Radar and Ultrasound Hybrid System for Human Computer Interaction

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***Abstract*—Touchless hand gesture is one emerging technology for human computer interaction. In this paper, we investigate the feasibility of a hybrid system using frequency modulated continuous wave (FMCW) radar and ultrasound sensors with one transmitter and one receiver to detect hand movement for controlling a computer. Ultrasound will be used for near range application (1 cm to 30 cm) based on range estimation. FMCW radar, on the other hand, will be used for far range application (30 cm to 120 cm) based on range, velocity, and angle of arrival estimation. Leveraging these advantages of combining both ultrasound and FMCW radar will facilitate human hand for interacting computer with better performance.**

Keywords—Touchless hand gesture, Ultrasound, FMCW Radar, Range Estimation, Velocity Estimation, Angle of Arrival.

I. Introduction

There are many groups researching about ultrasound for gestures and motion sensing. For example, Gupta [1] classifies gestures using "Doppler effect" with the use of a speaker and a microphone. Kalgaonkar [2] also uses "Doppler Effect" concept with one ultrasound transmitter and three ultrasound receivers. While these projects show the potential of "Doppler effect" used for ultrasound application, the "Doppler effect" also has disadvantages. When the hand is moved up or down, the shift frequency from "Doppler effect" can be easily detected by the ultrasound sensors. However, when moving our hand from left-to-right or from right-to-left, although the ultrasound sensors can detect the frequency shift, it cannot differentiate between left and right movement with one ultrasound receiver. Kalgaonkar [2], presented a method to detect left and right movement but requires three ultrasound sensor receivers. Although this ensures the accurate detection of gestures, the setup can become cumbersome, and hard to apply for controlling computer. Another disadvantage of using "Doppler effect" is the requirement of using Fast Fourier Transform (FFT) to convert data from time domain to frequency domain for detecting the shifted frequency. To achieve a high accuracy, longer data sets are needed for higher frequency resolution and this will increase the complexity of the algorithm and slow the response of the system. In this paper, a different approach is presented for detection by using one ultrasound transmitter and one ultrasound receiver. In this method, gestures such as up, down, left, and right-hand movement were detected based on range estimation.

Ultrasound is advantageous for identifying both fast and slow movement of a single hand with high accuracy, it is a low-cost sensor and easy to use, However, ultrasound sensors have the limited detection range. When the object moves farther away, the accuracy of ultrasound begins to decrease. FMCW radar, on the other hand, is beneficial for longer detection range, both single and two hand gesture recognition. Nevertheless, FMCW radar can only identify slow movement due to the complexity in the noise removal and detection algorithm. Obviously, the time response of the FMCW radar in this application for human computer interaction is slower than ultrasound. Therefore, ultrasound and FMCW radar are complementary for each other.

II. System Design

As presented in the previous section, there are several limitations with previous designs presented in literature. First, the use of "Doppler effect" implies the necessity of performing an FFT to obtain a frequency shift. With this approach, although it is accurate, it increases the computing requirements of the system and thus slows down the response. Second, since a single ultrasound is not capable of differentiating between a "swiping right" gesture and a "swiping left" gesture, it requires extra ultrasound receivers to accurately map direction. Hence, classification of these gestures requires additional processing. Third, the ultrasound sensor also has a limited optimal range of operation. Outside of this range, the accuracy of the ultrasound sensor is not reliable. Fourth, the use of Doppler for movement estimation implies that the detection of two hands at the same time can introduce processing complexity. Due to these limitations, a hybrid system composed of one ultrasound sensor and an FMCW Radar module are proposed. Air ultrasound ceramic transducers 400ST/R160 [3] was used to obtain raw data. This is then combined with a 77 GHz FMCW Radar. To avoid the processing requirements of a Doppler system, the proposed system takes advantage of the range detection capabilities of both the ultrasound and FMCW Radar. This allows detection of movement with no FFT during short range, and the use of a range-radar when the signal is beyond the ultrasound's optimal detection distance. Additionally, range radar can efficiently detect more than one target on the same energy spectrum, and thus presents no limitation during detection of gestures with both hands.

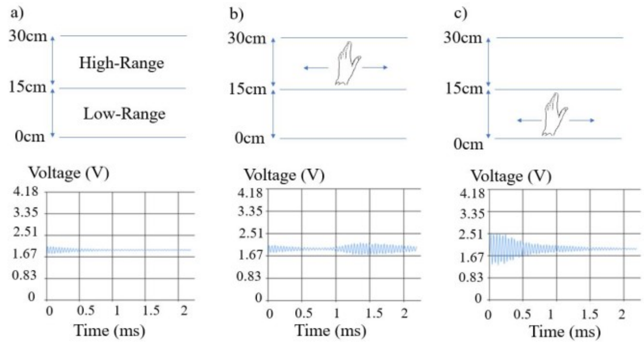

Fig. 1. a) Ultrasound waveform with no hand movement. b) Ultrasound waveform with hand in high-range region. c) Ultrasound waveform with hand in low-range region

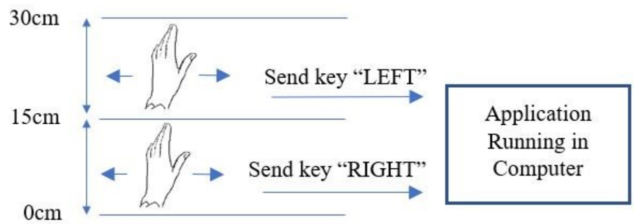

Fig. 2. Illustration of moving left or right gesture of ultrasound system.

A. Ultrasound System

1) Algorithm Implementation

Air ultrasound ceramic transducers 400ST/R160 has center frequency 40 kHz, transmitting sound pressure level minimum is 120dB, and minimum receiving sensitivity is -65dB. From pure analog data of the received signal, the range of the object can be estimated based on the propagation time of ultrasound in air. The presented system prototype's ultrasound transmitter/receiver has best accuracy for hand detection within the range of 30 cm. The detection algorithm uses two regions: *low-range region* (0 cm to 15 cm) and *high-range region* (15 cm to 30 cm). In Fig. 1, there are 3 graphs corresponding to the waveforms of no hand movement, movement at the *high-range region* and *low-range region*. Based on the difference analog waveform for each *range region*, propagation time of the ultrasound wave was extracted and used to estimate the range of the hand according to the following formula:

$$d = \frac{vt}{2} \tag{1}$$

where d stands for range estimation, v stands for velocity of sound in the air (344 m/s), and t stand for time propagation of ultrasound.

Gupta [1] used lower frequency shift of "Doppler effect" to detect up movement, and higher frequency shift for detecting down movement. The ultrasound system detects up movement by moving hand from *low-range region* to *high-range region*. The program that writing on Visual Studio will compare the data from this movement with no hand movement data then send a keystroke "UP" to the application running in the computer. Similarly, down movement is identified by moving hand from *high-range region* to *low-range region*. For left-to-right and right-to-left movement, Kalgaonkar [2] use one ultrasound transmitter and three ultrasound receivers. They place all the receiver in a triangle pattern where these gestures could be performed and sensed. The proposed ultrasound system algorithm detects left-to-right movement by moving hand in the *low-range region*. The program will compare the data from this movement with no hand movement data then send a keystroke "RIGHT" to the application running in the computer. As such, the algorithm is able to perform a "RIGHT" movement if the detected hand motion is within the *low-range region*, regardless of the direction of movement. Similarly, the program will send keystroke "LEFT" when moving the hand in the *high-range region*. These gestures will be illustrated in Fig. 2. This ensures that the correct gesture can be detected without the need for a triangular setup of three ultrasound receivers. This range is quite wide for a human hand (15 cm for each region) and it is easy for human to recognize these ranges.

The advantage of this algorithm is that the use of an FFT is not needed. This reduces the complexity for the detection algorithm so that it can detect both slow and fast movement. Another advantage is that this algorithm requires one ultrasound transmitter, one ultrasound receiver and no special setup.

2) Gestures and Use Cases

The 8 sets of gestures will provide to control the application running in the computer:

Swiping Right (R): Swiping hand in *low-range region*. The program will send one keystroke "RIGHT" to the application running in computer.

Swiping Left (L): Swiping hand in *high-range region*. The program will send one keystroke "LEFT" to the application running in computer.

Swiping Down (D): Swiping hand from *high-range region* to *low-range region*. The program will send one keystroke "DOWN" to the application running in computer.

Swiping Up (U): Swiping hand from *low-range region* to *high-range region*. The program will send one keystroke "UP" to the application running in computer.

Scrolling Up (SU): Holding hand at *high-range region*. The program will send keystrokes "UP" continuously to the application running in computer.

Scrolling Down (SD): Holding hand at *low-range region*. The program will send keystrokes "DOWN" continuously to the application running in computer.

Enter Program (EN): Tapping 2 times in front of the ultrasound sensor. The program will send one keystroke "ENTER" to the application running in computer.

Exit Program (EX): Holding hand at *high-range region* for 4s then moving up. The program will send one keystroke "ALT+F4" to the application running in computer.

These gestures could be used for a lot of touchless application. For example, it can scroll a web page or a pdf file using gestures scrolling up/down. It can also watch picture, read pdf file, using PowerPoint Presentation by gestures moving left/right.

B. Radar System

1) Algorithm Implementation

a) Range Estimation

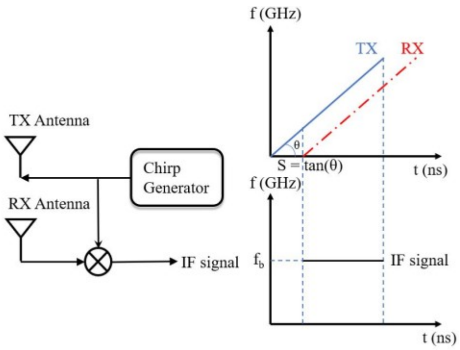

Fig. 3. Range Estimation Theory of FMCW Radar System

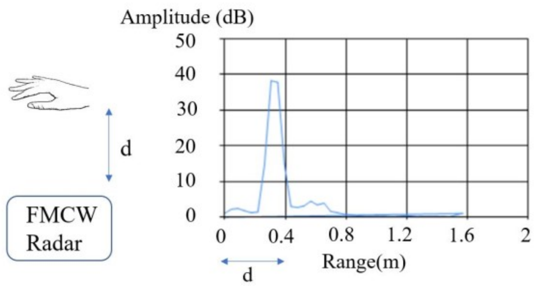

Fig. 4. Range Estimation Result of FMCW Radar System

FMCW radar transmits a signal called a "chirp". A chirp is a sinusoid whose frequency increases linearly with time. The chirp is transmitted by the TX antenna then the chirp is reflected off an object and the reflected chirp is received at the RX antenna. TX and RX signal go through mixer resulting the IF signal [6]. This is shown in Fig. 3. After taking FFT (called Range FFT) of the IF signal, the beat frequency f_b is obtained to estimate the range of the detected object by the formula:

$$d = \frac{cf_b}{2S} \tag{2}$$

where d stands for range estimation, c stands for speed of light, f_b stands for beat frequency, and S stands for slope of the chirp signal.

Fig. 4 show the result of the range estimation when hand was hold at the range d from the FMCW radar system.

b) Velocity Estimation

To identify the velocity of the object, FMCW Radar will send multiple chirps signal (called a frame). Each chirp reflected signal, after taking range FFT, it will give the information about the beat frequency and the phase of the reflected signal. From the beat frequency, the range of the object can be detected. And from the phase, the velocity will be identified. Since the phase of the IF signal is very sensitive to small changes in object range, the range FFT corresponding to each chirp will have the peaks in the same location but different in phase. After gathering all the phase information after each frame, another FFT is performed (called Doppler FFT or 2D FFT) which is shown in Fig. 5. Afterwards, the phase difference (ω) obtained corresponds to a motion in the object and the velocity is calculated with the formula:

$$v = \frac{\lambda\omega}{4\pi T_c} \tag{3}$$

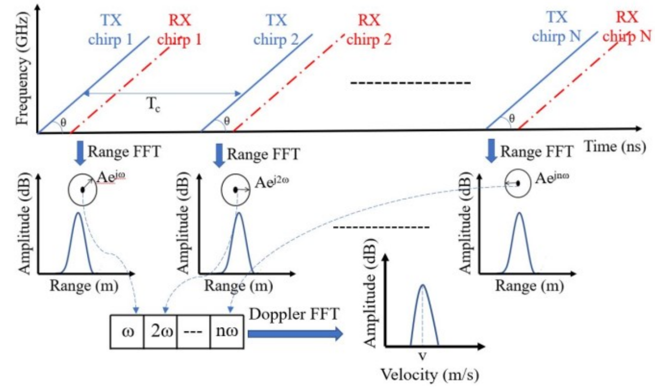

Fig. 5. Velocity Estimation Theory of FMCW Radar System

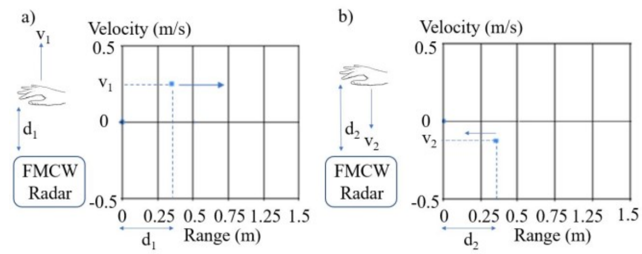

Fig. 6. a) Result of Velocity Estimation of FMCW Radar system while moving hand up. b) Result of Velocity Estimation of FMCW Radar system while moving hand down

where v stands for velocity estimation, λ stands for wavelength of transmit signal, ω stands for phase difference after taking 2D FFT, and T_c stands for time between 2 consecutive chirps

By comparing the range and the power of the object from the range estimation with the range from the velocity estimation, the noise removal algorithm will filter out unwanted movement from surrounding environment, only the information from moving hand will be kept. The result of the 2D FFT is shown in Fig. 6. If the hand performs an upward movement, the sign of the velocity will be positive. This is shown in Fig. 6 (a) as a movement to the right. In constract, if the hand moves down, the sign of the velocity will be negative and it will move left as shown in Fig. 6 (b).

c) Angle Estimation

Estimating the angle of arrival of an object requires at least 2 RX antennas. The 77 GHz FMCW Radar is a multiple-input-multiple-output radar (MIMO), with 2 TX and 4 RX antenna used to increase the angle resolution. A Time-Division Multiplexing (TDM) MIMO technique is employed for transmitting [6]. As such, alternating time slots are dedicated for TX1 and TX2 for TDM. For example, TX1 will transmit the first chirp, TX2 will transmit the second chirp, then TX1 transmits again with a third chirp and so on. A transmission from TX1 results in a phase of 0, ω, 2ω, 3ω at RX1, RX2, RX3, RX4 antennas respectively. TX2 is placed at a distance of 4d from TX1. A transmission from TX2 results in a phase of 4ω, 5ω, 6ω, 7ω at the same 4 RX antennas respectively. This performance behaves like one virtual TX and eight virtual RX antennas as shown in Fig. 7.

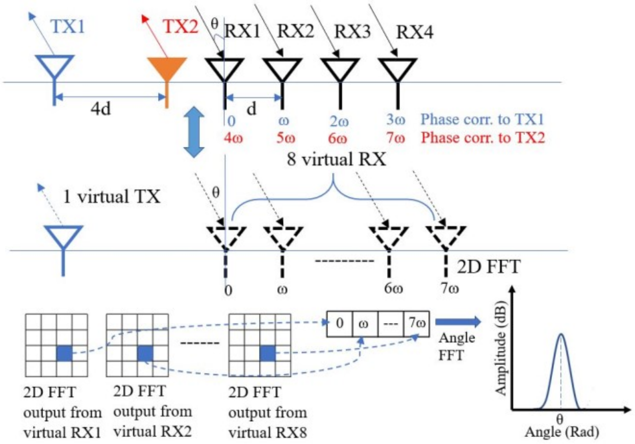

Fig. 7. Angle of Arrival Theory of FMCW Radar System

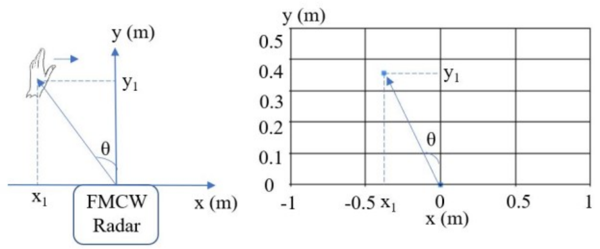

Fig. 8. Result of Angle of Arrival Estimation of FMCW Radar System

After performing a 2D FFT for each TX-RX pair, each 2D FFT corresponds to one virtual RX antenna. Another FFT is performed (called angle FFT or 3D FFT) [7] on the corresponding peaks across these multiple 2D FFTs to identify the phase difference ω and estimate the angle of arrival with the following formula:

$$\theta = \sin^{-1}\left(\frac{\lambda\omega}{2\pi d}\right) \quad (4)$$

where θ stands for angle of arrival, ω stands for phase difference after taking 3D FFT, d stands for distance between each RX antenna, and λ stands for wavelength of transmitted signal. By using noise removal algorithm to compare the range and the power of the object from range estimation and the range from angle estimation, the unwanted objects will be removed, only the hand information will be displayed. The result of angle of arrival estimation is shown in Fig. 8.

2) Gestures and Use Cases

The 6 sets of gestures will provide for FMCW Radar to control the application in the computer:

Swiping Right (R): Swiping one hand from left to right, based on the angle estimation, the program will detect the hand location then send one keystroke "RIGHT" to the application in the computer.

Swiping Left (L): Swiping one hand from right to left, based on the angle estimation, the program will know the location of moving hand then send one keystroke "LEFT" to the application in the computer.

Scrolling Up (SU): Holding one hand for 2s then moving hand up. Based on velocity and range estimation, the program will send many keystrokes "UP" to the application in the computer.

Scrolling Down (SD): Holding one hand for 2s then moving hand down. Based on velocity and range estimation, the program will send many keystrokes "DOWN" to the application in the computer.

Enter Program (EN): Holding both hands at different range for 4s, one at the left and one of the right of the radar then moving both hand down slowly. The program will send one keystrokes "ENTER" to the application in the computer.

Exit Program (EX): Holding both hands at the different range for 4s, one at the left and one of the right of the radar then moving both hand up slowly. The program will send one keystrokes "ALT+F4" to the application in the computer.

The advantage of this algorithm is that by identifying these gestures with an FMCW radar, a response can still be obtained when the signal is detected beyond 30 cm and it can detect two hand gesture. However, the noise removal method for filtering noise in velocity and angle estimation is more complicated than ultrasound range detection algorithm, the response time for left and right detection of FMCW Radar will be slowed down in comparison with the ultrasound. Nevertheless, as the ultrasound cannot accurately estimate signals beyond 30 cm, this FMCW approach compensates for the lack of precision in ultrasound detection at longer range at the expense of processing time.

III. HARDWARE

The MSP430F5510 is the main processing unit of ultrasound system. An 8 square pulses sequence at 40 kHz will be generated from the MSP430F5510 will be the input of the ultrasound transmitter [3]. The analog signals at the ultrasound receiver sensor will be converted into digital signals by the analog to digital converter (ADC) module. Then the MSP430F5510 will send data to the computer using the USB Application Programming Interface (API) [4]. The radar system uses IWR1443 Evaluation Module, a programming FMCW Radar, from Texas Instrument (TI). IWR1443 can transmit a programming chirp signal at 77GHz from 2 TX antenna then receive the reflected signal from 4 RX antenna. The FMCW Radar will perform range, velocity and angle estimation then transmit all analyzed results through universal asynchronous receiver-transmitter (UART) to the computer [7]. Visual Studio with C# programming language is used to write a program which getting data from both ultrasound and FMCW radar then analyzing, performing noise removal algorithm, and sending command to control application in the computer. The block diagram of the hybrid system is shown in Fig. 9.

IV. EXPERIMENTS AND RESULTS

The hybrid system was tested on 5 different computers: 2 desktop PCs, 1 LG, 1 Dell Laptop and 1 MacBook Pro 13". The algorithm performs equally on different computers across different Operational Systems using Visual Studio. To guarantee that the system works with different hand sizes, we tested the program with 5 individuals. A male and female with average hand sizes, a small hand shape from elementary student and 2 males with bigger hand size. Both ultrasound and radar device were placed on the table, the direction of antenna

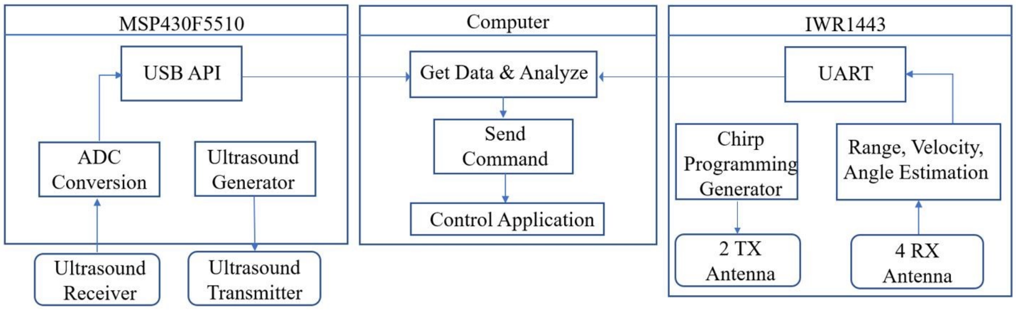

Fig. 9. Block Diagram of Ultrasound and FMCW Radar Hybrid System

TABLE I. AVERAGE % OF PRECISELY RECOGNIZED GESTURES OF ULTRASOUND FROM 0 TO 0.3M

Location	L	R	U	D	SU	SD	EN	EX
Home (0-0.3 m)	96.6	97.3	93.3	91.3	98.6	98	88.6	92
Library (0-0.3 m)	94.6	96	92	92.6	98	97.3	89.3	90

TABLE II. AVERAGE % OF PRECISELY RECOGNIZED GESTURES OF FMCW RADAR FROM 0.3M TO 1.2M

Location	Range	L	R	SU	SD	EN	EX
Home	0.3 m – 0.7 m	86.6	87.3	90	89.3	82.5	80.5
	0.7 m – 1 m	83.3	84	91.3	89.3	81.5	80
	1 m – 1.2 m	57.3	54.6	66.6	68	66	69
Library	0.3 m – 0.7 m	85.3	86.6	90.6	91.33	78.5	78
	0.7 m – 1 m	81.3	83.3	88	86.6	73.5	76
	1 m – 1.2 m	49.3	50.6	65	66	62.5	64

and ultrasound aim to the roof. The distance between the radar and the roof must be larger than 1.5 meter. The roof acts as clutter during FMCW Range detection. This minimum distance is required so that the energy estimation of the range of the hand is not affected by the roof's energy response. The users were asked to control three applications using various gestures: (i) open an image folder and use hand gestures to scroll for an image, open and close said image; (ii) scrolling the web page; (iii) open a PDF file, where the user will turn pages and scroll through the document. The system was also placed in a hollow box and covered with paper, plastic, glass, porcelain, wood, fiber or nylon to investigate the performance of the system with different materials hindering the signal. All users were able to successfully control all four applications with different range (1cm to 120cm). Each user will perform 10 repetitions for each gesture for both home environment (lightly populated) and in a library environment (heavily populated). 200 repetitions of each gesture were recorded in total. Based on these data sets, performance results are shown in Table 1 for ultrasound and Table 2 for radar.

The ultrasound performs well in the range of 1 cm to 30 cm. It can detect both fast and slow movement with high accuracy. It also works well with different hand sizes. Beyond Radar performs quite well in the range from 30 cm to 70 cm. However, when the range increase from 70 cm to 120 cm, the accuracy will begin to decrease. 4 gestures (L, R, SU, SD) could be useable, the other 2 gestures (EN, EX) need to improve more. The hand sizes also influence to the performance of radar, the big hand sizes give us better performance while testing in the range from 70 cm to 120 cm. Big hand sizes can reflect the signal easier than the small hand sizes. In the test of penetration ability, only radar work in these conditions cover the system with paper, plastic, glass, porcelain, wood, nylon. All 6 gestures can be detected with nylon cover from range 30 cm to 70 cm, only 2 gestures SU and SD can be detected from the other cover in the range from 30 cm to 70 cm and no gestures are recognized in the range from 70 cm to 120cm. These results show us the potential of application of radar for human computer interaction even if the radar is covered by different materials.

V. CONCLUSION

In this paper, a hybrid system was created by using ultrasound sensors and FMCW radar to control the computer. Ultrasound works at short-range (1 cm – 30 cm) and can detect both slow and fast hand movement with high accuracy. Radar works at long-range (30 cm – 120 cm), detecting slow movement and able to detect two hand movements. Future work will focus on detect fast movement using FMCW radar by reduce the complexity of noise removal algorithm and process hand gesture movement when the radar set up front of the user. The radar can separate human hand and human body while the user moving in the radar's field of view and the user still control the computer.

ACKNOWLEDGMENT

The authors gratefully acknowledge grant support from National Science Foundation (NSF) ECCS-1254838 and CNS-1718483.

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