DeskWave: Desktop Interactions using Low-cost Microwave Doppler Arrays

Jess McIntosh
University of Bristol
Bristol, BS8 1TH, USA
jm0152@my.bristol.ac.uk

Paul Worgan
University of Bristol
Bristol, BS8 1TH, USA
Paul.Worgan@bristol.ac.uk

Mike Fraser
University of Bristol
Bristol, BS8 1TH, USA
Mike.Fraser@bristol.ac.uk

Asier Marzo
University of Bristol
Bristol, BS8 1TH, USA
amarzo@hotmail.com

CHI'17 Extended Abstracts, May 06-11, 2017, Denver, CO, USA.
© 2017 ACM. ISBN 978-1-4503-4656-6/17/05.
DOI: http://dx.doi.org/10.1145/3027063.3053152

Abstract
Microwaves are a type of electromagnetic radiation that can pass through a variety of commonly found materials but partially reflect off human bodies. Microwaves are non-ionizing and at controlled levels do not pose a danger. A wave that is capable of passing through materials could have useful applications in human-computer-interaction. However, only recently the full potential of microwaves for interactive devices has begun to be explored. Here, we present a scalable, low-cost system using an array of off-the-shelf microwave Doppler sensors and explore its potential for tabletop interactions. The arrays are installed beneath a desk, making it an ubiquitous device that enables a wide range of interactions such as 3D hand tracking, gesture recognition and different forms of tangible interaction. Given the low cost and availability of these sensors, we expect that this work will stimulate future interactive devices that employ microwave sensors.

Author Keywords
Tabletops; 3D tracking; Gesture recognition; Wireless power transfer; Microwave Sensors.

ACM Classification Keywords
H.5.m [Information interfaces and presentation (e.g., HCI)]: Miscellaneous

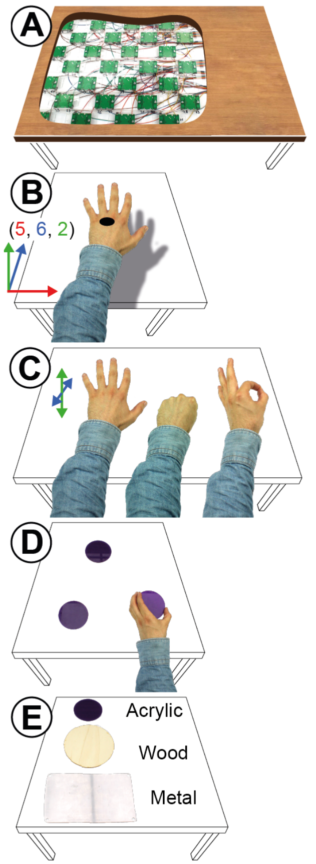

Figure 1: A) A DeskWave array is placed underneath a table, enabling various interactions such as: B) 3D tracking, C) gesture recognition, D) tangible interaction with support of stacking, and E) material recognition.

Introduction

The desktop has become the place where modern workers spend a significant amount of time during the day [3]. The tools that populate the desktop have been evolving; from quill and paper, to the typewriter and ultimately to the personal computer with the mouse and keyboard as the established peripherals. However, new paradigms of interaction have been introduced to facilitate how we work with digital information. For instance, tangible interaction [5] allows us to control digital entities through physical representations [12]. As an example, the Reactable [6] is a tabletop interface that visually recognizes the position of the objects located on the surface. At the same time, mid-air interactions using the 3D position of our hands or finger gestures have become widespread thanks to commercially available sensors such as the Leap Motion or Microsoft Kinect.

We propose using an array of low-cost and low-power microwave Doppler sensors to sense user's gestures and interactions above desks. These sensors can be placed below the table and will sense through non-metallic surfaces, allowing for easy integration of the system in a wide range of office and home environments. The system is easily scalable, allowing coverage of any required size or shape of desk. We present potential applications in hand tracking for generic 3DOF input, gesture recognition, tangible interaction and material characterisation (Figure 1). Microwave sensing presents several advantages over optical systems such as robustness against occlusions from objects and lighting conditions. Since the device can operate behind surfaces, the device is less obtrusive than other methods which may require the sensing equipment to be visible. Additionally, non-camera based solutions are generally perceived as more private [8]. Ambient environmental integration of the system follows Weiser's principle of calm technology [17], where the table can be used in a traditional sense and the input mechanism can remain in the user's periphery.

With the release of off-the-shelf Doppler microwave sensors (HB100 - 10GHz) a range of new possibilities for interactive devices in HCI appears. These sensors are affordable for sensing applications but possess some limitations compared to expensive specialised Doppler equipment. In this paper we explore the new interactions offered by the HB100 sensors despite their simplicity.

Related Work

Microwaves have been used in the past for human-computer interaction. Using the change in frequency from a WiFi Doppler signal, it is possible to detect simple body movements [11] [14]. A portable system was able to recognize simple hand movements [7] with existing radiation from TV or other emitters and had very low power consumption due to its direct but effective algorithm. Microwaves and depth sensors have been combined to detect hand gestures under adverse conditions of visibility [10].

Using multiple microwave sensors it is possible to determine the position of objects. MTrack [16] employs a 60 GHz transmitter and 2 receivers to track a pencil or a metallic object inside a small 2D space. RFCapture [1] is an array composed of 16 emitters and 4 receivers, operating over a frequency band from 5 GHz to 7 GHz, capable of tracking the human body through a wall.

Recently, project Soli [9] has been released. It is a custom-built microchip with 2 emitters and 4 receivers operating at 60 GHz allowing detection of fine hand gestures [15]. Soli can also recognize objects and material that above it [18]. However, at 60 GHz the attenuation of microwaves is greater than at lower frequencies limiting the sensors range and capability to pass through dense materials. Further-

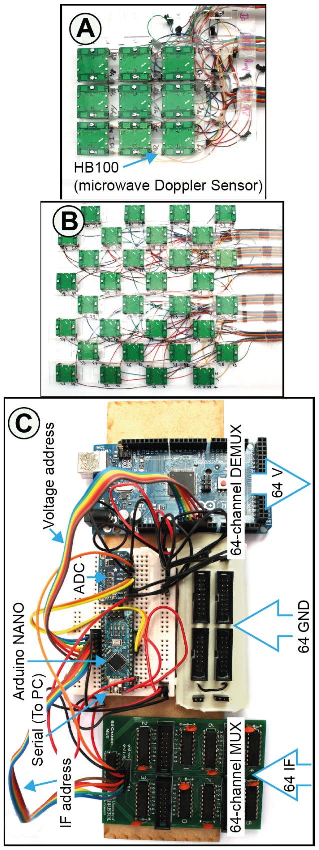

Figure 2: a) A 3x3 array b) A 32 element array with a checkboard pattern. c) Acquisition board.

more, due to the high frequency used and small factor of the chip the interaction space is limited above the device and cannot be easily expanded. This makes Soli unsuitable for the larger scale tabletop interactions we have envisioned.

A limitation that we found in previous systems is that they use RF equipment and thus required especial expertise beyond the traditional Maker skills (e.g. RF connectors, coax wiring or impedance matching). Soli can be use directly off-the-shelf but it is proprietary and controlled by Google and currently for obtaining one the prospective users have to go through an application process. In contrast, we analyse the interactions enabled by simple, low-cost and off-the-shelf sensors. We explore a free open design which can be assembled and modified by everyone.

Principles of Microwave Doppler

Microwaves are part of the electromagnetic spectrum positioned between radio and infrared with a frequency range from approximately 1 GHz to 110 GHz, giving a wide variation in wavelength, i.e. from tens of centimeters to millimeters. Microwaves are non-ionizing radiation, meaning they do not possess enough energy to push electrons from atoms or molecules. Microwaves get reflected by most metals and the human body; whilst microwaves get absorbed by water, they mostly pass unimpeded through common solids such as wood, concrete or plastic.

The Doppler effect occurs when an wave, reflects off a surface moving towards or away from the emitter. This reflected signal is frequency shifted in accordance to the velocity of the reflector. In the GHz range, equipment that directly measures frequency is expensive. This is why it is common to mix the emitted signal with the received signal in an analog circuit. Due to trigonometric identities, the mixed signal has a high frequency component equal to the addition of the emitted and received signal frequencies, and a low frequency component which is the difference between the signals frequency. The high-frequency component can be low-pass filter and the low-frequency difference signal can be easily sampled.

Advanced Doppler systems can detect the direction of movement using IQ demodulation, side band filtering or carrier demodulation [2]. Also, the distance to the target can be estimated with Frequency Modulated Continuous Wave (FMCW) systems [13]. These features are not implemented by the HB100 sensor.

DeskWave System

A DeskWave array is composed of several HB100 microwave Doppler sensors in different layouts (Figure 2 a and b) that depend on the desired application, an acquisition board based on Arduino, common electronic components, and a PC able to process the signals and run interactive applications. The system is installed behind a surface or below a desk. In our experiments we deployed the system below a 3mm Medium Density Fiberboard (MDF) board, 3mm acrylic sheet or also a 7mm pine wood table but we consider the system could support a wider variety of materials.

HB100 microwave Doppler sensor

The HB100 microwave Doppler sensor is an off-the-shelf component that can be purchased for less than 3$. The HB100 operates at 10.525 GHz and consumes an approximate current of 40mA at 5V DC. The sensor is an integrated package comprising an oscillator, transmitting and receiving dipole antennas, an amplifier and a mixer. The sensors has three connections: 5V, GND and IF (which is the mixed signal).

Specialized systems are compatible with IQ-demodulation and FMCW methods which provide a rich set of information. Unfortunately out-of-the-box, the HB100 does not support IQ-demodulation. For IQ, it is necessary to have access to the individual emitted and received signals and mix signals across different sensors. However, the HB100 comes as an integrated chip and does not support external signal mixing. Whilst driving the HB100 with different voltages, there was no observed change in the fundamental transmit frequency, ruling out FMCW radar applications.

The HB100 exhibited frequency variations across different sensors and the mixed signal was not consistent, making phase tracking difficult. Also, the values the sensors output at the IF were not uniform in range or in offset; values from -300mV to 300mV DC covered all the sensors that were tested.

Electronics such as smart light bulbs come equipped with microwave Doppler sensors but it is hard to separate the sensor from the rest and the cost is higher. Another alternative are Gunn diodes like the ones used in speed guns, the problem is that they are ten times more expensive and require a bulky horn antenna to function, contrary to the PCB-integrated dipole antenna used in the HB100. These facts make the HB100 the best alternative for affordable microwave Doppler arrays.

Acquisition Board

An Arduino Nano was used as the open source controller on the acquisition board. A 64-channel custom-made multiplexer was used to receive the mixed signals from the sensors. The Doppler signals were not higher than 30Hz so an ADS1015 12-bits Analogue to Digital Converter (ADC) with a sampling rate of 3.3Ks was used to convert the values into a digital signal. A higher precision ADC would have been desirable, but using readily available common components opens the design up. The ADC was used in differential mode with a set gain of x16 and powered with the 3.3V DC from the Arduino Nano. An Arduino MEGA was used as a 64 channel demultiplexer (Figure 2.c).

The Arduino Nano uses 6 digital outputs to address the sensor to be read through the multiplexer. The same address is fed into an Arduino MEGA with 64 digital outputs to power the sensors. When a specific sensor is powered and addressed, the ADC performs a reading. The Arduino Nano iterates over all the connected sensors and sends the values to the computer through serial communication functioning at 2.5 Kbaud. Sensors values were sent while the ADC was obtaining the data, to maximize system speed. The system could sample up to 64 channels with a sampling rate of 2Ks amongst all the channels.

Signal processing

For each Doppler signal, we normalized the raw signal using the maximum and minimum values observed for the specific channel. Several features were extracted from the Doppler signal. The DC offset is the difference between the current value and the neutral value; where the neutral value is the voltage value that the sensor provides with no objects above it, i.e. a quiescent value. Additional features from the time domain are extracted, namely amplitude, frequency and phase. We tested a traditional Fast Fourier Transform (FFT) with 128 samples and a Blackman window, however a peak detection algorithm provided better results.

On previous systems, state of the art sensors and electronics with high component tolerances were used to give uniform and predictable results. Using HB100 sensors makes microwave Doppler input modalities available to a wider audience. However, since the sensors were designed only to broadly detect movement, some of the advance techniques implemented in previous work employed were not available. For instance, IQ-demodulation cannot be used to determine

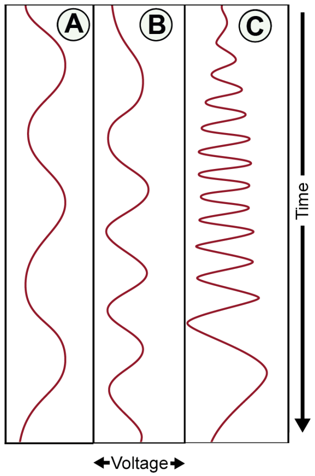

Figure 3: Doppler signals from a single sensor. An object moving at low speed towards the sensor (a) and a faster object moving away from the sensor (b); a skew on the sine wave towards the right or left is caused depending on the direction of movement. c) rapid movement towards the sensor, the direction is indicated by the increase in amplitude.

the direction and FMCW does not work to determine the distance. Moreover, the phase of the signal is difficult to use for estimating distance. As a result we rely on less traditional features such as the amplitude or the voltage offset.

Enabled Interactions

In this section we describe how to combine different layouts of sensors and algorithms to enable various types of interactions.

3D Hand Tracking

This interaction encompasses the estimation of the 3D position of a hand or similar object above the sensor array. This interaction can be used for navigating 3D scenes, as a game input or simply as a cursor on normal GUI applications. At least a 3x3 layout was required to obtain useful positions. The best result was obtained using the amplitude of the oscillating signals. This amplitude is proportional to the distance from the sensor, the size of the object, the material and the angle. The simplest algorithm was to estimate the XY position using the centroid of the amplitudes and the height using the magnitude of it. The algorithm that provided the best results was a Multi-layer Perceptron (MLP) Regressor with 5 hidden layers. The neural network was trained using amplitude data from the sensors as input, and 3D hand positions from a Leap Motion as target. We used the AlgLib library with Batch L-BFGS as training method. In the attached video it can be seen that the results were accurate enough to enable various applications.

The direction of movement can be sensed using the HB100 with only one sensor and without IQ modulation. Owing to small distortions on the sensor circuitry, the Doppler signal presented a skewness which can be used to obtain the direction of the movement. Therefore, if a maximum peak was closer to the previous minimum, the object was moving towards the sensor; whereas if the maximum peak was closer to the next minimum, the object was moving away. The amplitude of the received signal can be used an indicator of the distance of the sensor, since the received signal strength decreases as the object moves away and vice versa (Figure 3).

Gestures

Gestures of the hand usually include movement of the fingers as well as swipe gestures. The frequency of the Doppler signal is proportional to the speed of the moving object and the amplitude is closely related to the object's size, distance, angle and material. Therefore different gestures can be detected using a combination of the received signal properties. For example, a closing hand gesture can be differentiated from a finger bending at the same speed by their received signal amplitudes, as in the former case a larger object is moving. A swipe towards one direction generates a received signal increasing in amplitude, initially stronger in the sensor of origin and moves towards another sensor, the frequency can be used to determine the speed.

We conducted a pilot study with 4 participants, using a 3x3 layout, differentiating between 5 gestures: swipe left, swipe right, push towards the array, raise hand and closing fist. The gestures were repeated 5 times each for the training and another 5 for the evaluation. Using an MLP classifier (12 hidden layers); RMS, amplitude and frequency data from the sensors was used as input. The system was able to classify these gestures with an average accuracy of 94% (SD=0.04). The study demonstrates even a simple system with minimal training provides similar accuracy to previous systems using specialized equipment.

Small gestures can be used alone as simple actions like scrolling with the browser or reading through emails. They can also be used in combination with traditional inputs such as mouse and keyboard to have gestural shortcuts at one side of the computer. The accuracy of hand tracking and gesture recognition is not as good as optical systems (e.g. Leap Motion) but Deskwave provides a more ubiquitous alternative besides offering other features such as tangible tracking and material characterization.

Tangible Interaction
Microwaves will be partially reflected by some materials above the table. Moreover, since the distance between the sensor and the object is fixed, the DC offset from the sensor can be used an as an estimator of either the thickness or material of the object. This can be used to track tangible tokens that are on the table. For this interaction, several sensors are required if support for multiple tokens is desired. The sensors can be as spread as possible to cover the largest area of interaction but if they are too separated the objects may fall into a blind area and not be detected. Here we made a cross-check layout of 32 sensors designed to sense objects around 2 times the size of the sensors.

The algorithm consists of generating a 2D image with the offsets and then using the centroids of the blobs as the position of the tokens. The magnitude of the centroid indicates either the thickness or the material of the token. This provides interesting interactions since the tokens can be stacked or identified by their composition.

Different objects cause specific DC offset values, for instance a wallet reflects less than a mobile phone or your keys. This can be used for context aware applications. For instance, the PC could establish a connection with your phone when it is detected on the surface, or open Amazon when your wallet is placed. Interestingly, this effect was continuous, so it was possible to roughly detect the amount of water poured into a plastic glass.

The mean quiescent value (n=20) when the sensor was placed below a 3mm thick MDF was 85.32mV (SD=0.24). When other sheets (100x100x3mm) were placed above, the value was: 86.24mV (SD=2.50) for clear acrylic, 90.48mV (SD=2.01) for MDF, 104.4mV (SD=1.62mV) for polyvinyl chloride and 87.56mV (SD=1.75) for plywood.

Microwaves can transfer a significant amount of power in a wireless manner with efficiencies as high as 90% [19]. This could be used in combination with 2D position tracking and material recognition for activating the sensor below a phone to charge it, or to blink the LED on your key chain. However, the design of a more efficient receiver and powerful emitter is needed.

Conclusion
We have presented different configurations of microwave Doppler arrays and algorithms that enable applications in hand tracking, tangible interaction, gesture recognition and material characterization. This work indicates that microwave Doppler sensing can be used for multiple interactions using simple, affordable and scalable systems.

Microwave sensing may not be favorably perceived due to their common use in food preparation. However, this radiation is safe if the intensity is kept below thresholds, ICNIRP 1998 [4]. Recently, there has been an increase in the use of microwave Doppler interactive devices but those systems, although clearly a feat of engineering, are not openly available to most researchers in the HCI community. Additionally, we have detected novel uses of the technology like tangibles with stacking. We hope to see more interactive devices using off-the-shelf microwave arrays since they offer a safe technology resilient to occlusions and light conditions with a multitude of interaction possibilities (code and hardware attached in the supplementary material).

References

[1] Fadel Adib, Chen-Yu Hsu, Hongzi Mao, Dina Katabi, and Frédo Durand. 2015. Capturing the human figure through a wall. *ACM Transactions on Graphics (TOG)* 34, 6 (2015), 219.

[2] P Bello. 1965. Some techniques for the instantaneous real-time measurement of multipath and Doppler spread. *IEEE Transactions on Communication Technology* 13, 3 (1965), 285–292.

[3] M. Duncan, A. Kazi, C. Haslam, S. Clemes, and L. Kerr. 2012. Sitting time and physical activity in the UK working population: A cross sectional study. *Journal of Science and Medicine in Sport* 15, Supplement 1 (2012), S305 – S306. DOI: http://dx.doi.org/10.1016/j.jsams.2012.11.744 Be Active 2012.

[4] International Commission on Non-Ionizing Radiation Protection. 1998. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields, Vol. 74. ICNIRP, 494–522.

[5] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*. ACM, 234–241.

[6] Sergi Jordà, Günter Geiger, Marcos Alonso, and Martin Kaltenbrunner. 2007. The reacTable: exploring the synergy between live music performance and tabletop tangible interfaces. In *Proceedings of the 1st international conference on Tangible and embedded interaction*. ACM, 139–146.

[7] Bryce Kellogg, Vamsi Talla, and Shyamnath Gollakota. 2014. Bringing gesture recognition to all devices. In *11th USENIX Symposium on Networked Systems Design and Implementation (NSDI 14)*. 303–316.

[8] Florian Kirchbuchner, Tobias Grosse-Puppendahl, Matthias R. Hastall, Martin Distler, and Arjan Kuijper. 2015. *Ambient Intelligence from Senior Citizens' Perspectives: Understanding Privacy Concerns, Technology Acceptance, and Expectations*. Springer International Publishing, Cham, 48–59. DOI: http://dx.doi.org/10.1007/978-3-319-26005-1_4

[9] Jaime Lien, Nicholas Gillian, M Emre Karagozler, Patrick Amihood, Carsten Schwesig, Erik Olson, Hakim Raja, and Ivan Poupyrev. 2016. Soli: ubiquitous gesture sensing with millimeter wave radar. *ACM Transactions on Graphics (TOG)* 35, 4 (2016), 142.

[10] Pavlo Molchanov, Shalini Gupta, Kihwan Kim, and Kari Pulli. 2015. Short-range FMCW monopulse radar for hand-gesture sensing. In *2015 IEEE Radar Conference (RadarCon)*. IEEE, 1491–1496.

[11] Qifan Pu, Sidhant Gupta, Shyamnath Gollakota, and Shwetak Patel. 2013. Whole-home gesture recognition using wireless signals. In *Proceedings of the 19th annual international conference on Mobile computing & networking*. ACM, 27–38.

[12] Bert Schiettecatte and Jean Vanderdonckt. 2008. AudioCubes: a distributed cube tangible interface based on interaction range for sound design. In *Proceedings of the 2nd international conference on Tangible and embedded interaction*. ACM, 3–10.

[13] M Vossiek, T v Kerssenbrock, and P Heide. 1997. Signal processing methods for millimetrewave fmcw radar with high distance and doppler resolution. In *Microwave Conference, 1997. 27th European*, Vol. 2. IEEE, 1127–1132.

[14] Qian Wan, Yiran Li, Changzhi Li, and Ranadip Pal. 2014. Gesture recognition for smart home applications using portable radar sensors. In *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, 6414–6417.

[15] Saiwen Wang, Jie Song, Jaime Lien, Ivan Poupyrev, and Otmar Hilliges. 2016. Interacting with soli: Exploring fine-grained dynamic gesture recognition in the radio-frequency spectrum. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 851–860.
[16] Teng Wei and Xinyu Zhang. 2015. mtrack: High-precision passive tracking using millimeter wave radios. In *Proceedings of the 21st Annual International Conference on Mobile Computing and Networking*. ACM, 117–129.
[17] Mark Weiser and John Seely Brown. 1997. Beyond Calculation. Copernicus, New York, NY, USA, Chapter The Coming Age of Calm Technolgy, 75–85. http://dl.acm.org/citation.cfm?id=504928.504934
[18] Hui-Shyong Yeo, Gergely Flamich, Patrick Schrempf, David Harris-Birtill, and Aaron Quigley. 2016. RadarCat: Radar Categorization for input & interaction. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 833–841.
[19] Jingwei Zhang. 2013. *Rectennas for RF wireless energy harvesting*. Ph.D. Dissertation. University of Liverpool.