Wireless Temporal-Spatial Human Mobility Analysis Using Real-Time Three Dimensional Acceleration Data

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Abstract— It is estimated that by the year 2010, the number of people over 65 years of age will reach 39 million. By 2030, that number is expected to over 70 million individuals in the 85 and older age group making them the fastest growing group of older individuals. Their growth rate is three times more than all of the 65 and older age groups put together. Falls and mobility issues are very common among older individuals and can have severe consequences. In older individuals, falls and mobility issues can occur as a result of normal age related changes such as changes in vision, gait, strength, disease progression, and medication.

We introduce wireless microcontroller hardware and software that leverages micro electro mechanical system (MEMS) transducers which communicate with a server-based heuristics analytics system. The real-time heuristics analytics system performs correlation analysis which will allow for measuring and detecting of mobility related events correlated with, for example, specific disease progression and/or changes in medication dosing and scheduling. If there is excessive inactivity detected within a selected time period, notification will be sent by the heuristics analytics system to a response center.

I. Introduction

The following describes methods and devices for wireless autonomous human mobility detection, monitoring and analysis. This hardware and software allows for detecting, monitoring and profiling/correlating human mobility such as falls, shaking (mild/violent), tremors and disability signaling through gesturing. Specific mobility events will require critical event processing such as an individual having a stroke, losing consciousness and as result is now falling [1]. This hardware and software will wirelessly relay this critical event to a collector facility that is in it default configuration attached directly to a medical managed service provider or care giver through a secure communication channel. This system requires no interaction from the monitored individual since the system is autonomous in its event processing.

II. Design Objectives

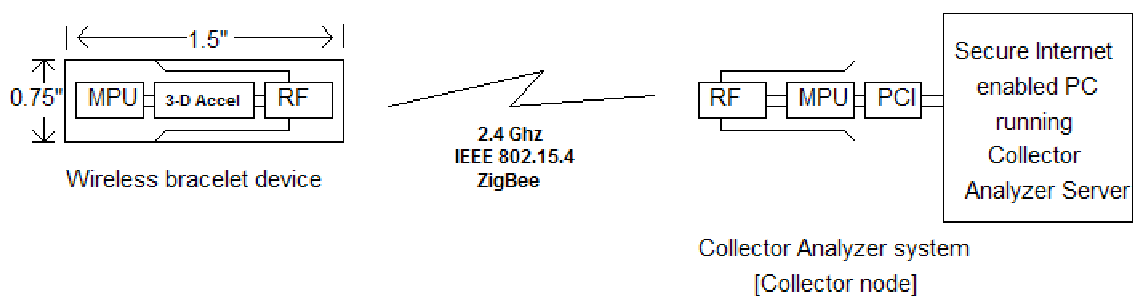
The research and development objective was to provide a method and apparatus for wirelessly detecting human falls and mobility events via a low-powered wireless bracelet worn on the wrist or ankle which bracelet would contain a micro-controller processor unit (MPU), a micro electro mechanical system (MEMS) based three dimensional accelerometer and incorporates a wireless sensor network transceiver to communicate three dimensional accelerometer motion data to the collection node attached to a securely attached internet-enabled PC. Multithreaded motion analysis software (Collector Analyzer server) determines normal motion vs. abnormal situations such as falls, violent shaking and/or tremors. The wireless bracelet and the Collector Analyzer server will be collectively referred to as the system. An additional capability that the system provides is monitoring of actual distance covered by the wireless bracelet device wearer. Movement of any distance within any or all of the three dimensions pre-determined can be tracked over any specified time period using

$$\text{Path}(x,y,z,t) = \sum\iint A_X \cdot dt + \sum\iint A_Y \cdot dt + \sum\iint A_Z \cdot dt \qquad (1)$$

Besides detecting major drastic events such as falling, the system will able to profile and correlate the spatial-temporal dynamics of the individual wearing the wireless bracelet device. This real-time/heuristic information will allow for the measuring and detection of motion related events correlated with, for example, specific disease progression.

The wireless bracelet device is worn by an individual to be monitored and it contains three accelerometers, one for each dimension X, Y and Z used to measure motion. Besides detecting major critical events such as falling, this system is be able to profile and correlate the spatial-temporal dynamics of the individual wearing the wireless bracelet device which is part of this system. This real-time/heuristic information will allow for the measuring and detection of motion related events correlated with, for example, specific disease progression.

Various states of motion such as static, rollover, free-fall, impact, tremors/shaking, complex linear and angular motion can be detected. The system implements a unique differential acceleration time derivative algorithm with heuristic functionality. The output of the acceleration axis' are sampled with a 10-bit Analog Digital Converter (ADC). This 10-bit ADC is contained in the system's wireless bracelet device micro controller, which integrates the sampled data and feeds it to the system's wireless bracelet device core processor. The following figure is a block has block diagrams illustrating wireless bracelet device and the Collector Analyzer server:



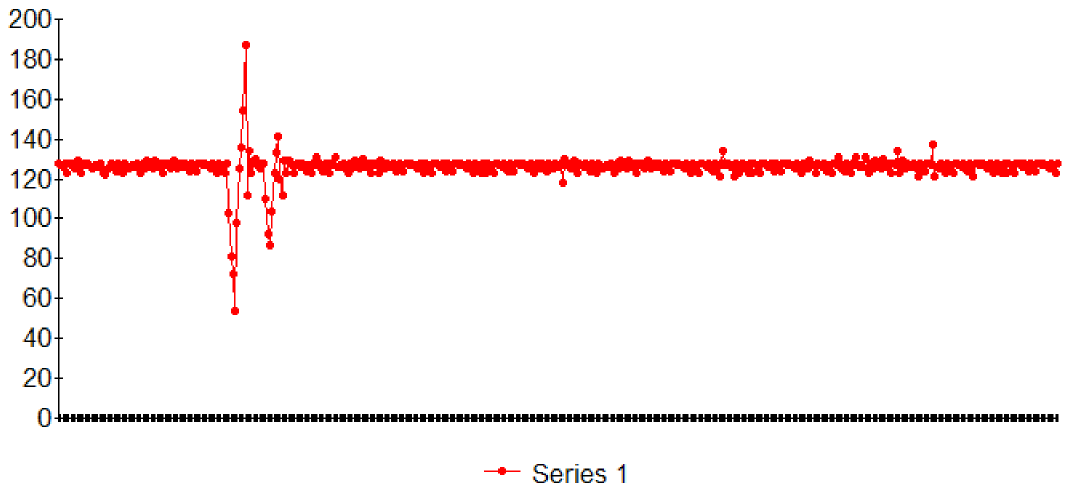
MPU - Micro-controller Processor Unit   RF - Radio Frequency Transceiver   PCI - PC Interface

Figure 1. A simplified high-level block diagram of the process flow between the wireless bracelet and the Collector Analyzer server.

The wireless bracelet device measures five acceleration vectors per second for the three dimensions of possible movement. These acceleration vectors are sent via the wireless IEEE 802.15.4 link to the Collector Analyzer server system. The acceleration vectors are signal averaged using weighted and/or not-weighted dynamically sized moving average convolution filters and used to determine distances traversed. Further analytics are performed by the Collector Analyzer server system to determine motion "groups" (rollovers, sudden spin, falls, etc.) and is used as input to calculate the differential acceleration time derivatives

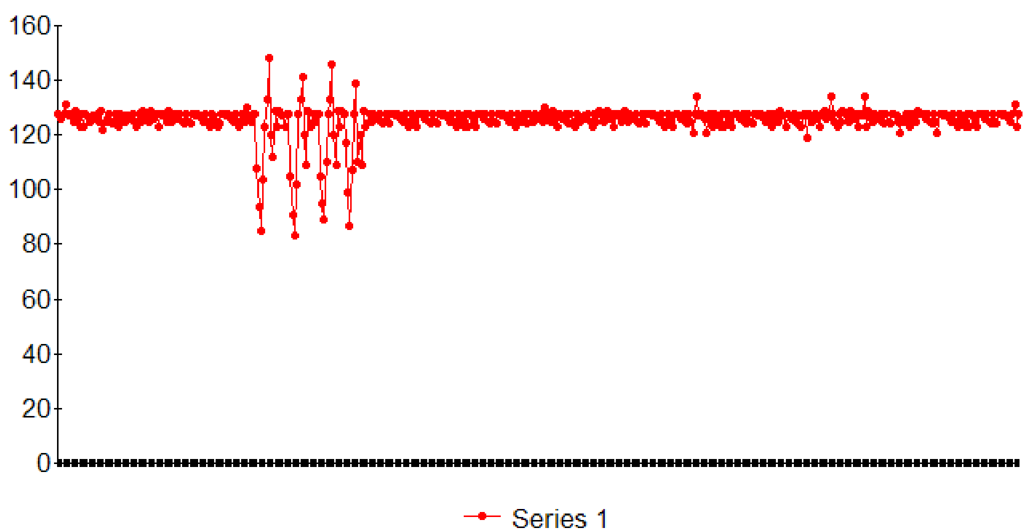
$$dA/dt = v \,\|\, ([d(A_X)/dt]^2 + [d(A_Y)/dt]^2 + [d(A_Z)/dt]^2) \,\| \qquad (2)$$

This algorithm is contained within Collector Analyzer server and is used for three dimensional shake and tremor detection. The following figure is a plot of the wireless bracelet's reported time-series acceleration data as processed by the Collector Analyzer server



Figures 2. Time-series plot demonstrating the differential acceleration time derivatives v ‖ $([d(A_x)/dt]^2 + [d(A_y)/dt]^2 + [d(A_z)/dt]^2)$ ‖ algorithm for three dimensional fall detection which is a result of the individual wearing the wireless bracelet which is sending three dimensional acceleration data (A_x, A_y, A_z) five times per second to the Collector Analyzer server.

These time-series plots are archived for further analysis such as profiling, event capture, group correlation of events, and data mining as required by the application. The figure 2 plot indicates a fall event (the large signal spike) with the vertical axis depicting acceleration in acceleration of gravity units (g = 9.8 meters/sec²) (128 units on y- axis = 0 g, 255 = +1.5 g, 0 = -1.5 g). The following figure is a plot of the wireless bracelet's reported time-series acceleration data as processed by the Collector Analyzer server



Figures 3. Time-series plot demonstrating the differential acceleration time derivatives V ‖ $([d(A_x)/dt]^2 + [d(A_y)/dt]^2 + [d(A_z)/dt]^2)$ ‖ algorithm for three dimensional shake and tremor detection which is a result of the individual wearing the wireless bracelet which is sending three dimensional acceleration data (A_x, A_y, A_z) five times a second to the Collector Analyzer server.

These time-series plots are archived for further analysis such as profiling, event capture, group correlation of events, and data mining as required by the application. The figure 3 plot indicates a shaking/tremor event (the large signal spikes) with the vertical axis depicting acceleration in acceleration of gravity units ($g = 9.8$ meters/sec²) (128 units on y- axis = 0 g, 255 = +1.5 g, 0 = -1.5 g). The following figure is time domain plot showing the distance traversed by the individual wearing the wireless bracelet which is sending three dimensional acceleration data (A_x, A_y, A_z) five times a second to the Collector Analyzer server which calculating the distance traversed using normalized position vectors

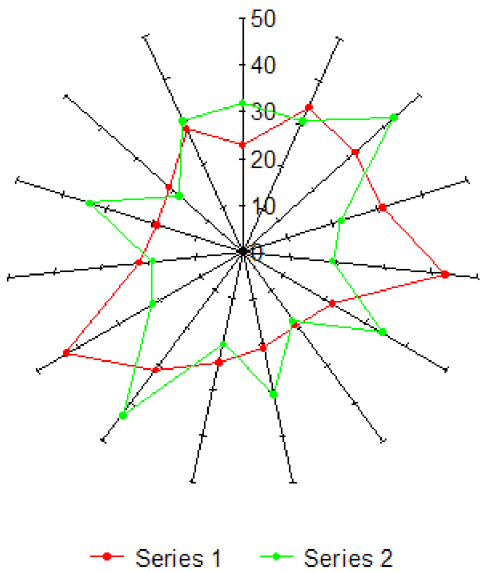


Figure 4. Time domain plot showing the distance traversed by the individual wearing the wireless bracelet which is sending three dimensional acceleration data (A_x, A_y, A_z) five times a second to the Collector Analyzer server which calculating the distance traversed using normalized position vectors.

The Collector Analyzer server system performs three dimensional double integrations five times a second where the

$$\text{Path}(x,y,z,t) \approx \sum A_x \cdot t^2/2 + \sum A_y \cdot t^2/2 + \sum A_z \cdot t^2/2 + C_x + C_y + C_z \qquad (3)$$

and the integration results are summed and accumulated over the entire observation and monitoring period to provide location data as it relates to the wireless bracelet and its wearer [2]. In figure 4, two of the dimensions are plotted since the wireless bracelet wearer only moved in a two dimensional plane (x and y and z = 0 indicating no height change up or down, as an example going up/down stairs, etc.).

The Collector Analyzer server will generate alarms and alerts based on pre-determined rules and the type of application used through a securely attached internet-enabled PC. These alarms and alerts are incidents which are dispatched to individuals identified as responders (neighbors, friends/family, be emergency service providers such as local community police, fire or ambulance) and medical managed service providers. Inactivity concerns will be monitored based on the Collector Analyzer server's pre-determined template-based software rules. If there is excessive inactivity detected within a selected time period, notification will be sent to the medical managed service provider and the appropriate alarms and alerts will be generated via predefined personalized call-lists [4]. The Collector Analyzer server can activate commands (rule sets) for desired function as a result of gross hand, arm, head, or gestured body movements coming from the individual which are detected by the wireless bracelet device and then sent to the Collector Analyzer server. The wireless bracelet device is waterproof and weighs less than 1 ounce. It can be worn in the shower or bath where critical mobility events can often occur.

For extreme data reliability, this system uses the wireless IEEE 802.15.4 ZigBee mesh network technology standard for the best protection against failure. By placing the wireless IEEE 802.15.4 ZigBee receivers and transmitters in groups, the mesh network that results provides redundant paths to ensure alternate data path routes exist and there is no signal point of failure should a node fail. Wireless IEEE 802.15.4 ZigBee routers (extra specialized software running in the node) are used to greatly extend the range of the network by acting as relays for nodes that are to far apart to communicate directly. This wireless technology standard for the communication required between the wireless bracelet and the Collector Analyzer server. The system's wireless data communications implement a 128-bit AES (Advanced Encryption Standard) algorithm for encryption and incorporates all the strong security contained within IEEE 802.15.4. The security services implemented include methods for key establishment and transport, device management and frame protection. The system leverages the security concept of a “Trust Center”. The “Trust Center” allows the system’s node devices access into the network, distribute keys and enable end-to-end security between the wireless bracelet and Collector Analyzer server devices.

III. Wireless Bracelete Hardware

The wireless bracelet uses an IEEE 802.15.4 compliant 2.4 GHz Industrial, Scientific, and Medical (ISM) band Radio Frequency (RF) transceiver. It contains a complete 802.15.4 Physical layer (PHY) modem designed for the IEEE 802.15.4 wireless standard which supports peer-to-peer, star, and mesh networking. It is combined with a MPU to create the required wireless RF data link and network. The IEEE 802.15.4 transceiver supports 250 kbps O-QPSK data in 5.0 MHz channels and full spread-spectrum encode and decode.

All control, reading of status, writing of data, and reading of data is done through the RF transceiver interface port. The wireless bracelet MPU accesses the wireless bracelet RF transceiver through interface “transactions” in which multiple bursts of byte-long data are transmitted on the interface bus. Each transaction is three or more bursts long depending on the transaction type. Transactions are always read accesses or write accesses to register addresses. The associated data for any single register access is always 16 bits in length.

Receive mode is the state where the wireless bracelet RF transceiver is waiting for an incoming data frame. The packet receive mode allows the wireless bracelet RF transceiver to receive the whole packet without intervention from the wireless bracelet MPU. The entire packet payload is stored in RX Packet RAM and the micro controller fetches the data after determining the length and validity of the RX packet.

The wireless bracelet RF transceiver waits for preamble followed by a Start of Frame Delimiter. From there, the Frame Length Indicator is used to determine length of the frame and calculate the Cycle Redundancy Check (CRC) sequence. After a frame is received, the wireless bracelet application determines the validity of the packet. Due to noise, it is possible for an invalid packet to be reported with either of the following conditions: A valid CRC and a frame length (0,1, or 2) and/or Invalid CRC/invalid frame length. The wireless bracelet application software determines if the packet CRC is valid and that the packet frame length is valid with a value of 3 or greater.

In response of the interrupt request from the wireless bracelet RF transceiver, the wireless bracelet MPU determines the validity of the frame by reading and checking valid frame length and CRC data. The receive Packet RAM register is accessed when the wireless bracelet RF transceiver is read for data transfer.

The wireless bracelet RF transceiver transmits entire packets without intervention from the wireless bracelet MPU. The entire packet payload is pre-loaded in TX Packet RAM, the wireless bracelet RF transceiver transmits the frame, and then the Transmit is complete status is given to the wireless bracelet MPU. When the packet is successfully transmitted, transmit interrupt routine that runs on the wireless bracelet MPU reports the completion of packet transmission. In response to the interrupt request from the wireless bracelet RF transceiver, the wireless bracelet MPU reads the status to clear the interrupt and check successful transmission.

Control of the wireless bracelet RF transceiver and data transfers are accomplished by means of a Serial Peripheral Interface (SPI). Although the normal SPI protocol is based on 8-bit transfers, the wireless bracelet RF transceiver imposes a higher level transaction protocol that is based on multiple 8-bit transfers per transaction. A singular SPI read or write transaction consists of an 8-bit header transfer followed by two 8-bit data transfers. The header denotes access type and register address. The following bytes are read or write data. The SPI also supports recursive 'data burst' transactions in which additional data transfers can occur. The recursive mode is primarily intended for Packet RAM access and fast configuration of the wireless bracelet RF transceiver.

IV. Wireless Bracelete Software

The software architecture for the wireless bracelet device's MPU uses an interrupt-driven architecture. The interrupt routines include the reading of the ADC (Analog Digital Converter), timers for creating the sampling frequency and handling interrupts from the IEEE 802.15.4 RF Transceiver. There a number of interrupt handlers that process data asynchronously from the non-interrupt main loop routine described before. The first is the Timer interrupt routine which is used as a time base and generates the sampling rate frequency used by the ADC. The second is the ADC interrupt routine which occurs when the ADC conversion of the three acceleration vectors A_x, A_y, A_z is complete. It formats the ADC readings for read by the non-interrupt main processing loop. The third is the wireless bracelet device's RF transceiver status and data transfers interrupt handler.

RF transceiver status/data transfers interrupt handler is used to process wireless bracelet device's RF transceiver events, transmit acceleration (A_x, A_y, A_z) data/link energy data via wireless bracelet device's RF transceiver to the Collector Analyzer server, and receive control/acknowledgement data via the wireless bracelet device's RF transceiver from the Collector Analyzer server system. The following figure is a sequence diagram of successful transmission of acceleration data (A_x, A_y, A_z) from the wireless bracelet to the Collector Analyzer server system

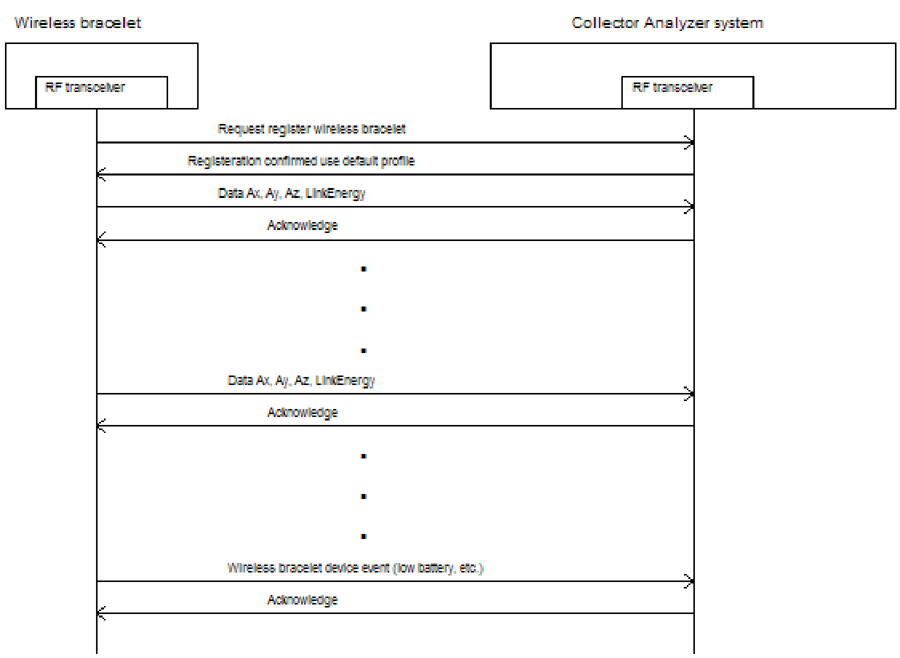


Figure 7. Sequence diagram of successful transmission of acceleration data (A_x, A_y, A_z) from the wireless bracelet to the Collector Analyzer server.

The Collector Analyzer server software is a multithreaded Java-based server that handles one or more wireless bracelet device communications channels for data gathering/control and secure internet communications with a medical managed service provider. The Java language was chosen so as to provide the broadest base of support for Collector Analyzer server hardware platform. The following figure illustrates the internal subsystems of the Collector Analyzer server

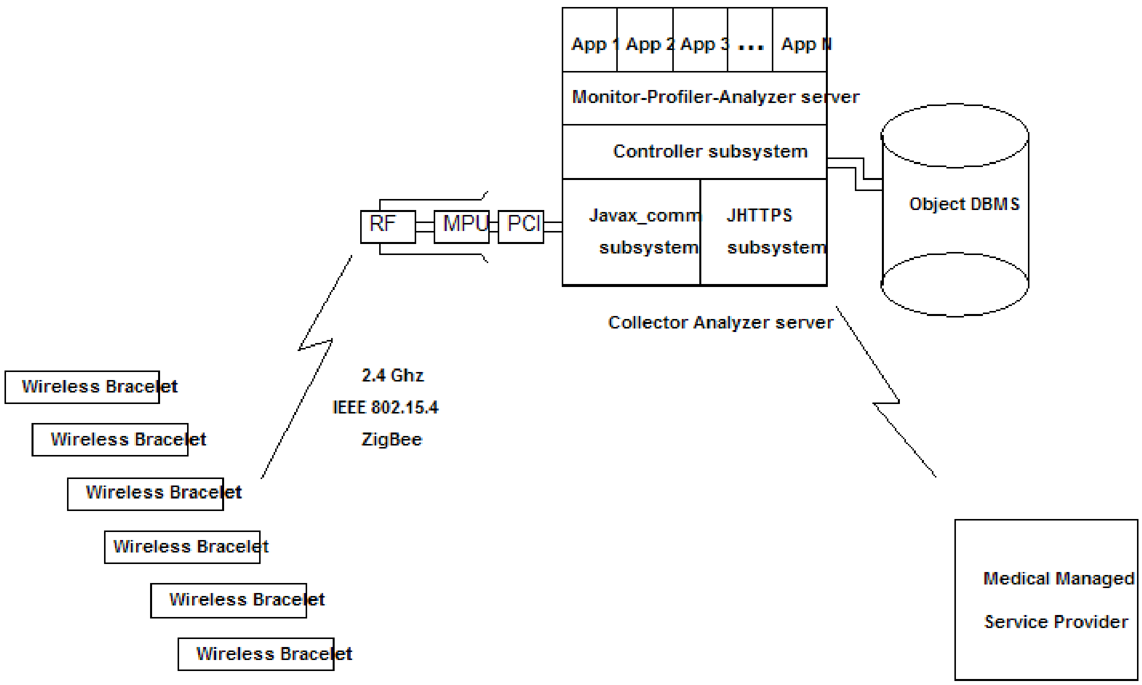


Figure 9. Internal subsystems of the Collector Analyzer server.

The Collector Analyzer server collects wireless bracelet three dimensional acceleration data (A_x, A_y, A_z) with the signal strength (Link energy) associated with the wireless communications channel between the wireless bracelet and the Collector Analyzer server. The wireless bracelet three dimensional acceleration data which is sampled a minimum of five times a second for each dimension, reflects the motion dynamics experienced by the wearer of the wireless bracelet in real-time. Once receiving the wireless bracelet three dimensional acceleration data, the Collector Analyzer server will perform some normalization functions on the acceleration data to remove zero gravity (g) offsets [3]. Next, the Collector Analyzer server will apply several signal averaging and Finite Impulse Response (FIR) filtering algorithms to the acceleration data for smoothing and signal noise reduction. This processed acceleration data now represents a time-series of dynamic events which now are reordered and analyzed for fall detection, shaking, and tremor events.

The Collector Analyzer server has numerous differential acceleration templates $v \parallel ([d(A_x)/dt]^2 + [d(A_y)/dt]^2 + [d(A_z)/dt]^2) \parallel$ in memory that profile the changes in acceleration data that exist when falls, shaking, and/or tremors occur. These templates are used to correlate the real-time acceleration data from the wireless bracelet with known events such as falls, shaking, and/or tremors contained in the differential acceleration templates. When the Collector Analyzer server detects a fall (or any other significant event), it immediately notifies all persons and services on a preprogrammed call list for this individual wearing this wireless bracelet.

The Collector Analyzer server archives data locally and at the medical managed service provider when necessary. When analyzing specific situations such as disease progression, massive amounts of data need to be archived for data mining purposes and in this case may require the additional storage of a medical managed service provider. The Collector Analyzer server can correlate events such as falls, shaking, and/or tremors with preprogrammed schedules of medication, exercise, and other bodily events.

The Collector Analyzer server is designed with layered software architecture that supports multithreading for concurrent processing of wireless bracelets, real-time data analysis, event processing, and medical managed service provider communication. The Collector Analyzer server runs on a Java Virtual Machine (JVM) architecture so as to support a broad range of computing platforms. The following figure is a process flow chart showing the information flow and processing steps of the wireless data collection method of the system

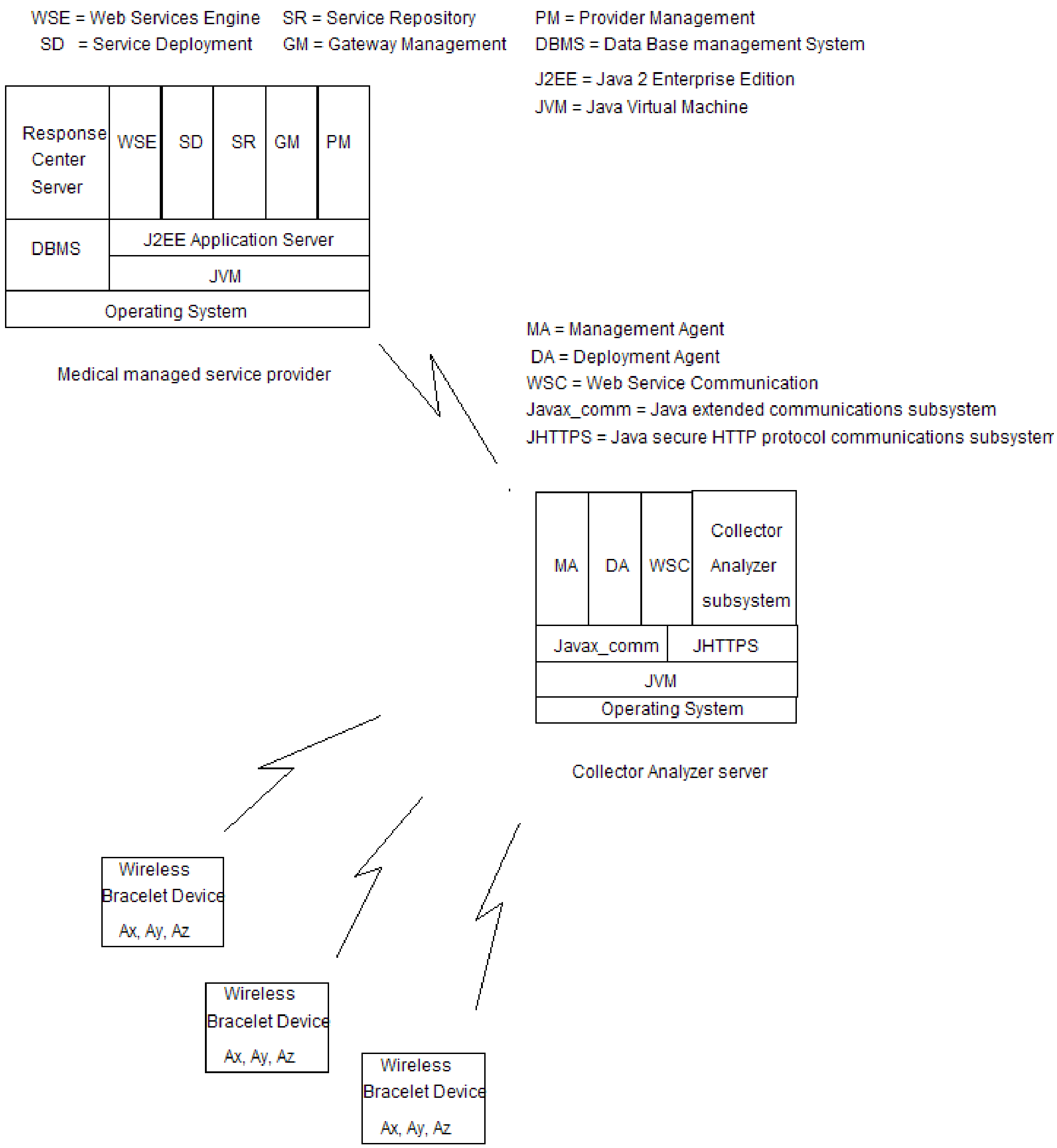


Figure 10. Process flow chart of the information flow and processing steps of the wireless data collection system.

V. CONCLUSION

Wireless sensor mesh-network technology with the use of micro electro mechanical system sensors and powerful microprocessor digital signal processing systems is allowing for the creation of the next generation highly integrated medical devices. Utilizing sensor fusion techniques multiple concurrent bio-telemetry monitoring and recording data streams are possible. The company has developed a prototype of wireless sensor fused device that incorporates what has been presented here and can in real-time simultaneously capture and process the user's electrocardiogram (EKG). This for the first time allow for active EKG/mobility monitoring of high risk target groups, concerned individuals with low risk incidents in their family history and/or high risk athletes for cardiac failure due to exercise stress and/or supplement/drug usage. In addition to the aging population, a growing portion of the child/adult population is experiencing dramatic increases in body weight which directly effects cardiac health.

1 Kai Kunze, Michael Barry, Ernst A. Heinz, Paul Lukowicz, Dennis Majoe, Jürg Gutknecht, "An Initial Experiment Using Wearable Sensors", INSTITUTE FOR COMPUTER SYSTEMS AND NETWORKS (CSN), UMIT, AUSTRIA, 2005

2 Daniele Giansanti, Member, IEEE, Giovanni Maccioni, Member, IEEE, and Velio Macellari, "The Development and Test of a Device for the Reconstruction of 3-D Position and Orientation by Means of a Kinematic Sensor Assembly With Rate Gyroscopes and Accelerometers", IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, VOL. 52, NO. 7, JULY 2005

3 S.B. Thies, P. Tresadern, L. Kenney, D. Howard, J.Y. Goulermas, C. Smith, J. Rigby, "Comparison of Linear Accelerations from three Measurements during reach and grasp", CENTRE FOR REHABILITATION AND HUMAN PERFORMANCE RESEARCH, UNIVERSITY OF SALFORD, 2006.

4 Huiyu Zhou and Huosheng Hu, "Human Movement Tracking and Stroke Rehabilitation", TECHNICAL REPORT: CSM-420, BY DEPARTMENT OF COMPUTER SCIENCES, UNIVERSITY OF ESSEX, 8 DECEMBER 2004.