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Lux et al.

(10) **Patent No.: US 9,870,457 B2**
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(54) **HERMA—HEARTBEAT MICROWAVE AUTHENTICATION**

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(73) Assignee: **California Institute of Technology**, Pasadena, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/828,452**

(22) Filed: **Aug. 17, 2015**

(65) **Prior Publication Data**

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Related U.S. Application Data

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(51) **Int. Cl.**
G06F 21/32 (2013.01)
A61B 5/05 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***G06F 21/32*** (2013.01); ***A61B 5/02444*** (2013.01); ***A61B 5/0507*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC .. G06F 21/32; G06F 21/83; G06F 2221/2139; G06F 3/017; G06F 19/3462;
(Continued)

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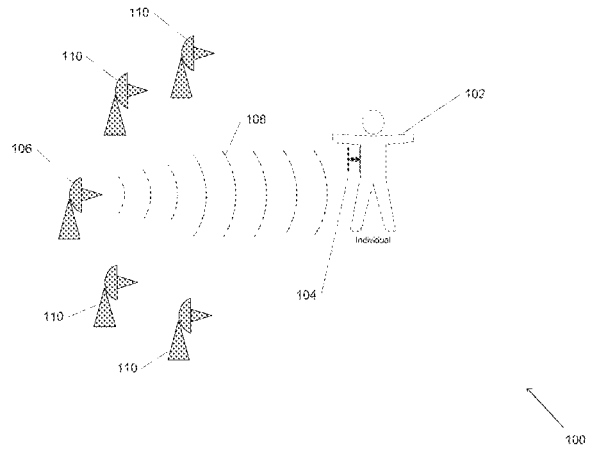
Primary Examiner — Mark Blouin
(74) *Attorney, Agent, or Firm* — KPPB LLP

(57) **ABSTRACT**

Systems and methods for identifying and/or authenticating individuals utilizing microwave sensing modules are disclosed. A HEaRtbeat Microwave Authentication (HERMA) system can enable the active identification and/or authentication of a user by analyzing reflected RF signals that contain a person's unique characteristics related to their heartbeats. An illumination signal is transmitted towards a person where a reflected signal captures the motion of the skin and tissue (i.e. displacement) due to the person's heartbeats. The HERMA system can utilize existing transmitters in a mobile device (e.g. Wi-Fi, Bluetooth, Cellphone signals) as the illumination source with at least one external receive antenna. The received reflected signals can be pre-processed and analyzed to identify and/or authenticate a user.

24 Claims, 9 Drawing Sheets



(51) **Int. Cl.**

H04W 12/06	(2009.01)
H04L 29/06	(2006.01)
A61B 5/024	(2006.01)

(52) **U.S. Cl.**

CPC ***H04L 63/0861*** (2013.01); ***H04W 12/06*** (2013.01); *A61B 5/02438* (2013.01)

(58) **Field of Classification Search**

CPC G06F 21/31; G06F 21/34; G06F 21/35; G06F 21/36

USPC 340/5.82

See application file for complete search history.

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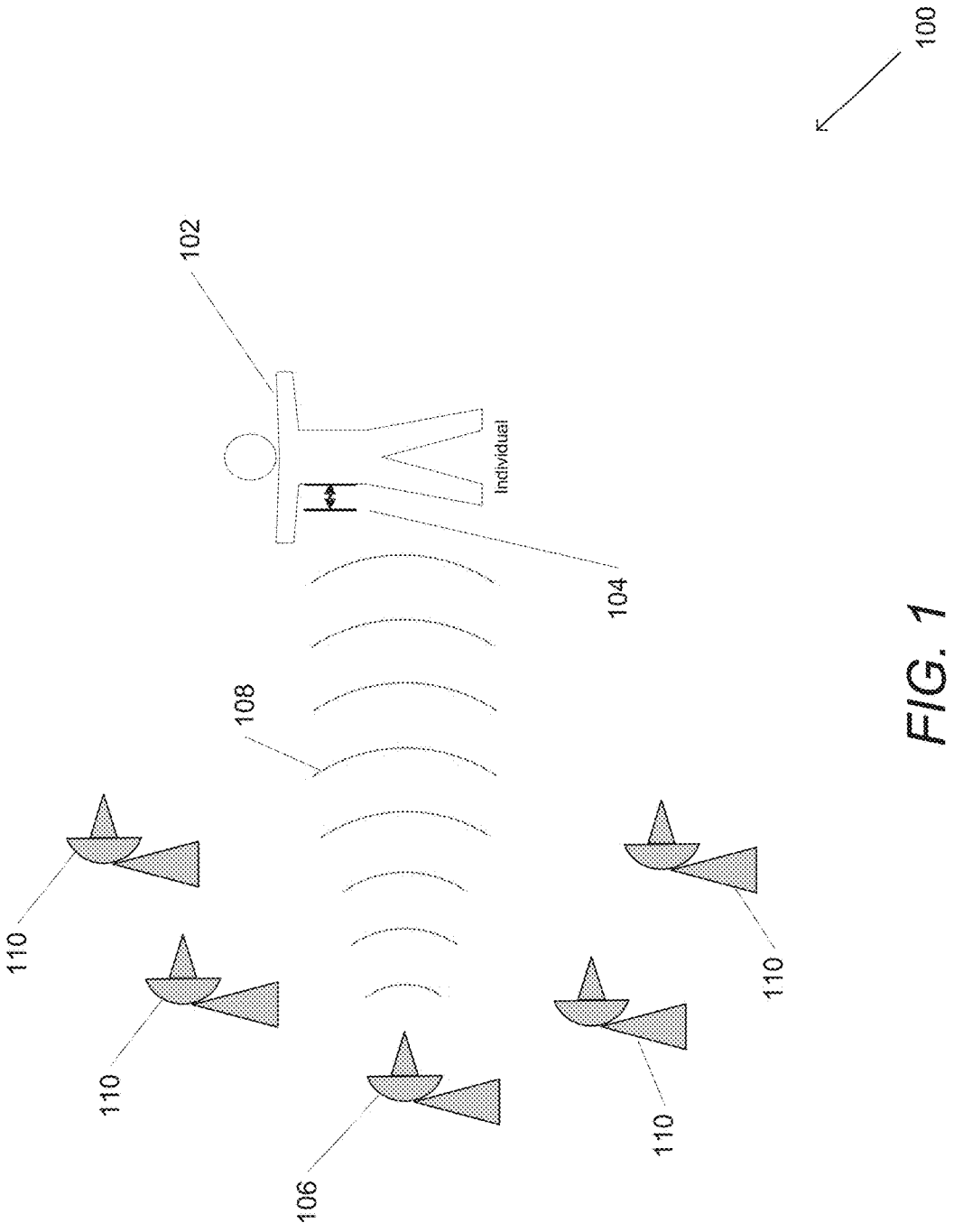

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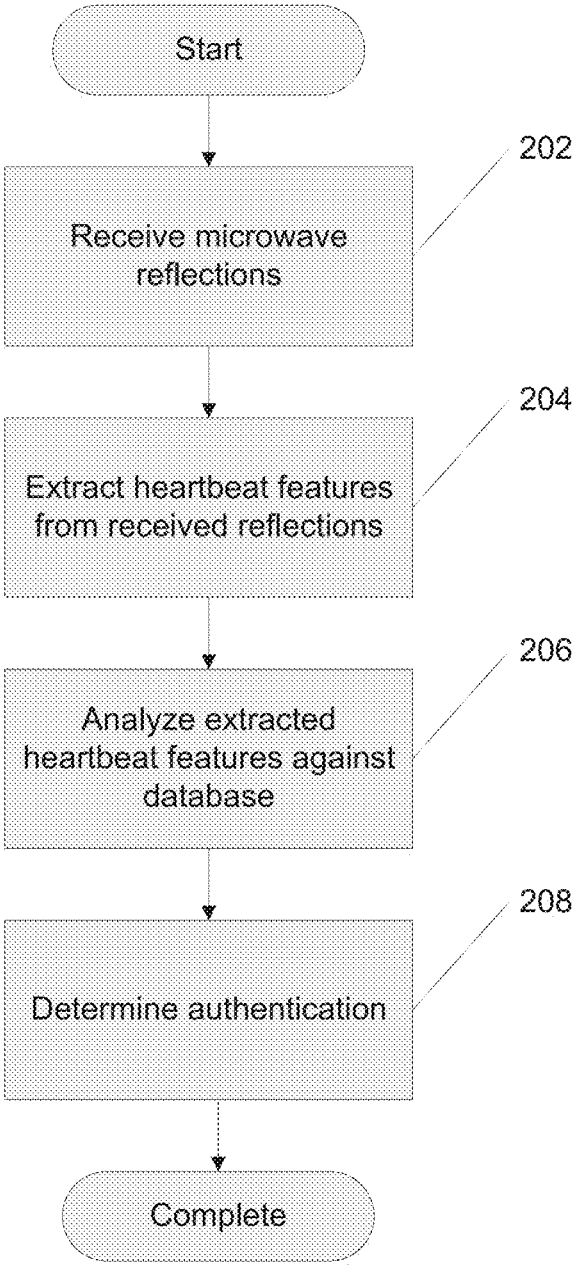

Start
Receive microwave reflections
202
Extract heartbeat features from received reflections
204
Analyze extracted heartbeat features against database
206
Determine authentication
208
Complete

FIG. 2

200

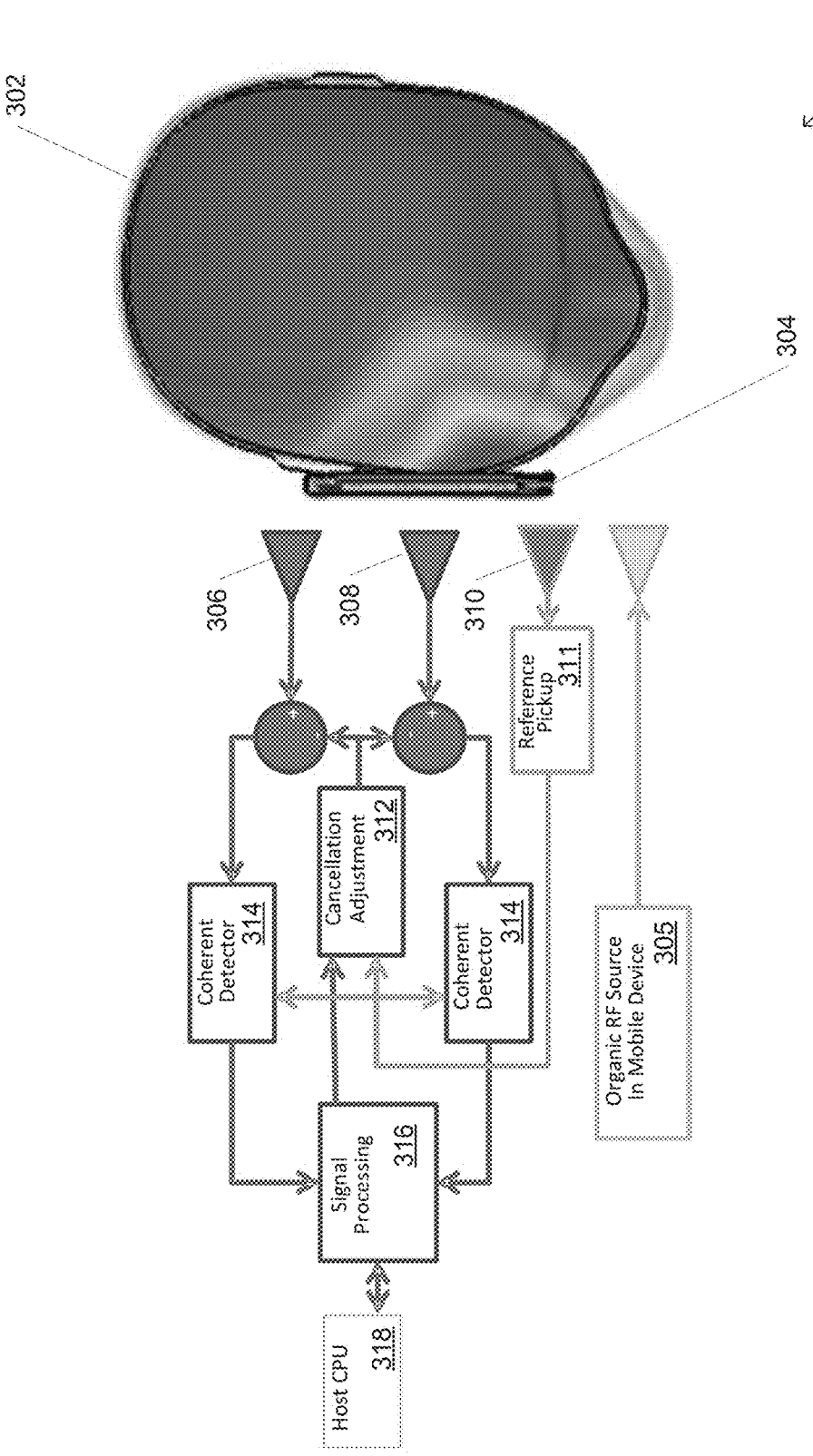

300
302
304
306
308
310
Reference Pickup 311
Cancellation Adjustment 312
Coherent Detector 314
Coherent Detector 314
Organic RF Source In Mobile Device 305
Signal Processing 316
Host CPU 318

FIG. 3

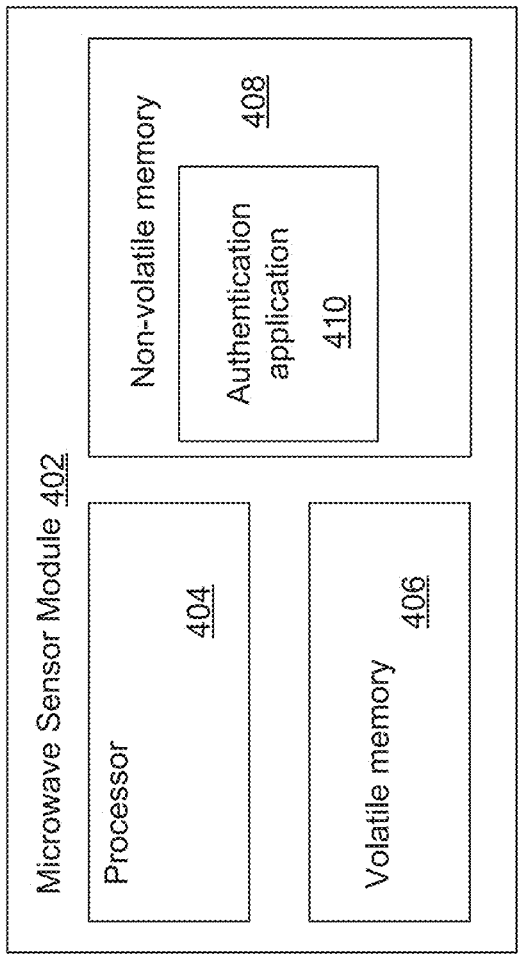
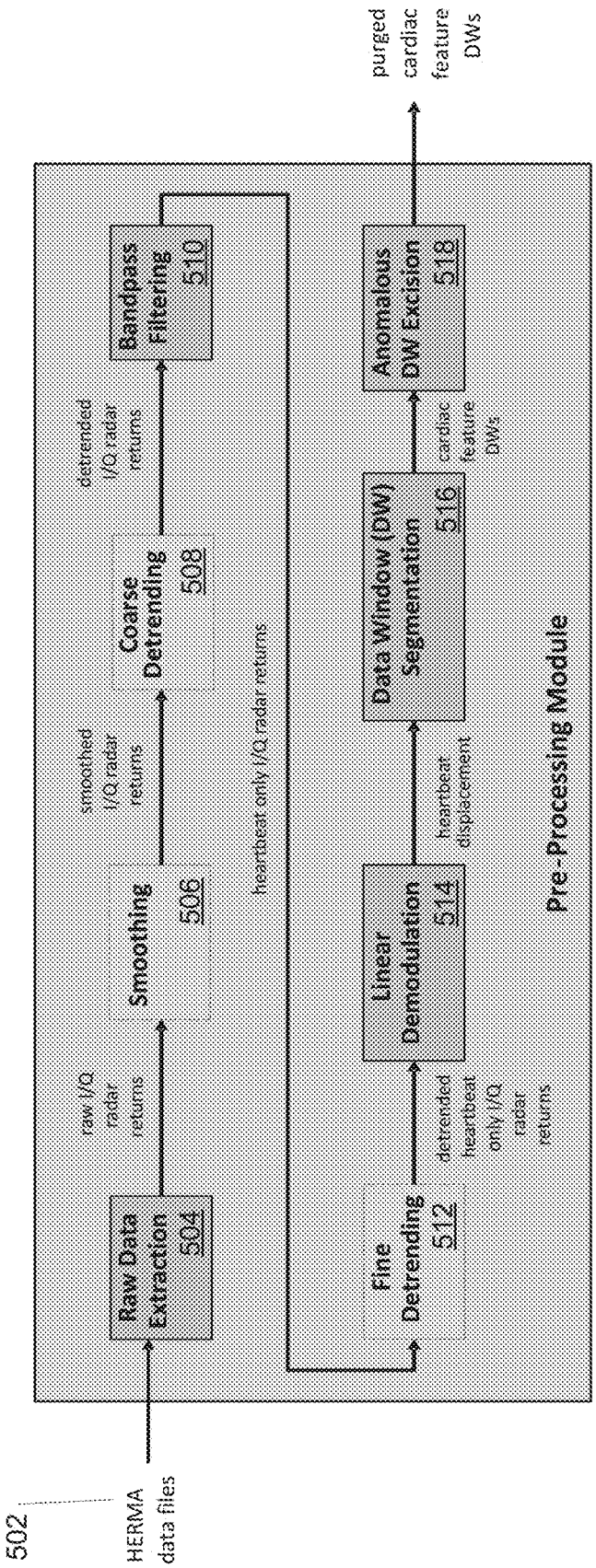

Microwave Sensor Module 402
Processor
404
Volatile memory
406
Non-volatile memory
408
Authentication application
410
400

FIG. 4


502
HERMA data files
Pre-Processing Module
Raw Data Extraction 504
raw I/Q radar returns
Smoothing 506
smoothed I/Q radar returns
Coarse Detrending 508
detrended I/Q radar returns
Bandpass Filtering 510
purged cardiac feature DWs
Fine Detrending 512
detrended heartbeat only I/Q radar returns
Linear Demodulation 514
heartbeat displacement
Data Window (DW) Segmentation 516
cardiac feature DWs
Anomalous DW Excision 518
heartbeat only I/Q radar returns

500

FIG. 5

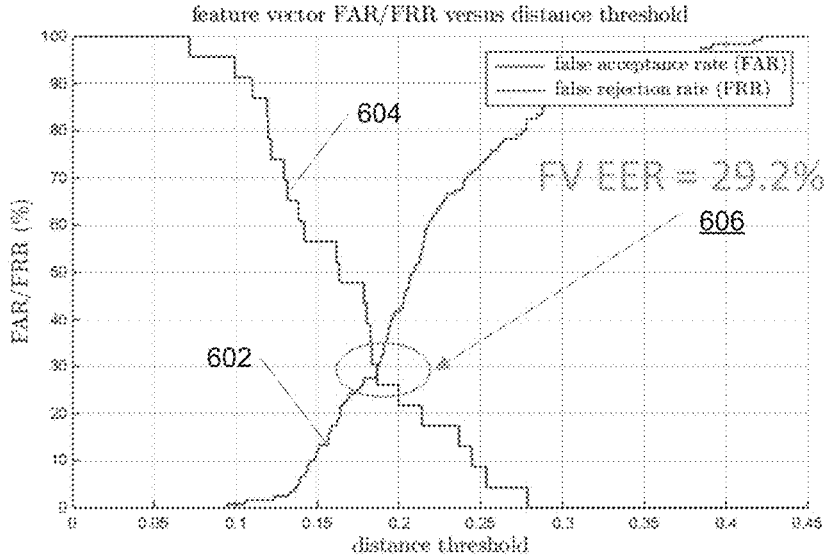


FIG. 6A

600

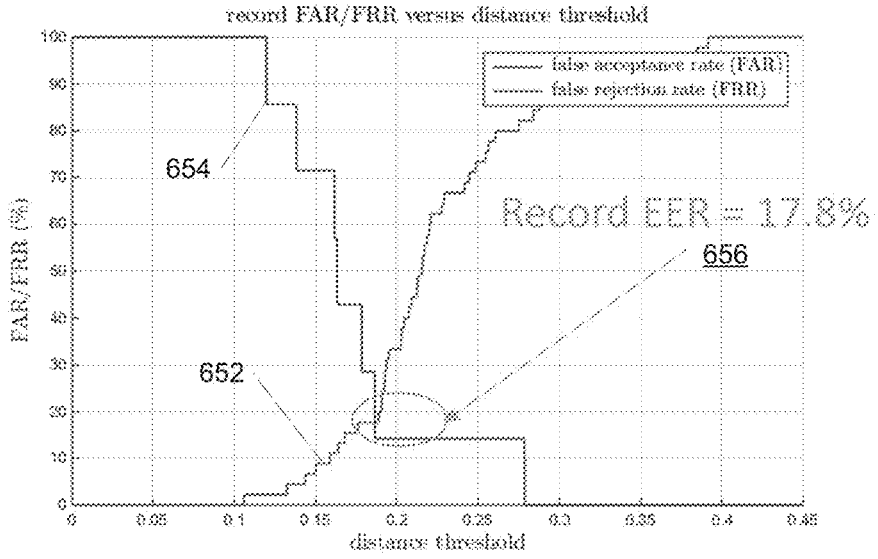


FIG. 6B

650

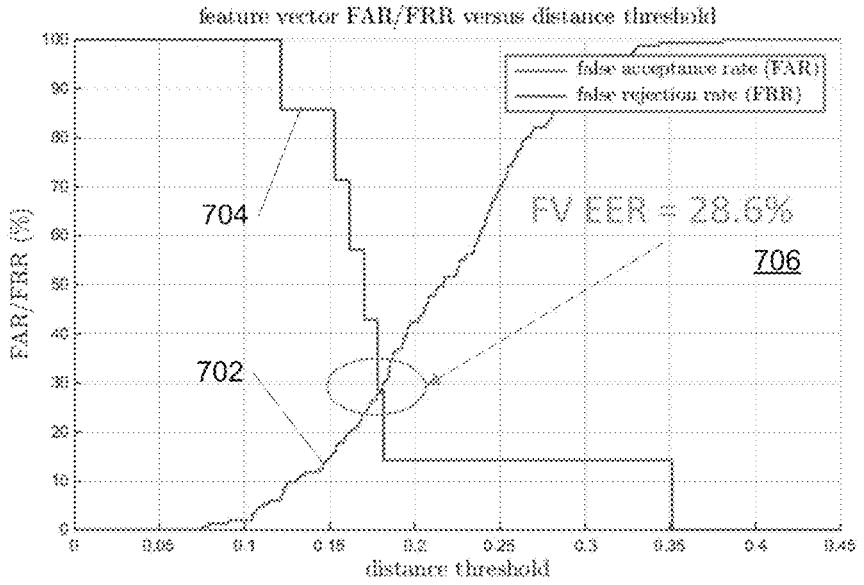


FIG. 7A

700

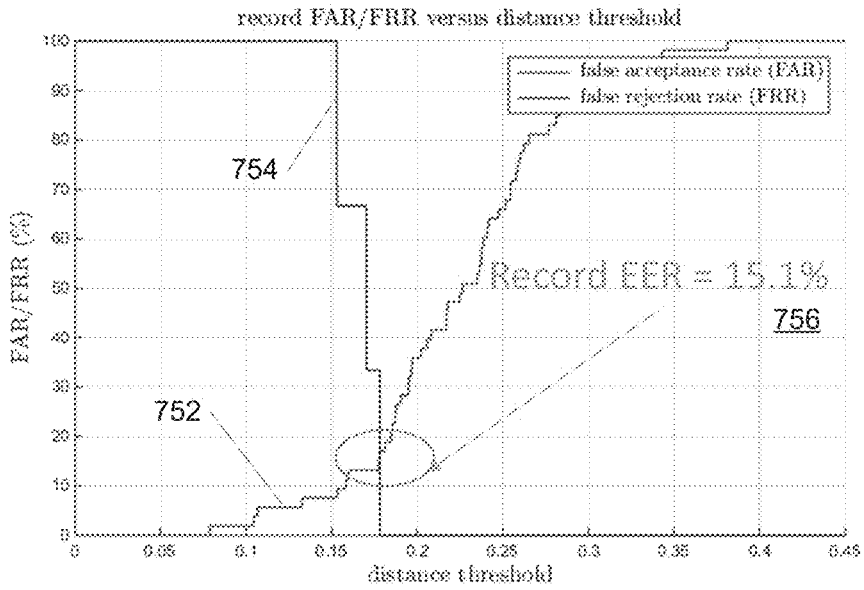


FIG. 7B

750

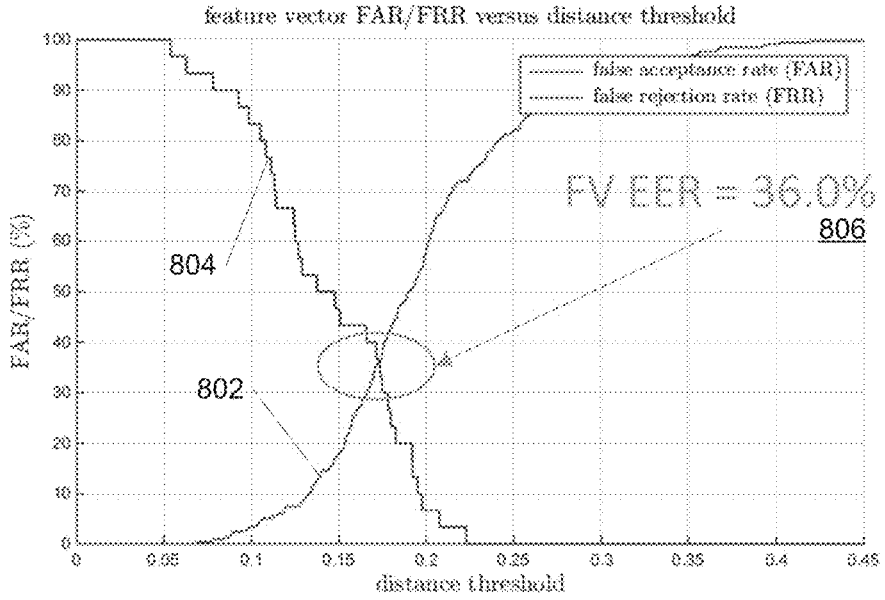


FIG. 8A

800

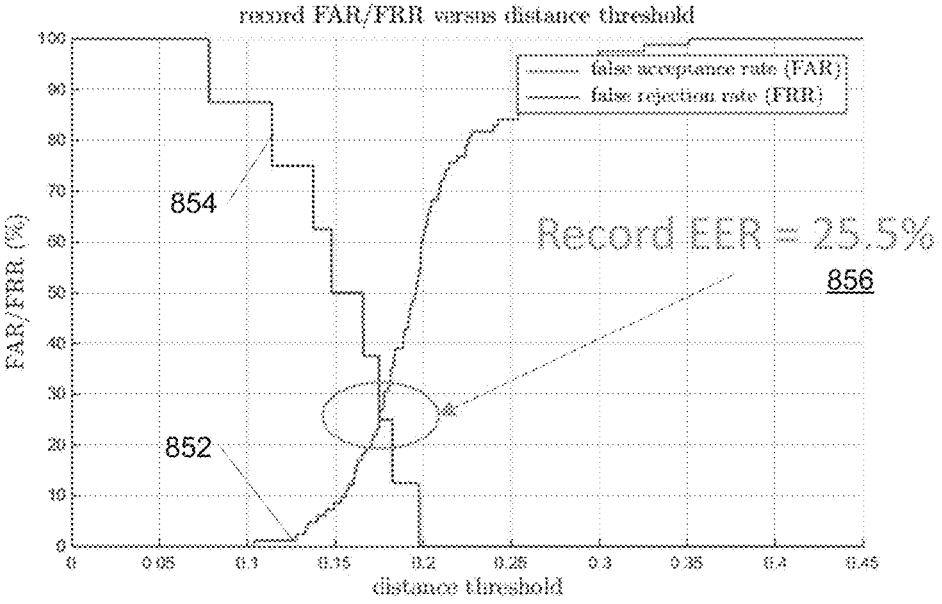


FIG. 8B

850

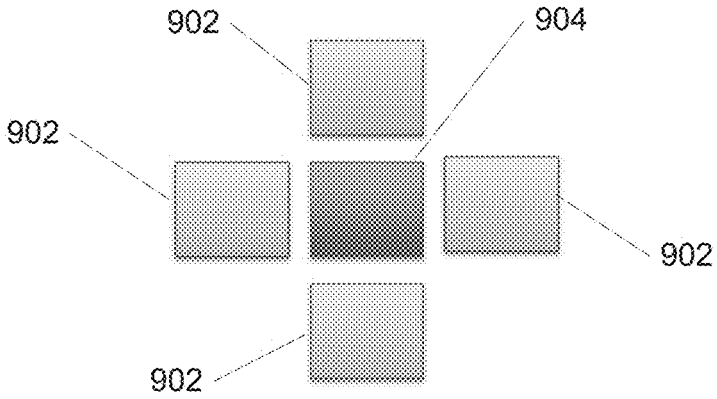


FIG. 9A

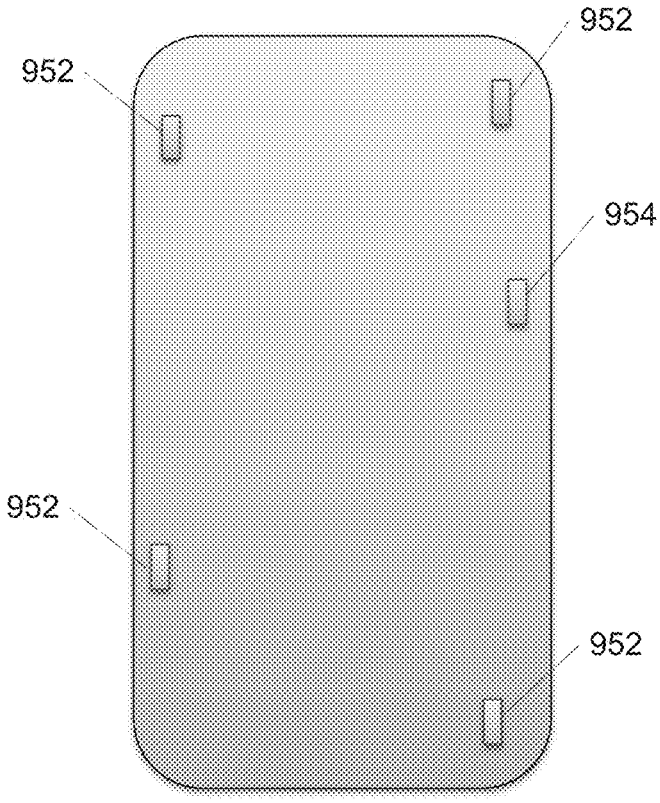


FIG. 9B

HERMA—HEARTBEAT MICROWAVE AUTHENTICATION

CROSS-REFERENCE TO RELATED APPLICATIONS

The current application claims priority to U.S. Provisional Patent Application No. 62/038,128 filed Aug. 15, 2014, the disclosure of which is incorporated herein by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 USC 202) in which the Contractor has elected to retain title.

FIELD OF THE INVENTION

The present invention generally relates to radars and more specifically to microwave radar sensor modules for systems and methods for detecting biometrics.

BACKGROUND

Biometrics refer to the quantifiable data (or metrics) related to human characteristics and traits. The quantifiable metrics can be gathered using various sensors and the collected data processed to identify and/or authenticate individual persons. Typically, biometric identifiers can be categorized as physiological and/or behavioral characteristics. Generally, physiological characteristics are related to the shape of the body and can include (but not limited to) fingerprint, palm print, DNA, and scent. In contrast, behavioral characteristics relate to a pattern of behavior and include (but not limited to) gait, voice, and typing rhythm. Biometric identifiers can also include characteristics that are more subtle such as respiratory and heartbeat patterns.

SUMMARY OF THE INVENTION

Systems and methods for identifying and/or authenticating individuals utilizing microwave sensing modules in accordance with embodiments of the invention are disclosed. In one embodiment, a microwave sensor module for authenticating a person using data related to the person's heartbeat includes at least one receiver configured to receive a reflected microwave signal from a person that contains information related to the person's heartbeat, a processor, a memory containing an authentication application, wherein the authentication application configures the processor to: extract heartbeat data from the reflected signal related to displacement as a result of the person's heartbeat, compare the extracted heartbeat data against at least one template profile, and authenticate the person based upon the comparison of the extracted heartbeat data and the at least one template profile.

In a further embodiment, the microwave sensor module further includes at least one transmitter configured to transmit a continuous wave (CW) radio frequency (RF) signal.

In another embodiment, the at least one transmitter is built in to a mobile device.

In a still further embodiment, the at least one transmitter is built in to an external illumination source.

In still another embodiment, the transmitted RF signal is a Bluetooth signal.

In a yet further embodiment, the transmitted RF signal is a WI-FI signal.

In yet another embodiment, the transmitted RF signal is a cellular phone signal.

In a further embodiment again, the authentication application further configures the processor to receive a portion of the transmitted RF signal using the at least one receiver, wherein the received portion of the transmitted RF signal is utilized as a reference for coherent detection.

In another embodiment again, the authentication application further configures the processor to receive a portion of the transmitted RF signal using the at least one receiver, wherein the received portion of the transmitted RF signal is utilized for noise cancellation.

In a further additional embodiment, the authentication application further configures the processor to extract heartbeat data from the reflected signal by: extracting raw data from the reflected signal by constructing an I/Q radar returns matrix and I/Q time series waveforms, bandpass filtering the I/Q time series waveforms to remove effects due to respiration and to isolate heartbeat only I/Q time series waveforms, translating and rotating the heartbeat only I/Q time series waveforms to lie along the Q-axis, where a scaled imaginary part yields heartbeat displacement waveforms, segmenting the heartbeat displacement waveforms into non-overlapping data windows (DW) of a fixed duration, and removing anomalous DW from the data set, where anomalous DW include any DW whose root mean square or maximum absolute value is outside of a specified interval.

In another additional embodiment, wherein the authentication application further configures the processor to extract heartbeat data from the reflected signal by: smoothing the I/Q time series waveforms to mitigate against outlier data points caused by motion artifacts, removing affine trends from the I/Q time series waveforms to mitigate against stationary clutter effects, and removing affine trends from the heartbeat only I/Q time series waveforms to remove residual clutter effects.

In a still yet further embodiment, a smoothed differentiator pre-filter is utilized to enhance the heartbeat data.

In still yet another embodiment, a method of authenticating a person using data related to the person's heartbeat, the method includes receiving a reflected microwave signal from a person using at least one receiver, where the reflected signal contains information related to the person's heartbeat, extracting heartbeat data from the reflected signal, where the heartbeat data is related to displacement as a result of the person's heartbeat, comparing the extracted heartbeat data against at least one template profile, and authenticating the person based upon the comparison of the extracted heartbeat data and the at least one template profile.

In a still further embodiment again, the method further includes transmitting a CW RF signal using at least one transmitter.

In still another embodiment again, the at least one transmitter is built in to a mobile device.

In a still further additional embodiment, the at least one transmitter is built in to an external illumination source.

In still another additional embodiment, the transmitted RF signal is a Bluetooth signal.

In a yet further embodiment again, the transmitted RF signal is a WI-FI signal.

In yet another embodiment again, the transmitted RF signal is a cellular phone signal.

In a yet further additional embodiment, the method further includes receiving a portion of the transmitted RF signal

using the at least one receiver, wherein the received portion of the transmitted RF signal is utilized as a reference for coherent detection.

In yet another additional embodiment, the method further includes receiving a portion of the transmitted RF signal using the at least one receiver, wherein the received portion of the transmitted RF signal is utilized for noise cancellation.

In a further additional embodiment again, the extracting heartbeat data from the reflected signal includes extracting raw data from the reflected signal by constructing an I/Q radar returns matrix and I/Q time series waveforms, band-pass filtering the I/Q time series waveforms to remove effects due to respiration and to isolate heartbeat only I/Q time series waveforms, translating and rotating the heartbeat only I/Q time series waveforms to lie along the Q-axis, where a scaled imaginary part yields heartbeat displacement waveforms, segmenting the heartbeat displacement waveforms into non-overlapping data windows (DW) of a fixed duration, and removing anomalous DW from the data set, where anomalous DW include any DW whose root mean square or maximum absolute value is outside of a specified interval.

In another additional embodiment again, the extracting heartbeat data from the reflected signal further includes smoothing the I/Q time series waveforms to mitigate against outlier data points caused by motion artifacts, removing affine trends from the I/Q time series waveforms to mitigate against stationary clutter effects, and removing affine trends from the heartbeat only I/Q time series waveforms to remove residual clutter effects.

In a still yet further embodiment again, a smoothed differentiator pre-filter is utilized to enhance the heartbeat data.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a diagram illustrating the conceptual operation of a Heartbeat Microwave Authentication (HERMA) system in accordance with an embodiment of the invention.

FIG. **2** is a flowchart describing a process for authenticating a user utilizing heartbeat features in accordance with an embodiment of the invention.

FIG. **3** illustrates a hardware design implementation of a HERMA system in accordance with an embodiment of the invention.

FIG. **4** is a microwave sensor module in accordance with an embodiment of the invention.

FIG. **5** is a chart illustrating a process for pre-processing reflection data in accordance with an embodiment of the invention.

FIGS. **6**A-B are graphs illustrating results from a 4 channel HERMA system with merged orientation in accordance with an embodiment of the invention.

FIGS. **7**A-B are graphs illustrating results from a 4 channel HERMA system with separated orientation in accordance with an embodiment of the invention.

FIGS. **8**A-B are graphs illustrating results from a single channel HERMA system with merged orientation in accordance with an embodiment of the invention.

FIGS. **9**A-B illustrate antenna configurations in accordance with an embodiment of the invention.

DETAILED DESCRIPTION OF THE DRAWINGS

Turning now to the drawings, systems and methods for identifying and/or authenticating individuals utilizing microwave sensing modules in accordance with embodiments of the invention are disclosed. In many embodiments, the HEaRtbeat Microwave Authentication (HERMA) system can enable the active identification and/or authentication of a user by analyzing reflected RF signals that contain a person's unique characteristics related to their heartbeats. In various embodiments, an illumination signal is transmitted towards a person where a reflected signal captures the motion of the skin and tissue (i.e. displacement) due to the person's heartbeats. Typically, heartbeat displacement is affected by the arrangement and size of the blood vessels under the skin and thus the displacement is unique to the individual.

In many embodiments, the HERMA system utilizes a RF energy source to illuminate a person and at least one antenna to receive the reflected signal. In various embodiments, the HERMA system utilizes existing transmitters in a mobile device (e.g. Wi-Fi, Bluetooth, Cellphone signals) as the illumination source with at least one external receive antenna. As further described below, the received reflected signals can be pre-processed and analyzed to identify and/or authenticate a user. In several embodiments, a reference copy of the transmitted signal can also be used for coherent detection and noise cancellation. Although specific configurations are discussed throughout, one of ordinary skill in the art would readily appreciate that the transmitter and receivers can be varied as appropriate to the requirements of a specification application. For example, the system can utilize dedicated transmitter(s) and dedicated receiver(s) in a mobile device. In other embodiments, external illumination sources (e.g. the cell tower, TV stations, Wi-Fi Access Points) can be utilized with the at least one receiver incorporated into a mobile device. Likewise, the system could utilize existing transmitters in a mobile device and utilize receivers in the area to receive the reflection. Similarly, the system could utilize signals radiated from a bystander's mobile device as the illumination source, and receive reflections either at the subject's phone, a bystander's phone, or some other external site. HERMA systems for identifying and/or authenticating a target in accordance with embodiments of the invention are further discussed below.

Conceptual Operation of a Heartbeat Microwave Authentication (HERMA) System

The authentication process can include measuring RF reflections including (but not limited to) microwave reflections at one or more receiver locations and a predetermined time segment such as (but not limited to) 5 seconds. For any given receiver antenna position, the measured reflected signal can be an integrated sum of the signals from all places "in view." Thus, changing the antenna position or the part of the body being illuminated can change the unique pattern that is received by a microwave receiver.

A diagram illustrating the conceptual operations of a HERMA system in accordance with an embodiment of the invention is shown in FIG. **1**. Typically, the HERMA system operates with an individual that is close in proximity to the unit with a clear line-of-sight path to the receiver modules. The diagram **100** includes an individual **102** that creates a displacement **104** due to their respiration and heartbeat effects. The diagram **100** illustrates a transmitter **106** that is configured to send out a continuous wave (CW) **108** signal at a predetermined frequency such as (but not limited to) 3.15 GHz. The transmitted CW signal illuminates and causes a signal to reflect from the individual **102**. In various embodiments, at least one antenna **110** receives the reflected signal, where the received signal is processed. In many embodiments, the receivers can mix the received waveforms with a transmitter reference signal to produce complex

baseband (i.e., in-phase (I) and quadrature (Q)) signals as further discussed below. In various embodiments, the analog complex baseband waveform can be low-pass filtered to 10 kHz and sampled at 50 kHz, and decimated to 200 Hz. In several embodiments, the received waveforms can also be recorded for 30 seconds yielding a 6,000 sample I/Q digital signal per record. Although specific conceptual operations of a HERMA system are discussed above with respect to FIG. **1**, any of a variety of modes of operation including various transmitters, receivers, and combinations of transmitter and receivers, for operating a HERMA system as appropriate to the requirements of a specific application can be utilized in accordance with embodiments of the invention. Processes for authenticating users utilizing heartbeat features in accordance with embodiments of the invention are discussed further below.

Authentication Using HERMA Systems

Although users can place their devices in different position, and thus change the nature of the detected microwave heartbeat waveform, the basic heart beat timing remains unique to that person. Thus, one of the values of utilizing a HERMA approach is that it allows users to continue to use their mobile devices in the same way or manner during authentication.

A process for authenticating a user utilizing heartbeat features in accordance with an embodiment of the invention is illustrated in FIG. **2**. The process **200** includes receiving (**202**) microwave reflections from an individual at one or more receiver locations for a set period of time including (but not limited to) a 5 second segment. In many embodiments, the segment length should be long enough to capture a plurality of heartbeats. In various embodiments, the reflection data can be evaluated for corruption from interference and/or motion artifacts. The process also includes extracting (**204**) features related to heartbeat displacement from the received reflection signal as further discussed below. The process can further include analyzing (**206**) the extracted features and comparing it against a database that can include templates previously recorded of the individual being authenticated. Based on the results, a determination (**208**) can be made authenticating the individual as the person in question.

The process of authentication a user with HERMA can be implemented using a variety of hardware configurations. A hardware design implementation of a HERMA system in accordance with an embodiment of the invention is illustrated in FIG. **3**. The diagram **300** illustrates a person **302** with a mobile device **304** that is placed near the person's right temple area. In the illustrated embodiment, the mobile device **304** is acting as an illumination source **305** of the CW transmitter signal. Typically, a mobile device may include multiple potential RF sources including (but not limited to) Bluetooth, 802.11 Wi-Fi, as well as the cellular voice and data services signals. In many embodiments, multiple receiving antennas can be utilized, where one antenna **310** can be placed close to the transmitter to pick up the reference signal **311**, and the others **306**, **308** can be placed farther away, so they receive a combination of the transmitted signal and the signals reflected from the subject. Typically, all antennas will receive some reflections, but the pickup antenna **310** will receive a much stronger transmit signal. As further discussed below, the reference antenna **310** does not need to be very far apart from the other antennas **306**, **308** so long as the relative levels of the direct and reflected paths are different. However, each mobile device will likely have a unique optimum location for the reference antenna **310** and biometric sensing antennas **306**, **308**.

In several embodiments, a cancellation process can be utilized to remove a portion of the coupled signal that is not changing, and thus leaving just the variable signal from the reflections of the person. A sample of the reference signal can be used to provide a cancellation signal for cancellation adjustment **312** and as a reference for the coherent detectors **314**. Cancellation adjustments utilizing various cancellation paths are disclosed in U.S. patent application Ser. No. 14/256,748, entitled "Life Detecting Radars," filed Apr. 18, 2014, the disclosure of which is incorporated by reference herein in its entirety. Using the transmitted signal as a reference allows for a narrow bandwidth detection system, reducing the amount of noise, and providing immunity to interference. In various embodiments, the HERMA system also includes a signal processing unit **316** that can be connected to a host CPU **318** or the Internet for remote access to data and control functionalities. In various embodiments, the detected signals can be digitized and processed by an application running on the host mobile device. In some embodiments, an application running on the host computer can be made aware of when the mobile device is transmitting the CW signal, or, at least, ensure that the interface is transmitting with enough to provide the needed illumination signal.

Modern cellphone and mobile device technology provides a fairly low risk path to implementation of extra circuitry needed for the sensing of the reflected microwave signals from the user. In the near term, an effective strategy may be to include the circuitry and antennas in a case that fits around the mobile device. However, the HERMA system can be implemented using hardware present on a mobile device, as a standalone module, or in combination. A microwave sensor module in accordance with an embodiment of the invention is illustrated in FIG. **4**. The illustration **400** shows a sensor module **402** that includes a processor **404**, volatile memory **406** and non-volatile memory. In the illustrated embodiment, the non-volatile memory **408** is a machine readable media that is utilized to store the machine readable instructions that configure the processor **404**. The non-volatile memory **408** contains an authentication application **410**, which is utilized to configure the processor **404** to authenticate a user utilizing heartbeat features as discussed above.

Although specific processes and hardware implementations for authenticating a user utilizing heartbeat features are discussed above with respect to FIGS. **2-4**, any of a variety of processes and hardware implementations as appropriate to the requirements of a specific application can be utilized in accordance with embodiments of the invention. Processing data from a reflected signal containing displacement information (i.e. HERMA data) in accordance with embodiments of the invention are discussed further below.

Pre-Processing of HERMA Data

Electrocardiogram (ECG) based recognition generally falls into two categories: fiducial and non-fiducial methods. Fiducial methods rely on extracting timing, duration, and amplitude of features specific to ECG signal shapes. In contrast, non-fiducial methods extract features from ECG waveforms based solely on the assumption that they are unique between individuals and consistent for a given individual. As heartbeat displacements obtained from HERMA do not empirically resemble ECG signal shapes, non-fiducial methods are utilized for authentication and/or identification.

In order to apply such techniques for HERMA based systems, reflection data can be pre-processed for extraction of heartbeat displacement of an individual. Typically, the received radar returns from HERMA contain respiration and

noise effects in addition to heartbeat features where respiration chest displacements are on the order of 4-12 mm at a rate of 0.1-0.3 Hz and heartbeat chest displacements are on the order of 0.2-0.5 mm at a rate of 1-3 Hz. While respiration effects are spectrally isolated from heartbeat effects, they are between 1-2 orders of magnitude larger. Because of this, harmonics from respiration may leak into the desired band of interest for heartbeat signature features (1-40 Hz). Further, the observed $1/f^2$ noise appears to adversely affect the signal-to-noise ratio (SNR) of the received heartbeat waveform noticeably.

Ideally, I/Q radar returns should trace out a circular arc in the I/Q plane centered at the origin where $x[n]=x_1+jx_Q[n]$. Further, the displacement effects d[n] is equal to the displacement due to respiration $d_R[n]$ and the displacement due to heartbeat $d_H[r]$. From the I/Q radar returns, the composite displacement d[n] (due to respiration $d_R[n]$ and heartbeat $d_H[n]$ effects) can be obtained as follows, where c is the speed of light and F_0 is the carrier frequency:

$$d[n] = \frac{c}{4\pi F_0}\arctan\left(\frac{x_Q[n]}{x_I[n]}\right)$$

Although the goal is to preserve the heartbeat displacement $d_H[n]$, in practice, the I/Q radar returns are corrupted by clutter/noise effects. For this case, the I/Q radar returns can be linearly detrend and then bandpass filter to the desired band of interest (1-40 Hz). This will yield a complex baseband signal y[n] that approximately spans a very small circular arc (between 4-8 degrees) corresponding solely to the heartbeat displacement $d_H[n]$. The signal y[n] can be translated and rotated to lie approximately along the Q-axis, yielding a signal z[n]. From this, the heartbeat displacement $d_H[n]$ can be approximately determined as follows (this process is called linear demodulation):

$$d_H[n] = \frac{c}{4\pi F_0}\mathrm{Im}[z[n]]$$

A process for pre-processing reflection data in accordance with an embodiment of the invention is illustrated in FIG. **5**. The process **500** includes raw data extraction (**504**) by reading HERMA data file(s) **502** and construction raw I/Q radar returns matrix and subject/record index matrix. An optional smoothing (**506**) of the I & Q time series waveforms can be carried out to mitigate against outlier data points caused by motion artifacts. The smoothing method can include a robust version of a local regression with weighted least squares and a 2^{nd} degree polynomial model. In some embodiments, the 'rloess' smoothing method in MATLAB was used with a window span of 1% of the total record length. Further, an optional affine (linear plus constant offset) trend can be removed (508) from the I & Q time series waveforms to mitigate against stationary clutter effects. Linearly detrending the smoothed data can help remove residual wander due to clutter. However, detrended data appears to have a prevalent respiration component. In many embodiments, time series waveforms can be bandpass filtered (**510**) to remove effects due to respiration and to isolate the heartbeat components. In some embodiments, a 6^{th} order Type II Chebyshev filter with stopband ripple of 60 dB and band edges at 0.7 Hz and 40 Hz can be used for bandpass isolation. In addition, the first 5 sec of the record can be removed to look past the bandpass filter transient effects.

An optional affine trend can also be removed (512) from the heartbeat only I & Q time series waveforms to remove residual clutter effects. In various embodiments, the input I/Q waveforms can be translated and/or rotated (i.e. linear demodulation) (**514**) to lie along the Q-axis and the scaled imaginary part yields the displacement. Then, each data record can be partitioned into data windows (DWs) (**516**) of constant size where the subject/record indices are stored. In this setting, the DWs can be formed by segmenting the heartbeat displacement waveforms into non-overlapping windows of 5 seconds in duration. To excise anomalous DWs from the data set, such as those due to motion artifacts or low signal gain, any DW whose root mean square (RMS) or maximum absolute value (MAV) is outside of a specified interval is deemed anomalous and excised (**518**). Consider accepting a given DW only if either the RMS or MAV of the window lied within a specified range. Large values of RMS or MAV suggest the presence of a motion transient that should be removed from the data set. Small values of RMS or MAV suggest that the gain of the signal path is too low. In this case, the heartbeat displacement waveform will look severely corrupted by noise and should be removed from the data set.

The received heartbeat displacement waveforms often possess a noticeable fundamental beat, but do not appear to have finer details as in the case of ECG signals. This may be the result of the I/Q anti-aliasing filters at the receiver modules, which noticeably shape the input noise with a $1/f^2$ type behavior. While the noise power drops off appreciably with frequency, which ensures good alias image suppression, for low frequencies, this could result in strong noise components seen in bands of interest such as the heartbeat band of 1-40 Hz. To mitigate against this effect, a smoothed differentiator pre-filter can be utilized to enhance the heartbeat fine details (i.e., the harmonics above the fundamental). This has resulted in improved authentication/identification performance for some embodiments.

Although specific processes for pre-processing reflection data are discussed above with respect to FIG. **5**, any of a variety of processes for pre-processing reflection data as appropriate to the requirements of a specific application can be utilized in accordance with embodiments of the invention. HERMA implementation using 4 channel and single channel systems in accordance with embodiments of the invention are discussed further below.

4 Channel and Single Channel HERMA System Implementations

Various non-fiducial methods implicitly extracted heartbeat signature features from the normalized AC of non-overlapping constant length DWs. In these methods, the normalized AC DW sequences were mapped to feature vectors (FVs) via a data transformation. Specifically, the three methods that we looked at for HERMA were the following: (1) applying a discrete cosine transform (DCT) and using the lower frequency components to form the FVs (referred to here as the AC/DCT method); (2) applying a principal component analysis (PCA) derived from the training set to form the FVs (referred to here as the AC/PCA method) and (3) applying a PCA followed by a linear discriminant analysis (LDA) derived from the training set to form the FVs (referred to here as the AC/PCLDA method). In testing system implementations, data from HERMA was collected using two antenna configurations: (1) a 4 channel cruciform arrangement in which the transmitter antenna was placed at the center of the cruciform and (2) a single channel system in which the transmitter and receiver antennas were adjacent to each other. A 4 channel cruciform arrangement in accordance with an embodiment of the invention is shown

in FIG. **9**A. The arrangement **900** includes four receive antennas **902** on each side of a transmit antenna **904** that is placed in the center of the four receive antennas **902**.

For the 4 channel cruciform arrangement, data was captured according to the following: 5 subjects, 3 orientations per subject (front facing, left temple profile, and right temple profile), and 2 data takes per orientation. For the single channel setup, data was captured according to the following: 6 subjects, 3 orientations per subject (front facing, left temple profile, and right temple profile), 6 data takes per orientation. For both configurations, considered both merged and separate orientations. For merged orientations, subject indices from data takes from a given individual at different orientations were merged together to correspond to one subject. For separated orientations, data takes from a given individual at different orientations were assigned separate subject indices.

The 4 channel system utilized DW construction with anomalous excision as discussed above. In particular, an experimental system used MAV criterion where only DWs with MAV levels between −80 dB and −74 dB were preserved. Thus, the original data set included 600 DWs with 5 sec non-overlapping windows from 120 record observations (5 subjects, 3 orientations, 2 takes per orientation, and 4 antenna channels per take) and the reduced data set included 163 DWs. The vast majority of the DWs that did not survive the MAV based purge came from Channels 1 & 3, which were known to yield noisy and heavily attenuated displacement signals. Further, DWs corrupted by random motion transients and artifacts were successfully removed, upon manual inspection.

A graph illustrating results from a 4 channel system with merged orientation in accordance with an embodiment of the invention is illustrated in FIGS. **6**A-B. The graph **600** of FIG. **6**A depicts the false acceptance rate (FAR) **602** and the false rejection rate (FRR) **604** for a feature vector (FV) in accordance with an embodiment of the invention. The equal error rate (EER) is shown as the intersection **606** of the FAR and FRR of a value of 29%. The graph **650** of FIG. **6**B depicts the FAR **652** and FRR **654** for a record vector in accordance with an embodiment of the invention. The equal error rate (EER) is shown as the intersection **656** of the FAR and FRR of a value of 17.8%. The results are also summarized below in Table 1.

	Distance threshold value	# of hits	# of trials	Observed rate	Lower limit of 50% confidence interval	Upper limit of 50% confidence interval	Note
FV FP	0.1864	35	120	0.2917	0.2608	0.3249	Set for EER
FV FN	0.1864	6	23	0.2609	0.1870	0.3511	Set for EER
Record FP	0.1864	8	45	0.1778	0.1340	0.2325	Set for EER
Record FN	0.1864	1	7	0.1429	0.0403	0.3407	Set for EER

Further, results as to identification using a 4 channel system with merged orientation in accordance with an embodiment of the invention are summarized below in Table 2. With anomalous DWs removed, trends were noticed with the normalized ACs between the different subjects. In various embodiments, setting the maximum lag to 1.4 seconds yielded the best results in terms of authentication and identification.

	# of hits	# of trials	Observed rate	Lower limit of 50% confidence interval	Upper limit of 50% confidence interval
FV accuracy	46	88	0.5227	0.4811	0.5639
Record accuracy	20	33	0.6061	0.5321	0.6753

A graph illustrating results from a 4 channel system with separated orientation in accordance with an embodiment of the invention is illustrated in FIGS. **7**A-B. The graph **700** of FIG. **7**A depicts the FAR **702** and the FRR **704** for a feature vector in accordance with an embodiment of the invention. The EER is shown as the intersection **706** of the FAR and FRR of a value of 28.6%. The graph **750** of FIG. **7**B depicts the FAR **752** and FRR **754** for a record vector in accordance with an embodiment of the invention. The EER is shown as the intersection **756** of the FAR and FRR of a value of 15.1%. The results are also summarized below in Table 3.

	Distance threshold value	# of hits	# of trials	Observed rate	Lower limit of 50% confidence interval	Upper limit of 50% confidence interval	Note
FV FP	0.1805	43	151	0.2848	0.2577	0.3138	Set for EER
FV FN	0.1805	2	7	0.2857	0.1380	0.4861	Set for EER
Record FP	0.1780	8	53	0.1509	0.1136	0.1984	Set for EER
Record FN	0.1780	1	3	0.3333	0.0914	0.6736	Set for EER

In addition, results as to identification using a 4 channel system with separated orientation in accordance with an embodiment of the invention are summarized below in Table 4.

	# of hits	# of trials	Observed rate	Lower limit of 50% confidence interval	Upper limit of 50% confidence interval
FV accuracy	28	133	0.2105	0.1845	0.2396
Record accuracy	10	44	0.2273	0.1784	0.2855

The single channel system utilized DW construction with anomalous excision as discussed above. In particular, the single channel system employed an 11-tap smoothed differentiator feature enhancement pre-filter, as it yielded slightly improved performance. Further, it used MAV criterion where only DWs with MAV levels between −123 dB and −112 dB were preserved. The original data set included 540 DWs with 5 sec non-overlapping windows from 108 record observations (3 subjects, 3 orientations, 6 takes per orientation, and 1 antenna channel per take). However, the reduced data set included 411 DWs. The DWs were plagued by weaker heartbeat signals and higher noise levels at larger frequencies were appropriately excised, upon manual inspection. In addition, DWs corrupted by random motion transients and artifacts were successfully removed.

A graph illustrating results from a single channel system with merged orientation in accordance with an embodiment of the invention is illustrated in FIGS. **8**A-B. The graph **800** of FIG. **8**A depicts the FAR **802** and the FRR **804** for a feature vector in accordance with an embodiment of the invention. The EER is shown as the intersection **806** of the FAR and FRR of a value of 36.0%. The graph **850** of FIG. **8**B depicts the FAR **852** and FRR **854** for a record vector in accordance with an embodiment of the invention. The EER is shown as the intersection **856** of the FAR and FRR of a value of 25.5%. The results are also summarized below in Table 5.

	Distance threshold value	# of hits	# of trials	Observed rate	Lower limit of 50% confidence interval	Upper limit of 50% confidence interval	Note
FV FP	0.1734	121	336	0.3601	0.3413	0.3795	Set for EER
FV FN	0.1734	10	30	0.3333	0.2638	0.4112	Set for EER
Record FP	0.1747	21	82	0.2561	0.2198	0.2967	Set for EER
Record FN	0.1747	2	8	0.2500	0.1206	0.4332	Set for EER

Further, results as to identification using a single channel system with merged orientation in accordance with an embodiment of the invention are summarized below in Table 6. With anomalous DWs removed, trends with the normalized ACs between the different subjects were noticed. In various embodiments, wetting the maximum lag to 1.3 seconds and 1.2 seconds yielded the best results in terms of authentication and identification, respectively.

	# of hits	# of trials	Observed rate	Lower limit of 50% confidence interval	Upper limit of 50% confidence interval
FV accuracy	38	156	0.2436	0.2184	0.2711
Record accuracy	14	41	0.3415	0.2828	0.4059

Although specific implementations using 4 channel and single channel HERMA systems are discussed above with respect to FIGS. **6**A-**9**A and Tables 1-6, any of a variety of HERMA systems utilizing various transmit and receive antennas configured as appropriate to the requirements of a specific application can be utilized in accordance with embodiments of the invention.

As discussed above, a HERMA system can include antennas arranged and configured as appropriate to the requirements of a specific application. For example, the antennas can be arranged and placed into a case for a particular mobile device or class of devices. An antenna configuration where the antenna positions are chosen to be close to existing antennas in a mobile device in accordance with an embodiment of the invention is illustrated in FIG. **9**B. The phone case **950** includes four receive antennas **952** and a transmit antenna **954** placed where a mobile device may have various antennas including (but not limited to) main antennas, sub antennas, GPS antennas, Bluetooth and/or WLAN antennas. In various embodiments, the transmit antenna **954** can be replaced with a reference pickup antenna as described above. Although specific antenna arrangements are discussed above with respect to FIG. **9**B, any of a variety of antenna arrangements for HERMA system applications as appropriate to the requirements of a specific application can be utilized in accordance with embodiments of the invention.

While the above description contains many specific embodiments of the invention, these should not be construed as limitations on the scope of the invention, but rather as an example of one embodiment thereof. It is therefore to be understood that the present invention may be practiced otherwise than specifically described, without departing from the scope and spirit of the present invention. Thus, embodiments of the present invention should be considered in all respects as illustrative and not restrictive.

What is claimed is:

1. A microwave sensor module for authenticating a person using data related to the person's heartbeat, comprising:

at least one transmitter configured to transmit a continuous wave (CW) radio frequency (RF) signal;

at least one receiver configured to receive a reflected microwave signal from a person that contains information related to the person's heartbeat;

a processor;

a memory containing an authentication application, wherein the authentication application configures the processor to:

receive a portion of the transmitted RF signal using the at least one receiver, wherein the received portion of the transmitted RF signal is utilized as a reference for coherent detection;

extract heartbeat data from the reflected signal related to displacement as a result of the person's heartbeat;

compare the extracted heartbeat data against at least one template profile; and

authenticate the person based upon the comparison of the extracted heartbeat data and the at least one template profile.

2. The microwave sensor module of claim **1**, wherein the at least one transmitter is built in to a mobile device.

3. The microwave sensor module of claim **2**, wherein the transmitted RF signal is a Bluetooth signal.

4. The microwave sensor module of claim **2**, wherein the transmitted RF signal is a WI-FI signal.

5. The microwave sensor module of claim **2**, wherein the transmitted RF signal is a cellular phone signal.

6. The microwave sensor module of claim **1**, wherein the at least one transmitter is built in to an external illumination source.

7. The microwave sensor module of claim **1**, wherein a smoothed differentiator pre-filter is utilized to enhance the heartbeat data.

8. A microwave sensor module for authenticating a person using data related to the person's heartbeat, comprising:

at least one transmitter configured to transmit a continuous wave (CW) radio frequency (RF) signal;

at least one receiver configured to receive a reflected microwave signal from a person that contains information related to the person's heartbeat;

a processor;

a memory containing an authentication application, wherein the authentication application configures the processor to:

extract heartbeat data from the reflected signal related to displacement as a result of the person's heartbeat;

compare the extracted heartbeat data against at least one template profile; and

authenticate the person based upon the comparison of the extracted heartbeat data and the at least one template profile;

wherein the authentication application further configures the processor to extract heartbeat data from the reflected signal by:

extracting raw data from the reflected signal by constructing an I/Q radar returns matrix and I/Q time series waveforms;

bandpass filtering the I/Q time series waveforms to remove effects due to respiration and to isolate heartbeat only I/Q time series waveforms;

translating and rotating the heartbeat only I/Q time series waveforms to lie along the Q-axis, where a scaled imaginary part yields heartbeat displacement waveforms;

segmenting the heartbeat displacement waveforms into non-overlapping data windows (DW) of a fixed duration; and

removing anomalous DW from the data set, where anomalous DW include any DW whose root mean square or maximum absolute value is outside of a specified interval.

9. The microwave sensor module of claim **8**, wherein the authentication application further configures the processor to extract heartbeat data from the reflected signal by:

smoothing the I/Q time series waveforms to mitigate against outlier data points caused by motion artifacts;

removing affine trends from the I/Q time series waveforms to mitigate against stationary clutter effects; and

removing affine trends from the heartbeat only I/Q time series waveforms to remove residual clutter effects.

10. A method of authenticating a person using data related to the person's heartbeat, the method comprising:

transmitting a continuous wave (CW) radio frequency (RF) signal using at least one transmitter;

receiving a portion of the transmitted RF signal using at least one receiver, wherein the received portion of the transmitted RF signal is utilized as a reference for coherent detection;

receiving a reflected microwave signal from a person using the at least one receiver, where the reflected signal contains information related to the person's heartbeat;

extracting heartbeat data from the reflected signal, where the heartbeat data is related to displacement as a result of the person's heartbeat;

comparing the extracted heartbeat data against at least one template profile; and

authenticating the person based upon the comparison of the extracted heartbeat data and the at least one template profile.

11. The method of claim **10**, wherein the at least one transmitter is built in to a mobile device.

12. The method of claim **11**, wherein the transmitted RF signal is a Bluetooth signal.

13. The method of claim **11**, wherein the transmitted RF signal is a WI-FI signal.

14. The method of claim **11**, wherein the transmitted RF signal is a cellular phone signal.

15. The method of claim **10**, wherein the at least one transmitter is built in to an external illumination source.

16. The method of claim **10**, wherein the extracting heartbeat data from the reflected signal comprises:

extracting raw data from the reflected signal by constructing an I/Q radar returns matrix and I/Q time series waveforms;

bandpass filtering the I/Q time series waveforms to remove effects due to respiration and to isolate heartbeat only I/Q time series waveforms;

translating and rotating the heartbeat only I/Q time series waveforms to lie along the Q-axis, where a scaled imaginary part yields heartbeat displacement waveforms;

segmenting the heartbeat displacement waveforms into non-overlapping data windows (DW) of a fixed duration; and

removing anomalous DW from the data set, where anomalous DW include any DW whose root mean square or maximum absolute value is outside of a specified interval.

17. The method of claim **16**, wherein the extracting heartbeat data from the reflected signal further comprises:

smoothing the I/Q time series waveforms to mitigate against outlier data points caused by motion artifacts;

removing affine trends from the I/Q time series waveforms to mitigate against stationary clutter effects; and

removing affine trends from the heartbeat only I/Q time series waveforms to remove residual clutter effects.

18. The method of claim **10**, wherein a smoothed differentiator pre-filter is utilized to enhance the heartbeat data.

19. A microwave sensor module for authenticating a person using data related to the person's heartbeat, comprising:

at least one transmitter configured to transmit a continuous wave (CW) radio frequency (RF) signal;

at least one receiver configured to receive a reflected microwave signal from a person that contains information related to the person's heartbeat;

a processor;

a memory containing an authentication application, wherein the authentication application configures the processor to:

receive a portion of the transmitted RF signal using the at least one receiver, wherein the received portion of the transmitted RF signal is utilized for noise cancellation;

extract heartbeat data from the reflected signal related to displacement as a result of the person's heartbeat;

compare the extracted heartbeat data against at least one template profile; and

authenticate the person based upon the comparison of the extracted heartbeat data and the at least one template profile.

20. The microwave sensor module of claim **19**, wherein the at least one transmitter is built in to a mobile device.

21. The microwave sensor module of claim **19**, wherein the at least one transmitter is built in to an external illumination source.

22. A method of authenticating a person using data related to the person's heartbeat, the method comprising:

transmitting a continuous wave (CW) radio frequency (RF) signal using at least one transmitter;

receiving a portion of the transmitted RF signal using at least one receiver, wherein the received portion of the transmitted RF signal is utilized for noise cancellation;

receiving a reflected microwave signal from a person using the at least one receiver, where the reflected signal contains information related to the person's heartbeat;

extracting heartbeat data from the reflected signal, where the heartbeat data is related to displacement as a result of the person's heartbeat;

comparing the extracted heartbeat data against at least one template profile; and

authenticating the person based upon the comparison of the extracted heartbeat data and the at least one template profile.

23. The method of claim **22**, wherein the at least one transmitter is built in to a mobile device.

24. The method of claim **22**, wherein the at least one transmitter is built in to an external illumination source.

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