature surveyed.

Besides HCI-related literature, we also surveyed over 300 commercial products. These products were gathered from recent consumer electronics show proceedings, specialist sites (e.g. postscapes.com) and online searches. We limited our search to primarily everyday products, as opposed to industrial solutions such as RFID parcel tracking. Following the same criteria used for selecting relevant literature, we chose products that were able to both gather and transmit sensor data, culling the 300 down to 93 products. It is worth noting that the majority of products chosen do display some sense of interconnectivity, for example home lighting that is able to reflect environmental and social events. We then categorised these products according to the tasks they are primarily used for or domain they primarily focused on, for example home security or fitness tracking. This resulted in 20 categories of products. Then, we listed the sensors used, what they measure, how people could use them and in turn how they communicate with the user.

## FINDINGS

This section presents the findings from our review of 89 papers and 93 commercial products related to the IoT.

### Reviewing literature of the IoT

Our review of HCI-related literature (refer to Table 1) identified three categories of research efforts that reflect different approaches taken within design research projects. They are: i) evaluating for design ideas, ii) exploring systems through design and iii) exploring technical components through design. Due to space limitations, we have only included one reference to exemplify each area of focus under each of these three categories within Table 1. Paper counts from CHI proceedings and articles from PUC have been added to indicate the spread of literature across different categories. We detail our findings below under each of our three categories.

#### *Category 1: Evaluating for design ideas*

One area of HCI research is concerned with evaluating existing systems for ideas that can be used in future designs. We found research within four domains of interest, *utilities, smart home, healthcare and wellbeing* and *personal data and privacy.*

The first domain, *Utilities*, was mainly concerned with evaluating home electricity practices with a view to lowering usage (e.g. Pierce and Paulos 2012). Other home utilities were also explored, such as Internet bandwidth (e.g. Erickson et al. 2013). Another home-related concern was the evaluation of a wide array of objects in the home and the concept of a *smart home* (e.g. Brush 2011). *Health and wellbeing* was a large area of investigation, spanning from the evaluation of instrumented objects around the home meant to support people who regularly take medicine (Garcia-Vazquez et al. 2011), to evaluating whether older people or those with health concerns would benefit from new technologies such as surface computing (Piper et al. 2010). Some papers around health also began to explore the implications for health and data privacy that arise from new medical technologies (e.g. Denning et al. 2010). *Personal data, security and privacy* are prominent concerns that underlie many evaluations of IoT technologies. Explicit evaluations of privacy in ubiquitous computing include studies on the changing notions of privacy (e.g. Lin et al. 2013). Privacy literature in the IoT was found to be limited to whether the potential proliferation of monitoring devices can inadvertently portray more information than people thought was being monitored (e.g. Raij et al. 2011).

#### *Category 2: Exploring systems*

As Table 1 shows, HCI efforts in exploring systems was the most engaged and diverse of the three categories, covering 55 of the 89 papers we investigated. These efforts explored (i) domain-specific explorations such as *health and wellbeing,* and *personal development*, (ii) activity-related explorations such as *tracking people, automating* and *making the invisible visible*, and (iii) system-centric explorations such as *interfaces* and *exploring components working together.*

| Area of focus | Example | Number of papers |
|---|---|---|
| **Category 1: Evaluating for design ideas** | | |
| *Domain (18)* | | |
| Utilities | Pierce and Paulos (2012) | 5 (CHI) |
| Healthcare and well-being | Garcia-Vazquez et al. (2011) | 1 (PUC) 5(CHI) |
| Personal Data Security/Privacy | Raij et al. (2011) | 2 (PUC) 3 (CHI) |
| Smart Home | Brush et al. (2011) | 2 (CHI) |
| **Category 2: Exploring systems** | | |
| *Domain (16)* | | |
| Healthcare & wellbeing | Jara et al. (2011) | 10 (PUC) 3 (CHI) |
| Personal development | Nakajima and Lehdonvirta (2013) | 3 (PUC) |
| *Activity (20)* | | |
| Tracking people | Cafaro et al. (2013) | 5 (PUC) 2 (CHI) |
| Automating | Davidoff et al. (2010) | 3 (CHI) |
| Revealing the invisible (Utility/Environmental/Privacy) | Gaver et al. (2013) | 2 (PUC) 8 (CHI) |
| *System (19)* | | |
| Interfaces | Su et al. (2013) | 3 (PUC) 2 (CHI) |
| Components working together | Van der Vlist et al. (2013) | 10 (PUC) 4 (CHI) |
| **Category 3: Exploring technical components** | | |
| *System (14)* | | |
| Input | Harrison et al. (2010) | 2 (PUC) 3 (CHI) |
| Data processing and reasoning | Hong and Nugent (2013) | 5 (PUC) 1 (CHI) |
| Network | Chen et al. (2011) | 1 (PUC) |
| Middleware/Agent | Munoz et al. (2011) | 2 (PUC) |
| *Domain (2)* | | |
| Privacy | Marquardt et al. (2010) | 1 (CHI) |
| Utilities | Patel et al. (2010) | 1 (CHI) |

**Table 1: Summary table of relevant HCI-related literature, with one example paper from each area of effort**

Efforts surrounding *Healthcare and wellbeing* focused on a wide range of areas, including the power of real-time health data to inform diagnosis and treatment (e.g. Curmi et al. 2013). However, the majority of papers explored how illnesses could be better supported, either through connected objects specifically designed for the task (e.g. Jara et al. 2011), or through utilising and repurposing already available tools such as mobile phones (e.g. Hynes et al. 2011). A subset of efforts explored how to motivate people by creatively representing tracked data back to them in order to promote *personal development*. For example, using a bathroom mirror to reflect individual tooth-brushing behaviour with the aim to give feedback on brushing habits (Nakajima and Lehdonvirta 2013). Virtually all health and wellbeing, and personal development related IoT explorations we surveyed dealt with the monitoring and tracking of personal body metrics.

One example of activity-related research is concerned with *tracking people*, which included tracking people's movements and social dynamics. This tracking occurred both on a personal level, often to allow a system to interpret individual activities and respond accordingly (e.g. Lepri et al. 2010), as well as on a group level, generally to understand group movements or customise experiences for individuals within groups (e.g. Cafaro et al. 2013). Using tracked data from devices in the environment also allowed explorations of *automating* systems, where a system was able to learn about human routines and use that data to support activities in the home such as planning day-to-day events (e.g. Davidoff et al 2010). *Revealing the invisible*, that is measuring and representing data not ordinarily visible to people, was explored in fields such as utility usage (e.g. Weiss et al. 2012), environmental quality (e.g. Jacobs et al. 2013) and privacy safeguards (e.g. Benisch et al. 2011). This usually invisible data was most commonly communicated to people through commonly found screens such as mobile phones and tablets.

Some systems-centric papers proposed altogether new *interfaces* for connecting to other objects, thereby promoting interconnectivity more heavily than most other papers reviewed (e.g. Su et al. 2013). While others focused more broadly on creating connections between devices by exploring how *components worked together*, for example creating new ways to link components such as lights and sound systems together (Van der Vlist et al. 2013), or using audio feedback to add new devices to a home network (Costanza et al. 2010). While the above focuses on the exploration of systems as a whole, explorations of individual technical components, which we will explore next, also featured significantly in our review.

### *Category 3: Exploring technical components*

Efforts within the third category are those which explore individual technical components through design. These primarily consisted of (i) system-centric explorations such as new *inputs, networks, middleware and agents,* and *data processing*, and (ii) domain-specific explorations such as *privacy* and *utility* usage.

*Inputs* were a popular component investigated in system-centric explorations. A lot of research efforts focused on using the human body as a new source of interaction and input (e.g. Saponas et al. 2010; Harrison et al. 2010), as well as instrumenting the environment around the body (e.g. Rantala et al. 2011). Whilst most efforts acknowledged that their new component or device could be used to communicate in an ecosystem with multiple other devices, few papers considered in depth the possibilities this new level of communication could afford, nor the ramifications of this on other devices or the people that use them.

The key concerns and potential new designs for *networks* to handle the interconnectedness and increasingly ubiquity of IoT objects (e.g. Chen et al. 2011) were not well represented in the literature we surveyed. However approaches to *data processing* were well represented, including efforts that examined algorithms to process the vast amount of sensor data gathered by IoT objects in smart environments, as well as ways to repackage meaning through data (e.g. Hong and Nugent 2013; Grosse-Puppendahl et al. 2013). Software components, such as middleware and agents that allow much of the interaction between objects over the network to occur, are also being explored in limited quantity for their potential role in facilitating the interconnectedness of the IoT (e.g. Gamez and Fuentes 2011; Munoz et al. 2011).

Domain specific explorations such as *privacy* looked at how components can directly signify to a user when and where they are sending personal data (Marquardt et al. 2010). We also found efforts around the domains of *utility* tracking and investigating ways to increase the ease with which new devices are progressively added into a house.

### Reviewing commercial products of the IoT

In examining our 93 commercial products, we found that they reflected the market differentiation between *person-centric* and *home-centric*. In the following section we will discuss both of these categories in greater detail, highlighting the most common concerns and uses of these technologies. We also detail the types of sensors and the common ways whereby people could interact with these devices. Table 2 presents our results in more detail.

#### *Person-centric*

A *person-centric* product is one that is primarily designed to gather data about the human body, commonly by being worn or continuously carried. We found such concerns to focus mainly around tracking and logging, such as tracking *sleep*, *body, fitness and weight,* and logging of *events.* More unusual foci in this area included *audio-visual* and *event logging*, where the device is used to deduce the activities a person engages in by constantly logging audio and visual stimuli the body comes in contact with. Similarly, *EEG* tracking devices are used to constantly measure brainwave activity using small head-mounted devices, often with the goal of understanding how concentration levels may be affected by activity.

Our examination of the products revealed that the most common way for people to interact with these devices is through direct physical interaction, such as wearing the device or in the case of scales, standing on it. The second most common interaction style is to allow people to interact with a device through a mobile phone app. This is unsurprising, as people commonly carry their mobile phones with them. This proximity makes it easy to establish a direct connection between the mobile phone and the IoT device. Allowing the pairing of connections between mobile phones and other IoT devices carried on the person may be desirable as the phone has a larger display area and longer battery life than most of the person-centric devices we surveyed. These capacities of mobile phones take the strain off these IoT devices. With the phone doing most of the processing and displaying, the IoT devices' battery life and functionalities can also be extended.

We found that accelerometers were the most commonly used sensors amongst person-centric devices. This perhaps underscores the fact that accelerometers have been widely used and are an established sensor in other person-centric devices, such as mobile phones. Given this, it is unsurprising that we found many of the commercial products were designed to measure people's movements. In addition we found other sensors, such as EEG and EMG (see Table 2), used to represent body movement and activities. When combined with accelerometers, these sensors were able to give a more detailed picture of people's movements.

While physical interactions such as wearing or carrying the device were the most common way for people to interact with a person-centric device, how these devices communicate back to the user is often quite different. Our review revealed that these devices are commonly designed to communicate back to their users through a mobile application. For example, most fitness tracking devices are designed to gather data about the user while being worn during exercise, yet the gathered data can only be transmitted back to the user via a mobile phone application. This highlights the fact that many of the current person-centric devices are primarily designed only to log and transmit (people-related) data, and not to be a directly interconnected device in their own right.

The transmission of data gathered by these devices to a mobile phone has allowed for some form of *limited* data interconnection. In other words, data gathered from person-centric devices can, in some cases, be passed on to *other* devices besides the phone. This early form of interconnection suggests the possibility for a wider range of inputs and interactions with these devices. For example, if a fitness tracker is able to interconnect and transmit data with other objects, it opens up the possibility for the fitness tracker to gather data from objects such as gym equipment. In turn this data could be used to support aspects of fitness progress awareness, such as shopping suggestions to support the person's fitness regime.

#### *Home-centric*

*Home-centric* products were found to be designed to remain and function in the home. They primarily gather data about their immediate environment, which may include people, objects within the house, or even the house itself. An example of an application that is centred on people is a home security system that monitors for intruders. Applications centred on objects within the house included tracking the usage of certain items, such as how often a toothbrush is used. Applications centred on the house itself included utility monitoring and the automatic unlocking of doors. Overall, we found quite an even split between devices that are designed to monitor, and devices that can actuate, such as locking doors or altering the lighting and heating in a room. While home-centric products were primarily designed (and marketed) to be used within the domestic setting, it should be noted that many could also be repurposed in other enclosed environments such as an office space.

Interestingly, home-centric products that displayed greater interconnectivity were also used in more unusual applications. Products grouped under the category of *frequency tracking* and *configurable platforms* reveal the increasingly interconnected nature of such devices, where data from one device can trigger an action from another device. Devices designed for *frequency tracking* within the home are instrumented, often with the use of stick-on sensors, in order to transmit usage data about household items to a central server (often on the 'cloud'). This server then uses that information to trigger actuation in another device. For example, a toothbrush that can measure usage could remind you via your phone (or any object you choose) to brush your teeth before you leave the house. Devices designed as c*onfigurable platforms* are a group of tracking and actuating devices that can be placed around the home. They are often pre-programmed to work together in order to accomplish a myriad of possible user-designated tasks. For example, a sensor can monitor temperature and air quality, and then when a certain temperature or quality of air is reached, sends a signal to another device (an actuator) which opens the window.

There was a greater variety of sensors used in *home-centric* products than *person-centric* products. This perhaps reflects the more varied environments found within the home. Contact sensors, which are primarily designed to measure whether a door or window was open or closed, were the most commonly used. Motion, presence and camera sensors, which were used to measure people's movements in particular household spaces were also popular. These sensors allow for tracking and actuation based on human movements without the need to wear specialist devices while in the home.

Picking up or using home-centric devices was the most common form of interaction input, closely followed by touch-screens on the object itself. This likely reflects the fact that products designed for the home are under less pressure to be smaller and use less power, compared with devices designed to be worn. Interestingly, mobile phone notifications were again the most common way for devices to communicate back to people. This perhaps suggests that designers of such products assume people would always carry their phone with them, even within the house, and/or people care about being connected to and notified about their house when they are away.

We found *home-centric* devices are generally designed to have a higher level of direct interconnection with other devices, whereas *person-centric* devices are generally paired with a mobile phone and rely on it for connection to other devices. *Home-centric* devices also demonstrated a greater ability to alter the environment around them, either directly or via home objects such as air-conditioners and electronic door locks. This could be because home devices exist within a more controlled environment, where devices can be specially set up to work together. Person-centric devices, however, cannot rely on the specialist setup of a controlled environment, as they are constantly moved between locations.

Both *person-centric and home-centric* devices seek to tackle similar goals, such as monitoring, tracking and awareness. However, we found devices situated in the home were designed with a greater sense of interconnectivity and a greater ability to act directly back into their environment. In the next section we discuss these findings with the aim of identifying challenges and opportunities for HCI involvement with the IoT.

## DISCUSSION

Our review found very few efforts within the HCI literature that directly discussed the IoT. Furthermore, we found very little of the established HCI literature to be concerned with the truly interconnected objects of the IoT. This perhaps highlights that many more research efforts are needed in order to achieve the large-scale network of interconnected physical objects that make up the IoT. Yet, as Table 1 shows, current efforts (particularly that of ubiquitous computing) are making strides in better understanding tracking, monitoring and acting, which are similar to pursuits of the IoT vision. For HCI research to engage with the IoT in a more concerted way, we will need to first examine the domains and activities we are trying to support and the systems we are designing. Understanding current efforts, in both academic and commercial settings, can enable us to reflect on and explore ways in which interconnectivity can be incorporated into our practices.

### Discussion of HCI-related Literature

The summary of our HCI literature review, predominantly reviews ubiquitous and pervasive computing efforts. As already stated, there is a lack of explicit involvement with the IoT in this literature, though a recent exception is a NordiCHI paper by De Roeck et al. (2013), who presented a manifesto for designers and developers of the IoT. But given that the efforts and concerns of HCI-related ubiquitous computing are similar in many respects to the vision of the IoT, such literature would be a natural entry or continuation point for an HCI exploration of the IoT. Therefore it is likely that work with a strong current focus in HCI-related pervasive and ubiquitous computing literature would continue to have a strong focus in the beginnings of an HCI exploration of the IoT.

| | Category | Inputs and Sensor Types | User input interaction | How it interacts with you |
|---|---|---|---|---|
| **Person-centric** | **Sleep quality, EEG (Brainwaves)** - e.g. Somnus Sleep Shirt - *track movement and brain activity while asleep;*<br>Melon - *track brain concentration levels* | Accelerometer, EEG | Wearing the device, mobile app | Alarm, web app, app notifications, |
| | **Body tracking, Fitness tracking** - e.g Leap motion - *body control for computers;*<br>Basis bands - *Track fitness and body physiology* | Accelerometer, camera, electro-muscle sensors (EMG), thermometer, electrical conductance sensor, optical blood flow sensor | Movement, wearing the device, mobile app, buttons | Screen on object, web app, app notifications |
| | **Weight tracking** - e.g. Withings Wifi Bodyscale - *track weight and air quality over time* | Pressure, air quality | Standing on the scales, mobile app, web interface | Screen on object, web app, app notification, limited data interconnection |
| | **Audio-visual logging, Event logging** - e.g. Memoto - *continuous logging and transmission of activities*<br>Lena Baby monitor - *tracking the words a baby uses* | Accelerometer, camera, microphone, magnetometer, GPS | Wearing the device | Screen on object, web app, app notification, limited data interconnection |
| **Home-centric** | **Home appliances, Lighting** - e.g. LG SmartFridge - *adjusts temperature based on contents, orders food, suggests recipes;*<br>iRobot Roomba – *automatic vacuuming;*<br>Lifx – *internet-controlled light globes* | RFID, NFC, contact, thermometer, contact sensor, infrared sensor, radio-frequency sensor, light switch, third party data sources | Screen on object, mobile app, using the object, buttons | Screen on object, app notification, environment alteration, data interconnection, |
| | **Home security, Locks** - e.g. ismartalarm - *automatic home monitoring;*<br>Lockitron - *presence activated automatic house locks* | Contact, motion, video, microphone, twist sensor, buttons | Mobile app, movement, object use | Alarm, app notification, phone call, environmental alteration |
| | **Utility measurement, Environmental awareness** - e.g. WattVision - *tracking electricity, water, gas and internet usage;*<br>Nest thermostats - *adjust temperature based on room occupancy* | Thermometer, motion, light, buttons, inductive clamp, microphone, router | Utility usage, mobile app, screen on object, web interface | Environment alteration, screen on object, web app, limited data interconnection |
| | **Garden monitoring** - e.g Botanicalls - *monitor plant health to trigger watering or alerts* | Electrical resistance, light meter | Watering the plant | App notification, limited data interconnection |
| | **Frequency tracking, Location tracking** - e.g. GreenGoose - *stickers that track the duration of object usage;*<br>BiKn Tags – *attachable tags that allow object and person tracking* | Accelerometer, Zigbee, GPS | Moving the object, movement, web interface | App notification, web app, limited data interconnection |
| | **Reminders and Notifications** - e.g. Vitality GlowCaps - *bottle caps that remind you to take your medicine* | Accelerometer, contact, third party data sources | Moving the object | Screen/lights on object, app notification, phone call, SMS, limited data interconnection |
| | **Configurable platforms** - e.g. SmartThings - *components that are built to be reconfigured based on the task needing completion* | Accelerometer, motion, moisture, presence, contact, temperature, power | Moving the object, using objects, movement, mobile app | App notification, web app, environment alteration, data interconnection |

**Table 2: Summary table of relevant IoT-related commercial efforts**

We can explore the various domains, activities and systems prominently found in current literature and how these efforts could be extended towards developing technologies for the IoT. To date, it appears that healthcare and wellbeing, as well as home utilities, are the domains that most interest pervasive and ubiquitous researchers. We could envisage IoT technologies, specifically around the integration of interconnectivity, playing a greater role in developing these research areas. For example, in a domestic setting, we already have a range of scenarios for an ecosystem of connected objects, which would allow a person approaching the home to trigger events within the home such as alteration of climate and lighting and the unlocking of the front door. We could extend this and envisage having information, about for example the current state of wardrobes or grocery supplies, accessible outside the home.

Table 1 also highlights the limited number of areas currently explored within the HCI literature we reviewed. We found these areas to be mainly centred on the home, health, aged-care and personal data. At the same time, we can see the potential for HCI researchers to explore how IoT technologies can be applied to a wider range of domains and settings. For example the workplace, leisure, ageing and even education, could really benefit from the additional interconnectivity provided by the IoT. HCI's involvement with the IoT will likely stem from current pervasive and ubiquitous computing's concerns but there are clearly opportunities to investigate the benefits of engagement with domains not currently considered.

We have categorised HCI-related ubiquitous and pervasive computing efforts as either *evaluative* or *exploratory*. While such approaches are common in HCI research, efforts to understand the technologies and possible scenarios of use through user studies was missing in the literature we reviewed. We can see the need for HCI researchers to consider how they can engage users more in the development of technologies. This is crucial in order to ensure that people are central in the development and design of this emergent vision.

Furthermore, we found that much of the literature we reviewed was technologically-focused explorations of how new technical systems can support particular domains and activities. Even literature that touched on human concerns such as privacy have approached such issues from a purely technical feasibility standpoint (Riboni & Bettini 2012), without considering what privacy might mean for people in such an interconnected environment and how this is experienced. Despite this techno-focus, we acknowledge that such technical efforts are not trivial problems. Technical pursuits are key to building the infrastructures and components that will underpin the IoT. It is while these technical efforts are still evolving that HCI has the opportunity to ensure that a concern for people remains at the centre of the emergent efforts to realize the IoT.

One approach to ensure a human-centred focus in the evolving agenda of the IoT is to draw upon Participatory Design. This is because Participatory Design has an inherent concern for co-designing with people, encouraging people to imagine and shape how technology can best work within their lives. Participatory approaches may prove to be especially conducive to designing technologies for the IoT, as many of these will be used outside the organisational prerogatives of the workplace and rely on people making choices about the technologies they use.

While we found very few examples of HCI research producing IoT technologies for people to use, we can imagine user studies that use commercially available IoT products as stimuli to envisage future designs. Such products can also act to inform understandings of how technologies of the IoT can be used and appropriated by people in their everyday lives. Finally, these commercial products can be used as prototypes during design workshops to enable participants to better envisage ways to extend IoT technologies. Given such possibilities, this is one reason we reviewed commercial products of the IoT. Another is that commercial offerings can provide HCI researchers with a point of comparison, that can support reflection upon current pursuits and agendas. Furthermore, for HCI to engage with an emergent field such as the IoT, researchers can benefit from evaluating, reviewing and contrasting commercial products which are also pursuing similar explorations. While our discussion is focused on gains for the HCI community, these insights might also benefit commercial efforts.

### Discussion of Commercial Products

The commercial products we surveyed covered a broader range of domains and activities than those we surveyed in HCI-related literature. These areas included sleep quality, brainwave measurement, reminders and notifications, home security and garden monitoring. It is worthwhile for the HCI community to consider whether such domains could be of interest for HCI to explore in future research efforts. There were significant similarities between the domains of both the commercial efforts and HCI-related literature. Both have engaged in significant explorations of home utility monitoring, health and wellbeing, and personal tracking for development. While the commercial products surveyed were designed for a wide range of domains, we could envision a productive role for IoT technologies beyond the current narrow focus on *home-centric* and *person-centric* domains. For example, work-centric, family-centric, leisure-centric or transit-centric explorations could all be productive explorations for HCI researchers.

In addition to examining domains, we also examined the sensors and the interaction styles present in commercial devices. We found similarities in the interaction styles and sensors used in commercial products when compared to the HCI-related literature. However, some sensors were found more predominantly in commercial products, e.g., EEG (brain activity sensors), electrical resistance (often for monitoring the amount of water in soil), and to some extent, presence sensors which can indicate if people are in a room. Both HCI efforts and commercial offerings were found to use similar combinations of sensors. Commercial products often presented a higher concentration of sensors on the one product, whereas designs in the literature surveyed were more likely to explore one or two sensors at a time. This was especially noticeable in commercial domains such as *configurable platforms*, where devices in this area are often designed with many sensors allowing them to be re-purposed for different tasks over their lifetime.

Commercial products did not include any unique forms of interaction when compared to the HCI-related literature we reviewed. However, some forms of interaction were much more common in commercial efforts. These include direct interaction with the object, environmental alteration and mobile app notification. Our review revealed that particular modes of interaction, such as voice control appear to be absent from both commercial and literature offerings. This observation points to opportunities for modes that are not currently used to be explored in future efforts of the IoT.

Compared with the efforts found in the literature, commercial products were designed with a greater ability to share data in an intelligible way with other devices, as well as the ability to act based on data received from other devices. Configurable platforms and home appliances appeared to have the strongest engagement with this kind of interconnectivity out of any domain. In many cases this was achieved through the implementation of an entire network of devices produced by the same company. For example, SmartThings have built a network of devices that are capable of transmitting home security information amongst themselves. Whirlpool has also implemented their own *Smart appliances* series (mysmartappliances.com), which allows the remote monitoring and control of home devices. While this is a form of interconnection - with objects able to share data across devices, and even act based upon data received, this example is still in many ways a closed network. This closed nature of many commercial IoT offerings may be due to companies purposely limiting the use of their products with commercial competitors. However, it may also be partly due the lack of consensus around ways to exchange data between devices, despite the existence of standards (eg. Zigbee). We believe that if the IoT is to fully realise its potential, such commercial devices will need to engage with other devices outside of their own commercial sphere.

We have found it valuable to compare both commercial products and academic efforts because it allowed us to observe trends, gaps, differences and common areas of effort within the quickly expanding IoT. By highlighting how commercial efforts have considered specific ways to implement more interconnectivity into their devices, we have provided the HCI community (especially those working in ubiquitous and pervasive computing) with models or ideas to tackle interconnectivity in future explorations. This can support such explorations to develop technologies which are closer to the vision of the IoT.

## INSIGHTS FOR HCI

In discussing our review of the literature, we noted a lack of user studies when dealing with technologies closely related to the IoT. This can be problematic not only for ubiquitous computing efforts but it may also limit the potential for HCI to engage more productively with the IoT. As Kjeldskov and Graham (2003) noted in their review of mobile HCI research methods a decade ago, "the bias towards building systems and a lack of research for understanding design and use, limits the development of cumulative knowledge… and in turn inhibits future development of the research field as a whole" (p. 317). In addition, there clearly needs to be more ethnographically-inspired user research so as to inform human-centred designs of potential IoT technologies.

Our review of the commercial products revealed opportunities for HCI researchers to use these products as stimulus for design ideas and approaches within HCI. Such products can also be used as prototypes in the design process as things that can support envisionment. Furthermore, our review highlighted the potential for how we can use DIY technologies, such as electronic kits like Arduino (http://arduino.cc) to quickly (and relatively cheaply) construct prototypes that can further support the envisionment process of IoT technologies during design workshops. One possible approach we could take is to develop a kit using these prototyping technologies that could be used to explore the IoT vision with people. We acknowledge that software development kits related to the IoT do exist (eg. Microsoft's Lab of Things http://www.lab-of-things.com/), however these kits are often not used in design activities to prototype with people.

Our review suggested that HCI will need to increase its efforts in designing and implementing interconnectivity in technologies if it wants to contribute to the IoT vision. However, we also acknowledge the challenges that interconnectivity introduces. Perhaps a productive direction for HCI to pursue (by taking a cue from commercial efforts) is to expend more of its efforts exploring interconnectivity for devices within the home before tackling the more complex interconnectivity of devices that are used whilst on-the-move. This is because the relatively stable home environment allows researchers to more easily experiment with, and refine, design approaches that support interconnectivity amongst devices.

Finally, we see great opportunities for Participatory Design with its well-developed set of tools, methods and approaches and its commitment to mutual learning and the genuine engagement of people in the design of the technologies they might use in the future (e.g. Simonsen and Robertson 2013). With rich traditions of ethnographic research and deep understandings of co-design, through workshops, iterative prototyping, and many other design methods and tools, Participatory Design is well suited to support the development of future IoT technologies that are human-centred and respectful of their needs and those of their communities.

## CONCLUSION

There is evidence that HCI is growing its engagement with the IoT vision. This can be seen from recent HCI conference themes on the IoT (e.g., British Computer Society's HCI conference in 2013), special journal issues on the IoT (Carretero & García 2013), and various conference workshops (e.g., OzCHI 2012) on this topic. The motivation for this paper is to deepen and facilitate this engagement. By reviewing some of the recent HCI research that deal with technologies closely related to those of the IoT, as well as IoT commercial products, this paper provides an account of the current state of research within HCI and offers insights as to how we can strengthen HCI's engagement with the IoT. The paper also provides two tables that can be used as a resource to support thinking about categories and characteristics of IoT technologies, allowing us to examine current and possible future efforts. We have extended the resources of academic research by taking into account commercial contributions. This has allowed us to begin a dialogue between these two efforts, revealing opportunities, directions, gaps and approaches for the HCI community, ensuring that its engagement with the IoT agenda is firmly human-centred.

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