

WIRELESS INFANT/BABY TEMPORAL-SPATIAL MOBILITY ANALYZER USING REAL-TIME THREE DIMENSIONAL ACCELERATION DATA FOR THE PURPOSES OF DETECTING AND ALARMING A SUDDEN INFANT DEATH SYNDROME CONDITION VIA AN AD-HOC MESH NETWORK

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Abstract— Sudden infant death syndrome (SIDS) is the term used to designate the almost inexplicable deaths of seemingly healthy infants. Also known as, crib death, SIDS is the leading category of infant deaths between the ages of two weeks and one year and account for one-third of all deaths after the newborn period. It is agreed in the medical community that SIDS occurs in healthy infants because of the simultaneous occurrence of a series of seemingly unrelated biological events. Infants who have periods of apnea, or difficulty in breathing, sudden skin color change to blue or pale, changes in muscle tone either to limpness or rigidity and who appear to require help in breathing are more likely to be effected by SIDS. We have developed a wireless autonomous infant/baby mobility detection, monitoring, analysis and alarm event generation system. The system is capable of detecting, monitoring and profiling/correlating infant/baby mobility such as breathing, rollovers, falls, shaking (mild/violent), and tremors. Specific mobility events will require critical event processing such as an infant rolling over and as result could now be suffocating and may become a sudden infant death syndrome (SIDS) event. The system will wirelessly relay these critical series of events to a series of monitor/alarm mesh network node facilities for immediate caretaker notification. This system wirelessly relays these critical events to series of collector facilities that is in their default configuration, are attached directly to a medical managed service provider or care giver to support a large nursery or hospital pediatric unit.

I. INTRODUCTION

There are several medical devices available for SIDS monitoring such as apnea/bradycardia systems that monitor infant breathing by using electrodes attached to the infant's skin. The monitors provide an audible alarm if the baby stops breathing for a pre-determined period, or when the heart rate drops below a designated level, to indicate to the caregiver that the infant needs assistance in breathing. These devices have significantly reduction in the incidence of SIDS in high-risk groups; these SIDS monitors are intrusive and are subject to many false alarms making it difficult for the caregiver to maintain their watchfulness. The resultant large number of false alarms substantially increases caregiver anxiety and thus reduces the likelihood that successful monitoring will be properly performed on a long-term basis. In addition, various pulse oximeters devices to facilitate oxygen saturation measurements though also

intrusive, show promise for reducing SIDS. Oxygen saturation monitors measure a light signal passed through an extremity that determines the wavelength change created by oxygen containing red blood cells. Saturation probes are typically placed on the fingers, toes, hands or feet of the infant. Probe position on the infant's extremities therefore makes saturation measurements particularly susceptible to motion artifacts caused by movement of the infant. Positioning the probe electrodes on the infant's sternum or back has been proposed in an attempt to reduce the effects of infant movement. The integration of saturation monitoring with respiratory and cardiac monitoring has been proposed. Nasal airflow, detected for example with a thermistor in the airflow path, is well known. Other types of respiratory measurements, not requiring the placement of a probe in the nasal passageway, have been developed to reduce the practical difficulties and inconvenience of the respiratory probe location, but still are a major intrusion on the infant's environment. With these facts stated, an alternative method and system for SIDS detection and monitoring, without intrusive probe placement, is required.

II. DESIGN OBJECTIVES

As the primary design objective, we have constructed a SIDS detection and monitoring system, which leverages the latest in three-dimensional motion measurement and utilizes the most advanced digital signal processing techniques available today. In addition, we use non-negative matrix factorization to analyze in real-time, complex motion artifacts to determine motion artifacts such as breathing, rollovers, falls, shaking (mild/violent), and tremors. Our SIDS detection and monitoring system contains miniature pendant devices that measure 1.50 by 1.00 by 0.25 inches in size and incorporate micro-electro machine system (MEMS) transducers with an advanced micro processing unit (MPU), which leverag a wireless ad-hoc mesh sensor network. We have named this system SIDSense, which system also contains an extensive back-end infrastructure that will be described within this paper.

The wireless SIDSense pendant device that is attached to the infant's clothing or diaper to be monitored contains three accelerometers, one for each dimension X, Y and Z used to measure motion[1]. Besides detecting major critical events such as rollovers and falling, this system is able to profile and correlate the spatial-temporal dynamics of the infant with the wireless SIDSense pendant attached to the infant's clothing or diaper, which is part of this system[2]. This real-time/heuristic information will allow for the measuring and detection of motion related events correlated with, for example, specific SIDS development progression. Various states of motion such as static, rollover, free-fall, impact, shaking, complex linear and angular motion can be detected[1]. The system implements a unique differential acceleration time derivative algorithm with heuristic functionality. The outputs 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 SIDSense pendant device micro controller, which integrates the sampled data and feeds it to the system's wireless SIDSense pendant device core processor. Figure 1 is a block has block diagrams illustrating system's wireless SIDSense pendant device and the system's wireless SIDSense monitor server



The system's wireless SIDSense pendant 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 system's wireless SIDSense monitor server. 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 system's wireless SIDSense monitor server to determine motion "groups" (rollovers, sudden spin, falls, etc.) and is used as input to calculate the differential acceleration time derivatives

$$[d(A)/dt]^2 = ([d(A_x)/dt]^2 + [d(A_y)/dt]^2 + [d(A_z)/dt]^2) \quad (1)$$

which is an algorithm contained within system's SIDSense monitor server for three dimensional shake and tremor detection.

The wireless SIDSense pendant attached to the infant's diaper is sending three dimensional acceleration data (A_x , A_y , A_z) five times a second to the wireless SIDSense monitor server which calculating the distance traversed using normalized position vectors[2]. The wireless SIDSense monitor server performs three dimensional double integrations five times a second where

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

and each result is summed and accumulated over the entire observation and monitoring period to provide location data as it relates to the wireless SIDSense pendant and the infant attached to it. The system's wireless SIDSense monitor server will generate alarms and alerts based on pre-determined rules and the type of application used through a securely attached internet-enabled PC.

Inactivity concerns will be monitored based on the system's wireless SIDSense monitor 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. The system's wireless SIDSense monitor server can activate commands (rule sets) for desired function as a result of specific infant body movements which are detected by the system's wireless SIDSense pendant device and then sent to the system's wireless SIDSense monitor server. The system's wireless SIDSense pendant device is waterproof and weighs less than 1 ounce.

For extreme data reliability, the 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 too far apart to communicate directly. The system uses this wireless technology standard for the communication required between the system's wireless SIDSense pendant and the system's wireless SIDSense monitor 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 into the network, distribute keys and enable end-to-end security between the system's wireless SIDSense pendant and wireless SIDSense monitor servers.

III. AD-HOC MESH SENSOR NETWORK

The wireless SIDSense pendant 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 SIDSense pendant MPU accesses the wireless SIDSense pendant 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 SIDSense pendant RF transceiver is waiting for an incoming data frame. The packet receive mode allows the wireless SIDSense pendant RF transceiver to receive the whole packet without intervention from the wireless SIDSense pendant 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 SIDSense pendant 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 SIDSense pendant 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 SIDSense pendant application software determines if the packet CRC is valid and that the packet frame length is valid with a value of three or greater.

In response of the interrupt request from the wireless SIDSense pendant RF transceiver, the wireless SIDSense pendant 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 SIDSense pendant RF transceiver is read for data transfer.

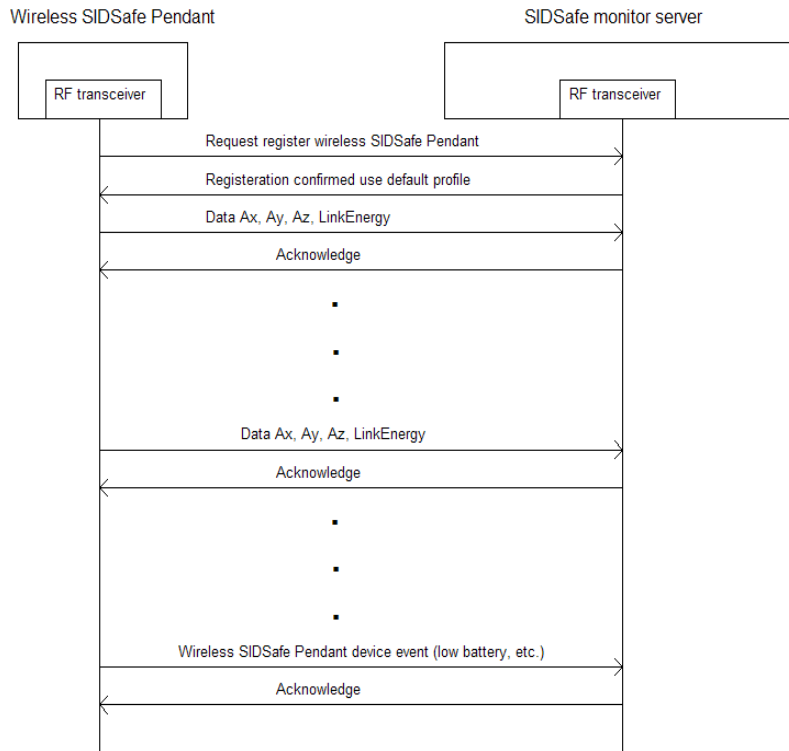
The wireless SIDSense pendant RF transceiver transmits entire packets without intervention from the wireless SIDSense pendant MPU. The entire packet payload is pre-loaded in TX Packet RAM, the wireless SIDSense pendant RF transceiver transmits the frame, and then the transmit complete status is given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

Control of the wireless SIDSense pendant 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 SIDSense pendant 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 SIDSense pendant RF transceiver.

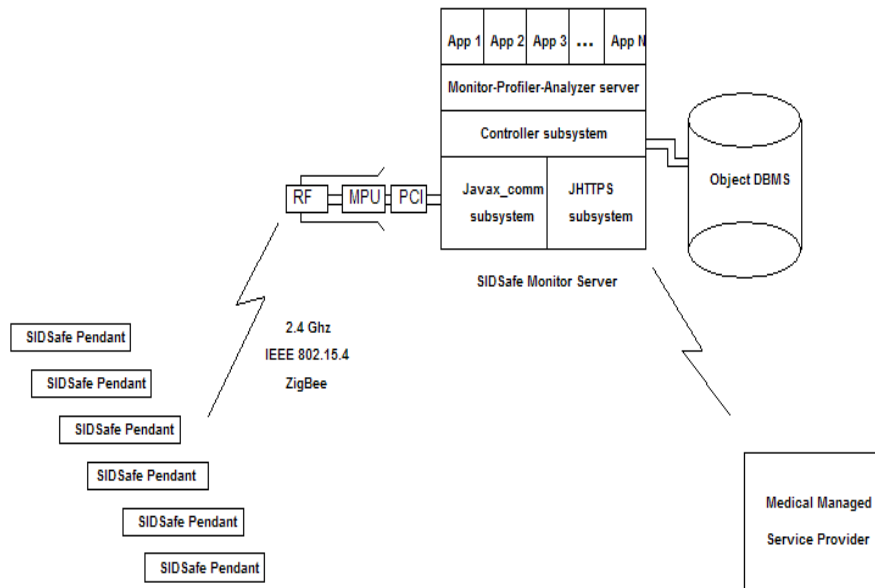
The software architecture for the wireless SIDSense pendant device’s MPU uses a interrupt-driven architecture. The interrupt routines include the reading of the ADC (Analog Digital Converter), timers for creating the sampling frequency and handling interrupts from the IEEE 802.15.4 RF Transceiver. Non-interrupt routines run on the wireless bracelet’s MPU are system initializations and the wireless communications to the wireless SIDSense monitor server system.

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 Ax, Ay, Az is complete. It formats the ADC readings for read by the non-interrupt main processing loop. The third is the wireless SIDSense pendant device’s RF

transceiver status and data transfers interrupt handler. This routine is used to process wireless SIDSense pendant device's RF transceiver events, transmit acceleration (A_x , A_y , A_z) data/link energy data via wireless SIDSense pendant device's RF transceiver to the SIDSense monitor server system, and receive control/acknowledgement data via the wireless SIDSense pendant device's RF transceiver from the wireless SIDSense monitor server. The following Figure 2 is a sequence diagram of successful transmission of acceleration data (A_x , A_y , A_z) from the wireless SIDSense pendant to the wireless SIDSense monitor server:



The wireless SIDSense monitor server software is a multithreaded Java-based server that handles one or more wireless SIDSense pendant 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 wireless SIDSense monitor server hardware platform. The following Figure 3 illustrates the internal subsystems of the wireless SIDSense monitor server:



The wireless SIDSense monitor server collects wireless SIDSense pendant 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 SIDSense pendant and the wireless SIDSense monitor server[4]. The wireless SIDSense pendant 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 SIDSense pendant in real-time[3] [4].

Once receiving the wireless SIDSense pendant three dimensional acceleration data, the wireless SIDSense monitor server will perform some normalization functions on the acceleration data to remove zero gravity (g) offsets[1]. Next, the wireless SIDSense monitor server will apply several signal averaging and Finite Impulse Response (FIR) filtering algorithms to the acceleration data for smoothing and signal noise reduction[5]. 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[4].

The wireless SIDSense monitor server has numerous differential acceleration templates ($[d(A_x)/dt]^2 + [d(A_y)/dt]^2 + [d(A_z)/dt]^2$) in memory that profile the changes in acceleration data that exist when falls, shaking, and/or tremors occur[6]. These templates are used to correlate the real-time acceleration data from the wireless SIDSense pendant with known events such as falls, shaking, and/or tremors contained in the differential acceleration templates. When the wireless SIDSense monitor server detects a infant rollover or fall (or any other significant event), it immediately generates an alarm and notifies all persons and services on a preprogrammed call list for this infant attached to the wireless SIDSense pendant via the infant's clothing or diaper. The wireless SIDSense monitor server archives data locally and at the medical managed service provider when necessary. When analyzing specific situations such as SIDS development 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 wireless SIDSense monitor server can correlate events such as rollovers, falls, shaking, and/or tremors with preprogrammed sleeping or feeding schedules.

The wireless SIDSense monitor server is designed with layered software architecture that supports multithreading for concurrent processing of wireless SIDSense pendants, real-time data analysis, event

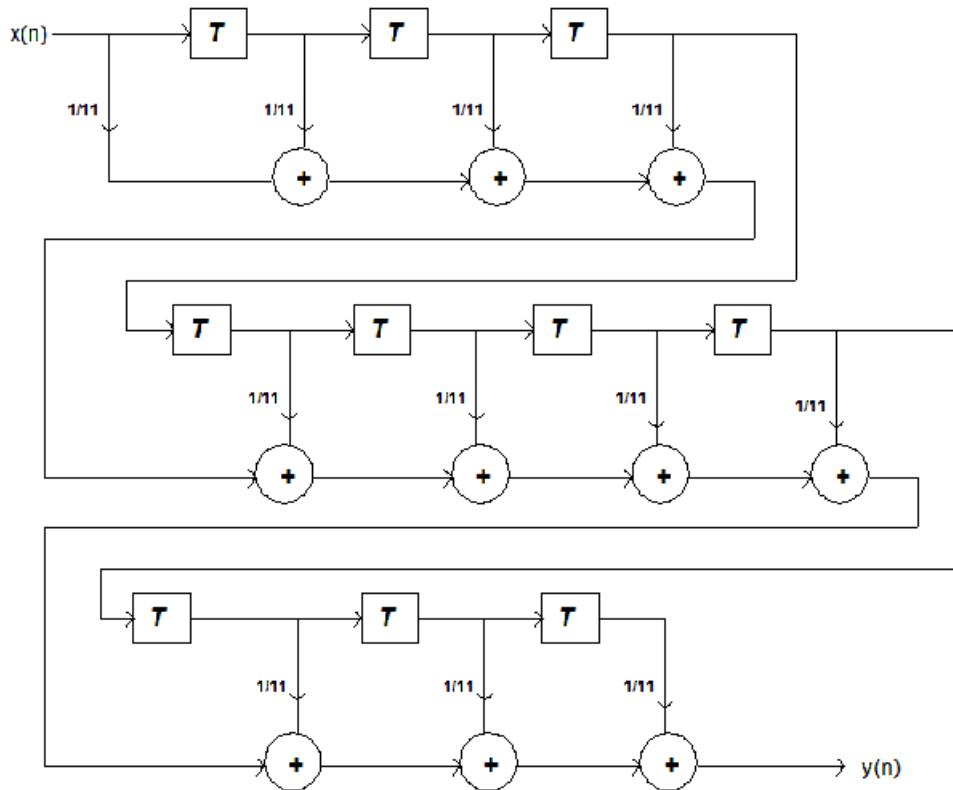
processing, and medical managed service provider communication. The wireless SIDSense monitor server runs on a Java Virtual Machine (JVM) architecture so as to support a broad range of computing platforms. The wireless SIDSense monitor server software uses a default Finite Impulse Response (FIR) filter that is implemented using a eleventh-order moving average convolution filter whereby the filter coefficients are found via:

$$\mathbf{B(i)} = 1/(\mathbf{P + 1}) \text{ for } i = 0, 1, 2, \dots, \mathbf{P}$$

Where $P = 10$ for creating the eleventh-order filter[5]. The impulse response for the resulting filter is:

$$\begin{aligned} \mathbf{h(n)} = & \delta(n)/11 + \delta(n - 1)/11 + \delta(n - 2)/11 + \delta(n - 3)/11 + \delta(n - 4)/11 \\ & + \delta(n - 5)/11 + \delta(n - 6)/11 + \delta(n - 7)/11 + \delta(n - 8)/11 + \delta(n - 9)/11 \\ & + \delta(n - 10)/11 + \delta(n - 11)/11 \end{aligned}$$

The following Figure 4 illustrates the block diagram of this eleventh-order filter:



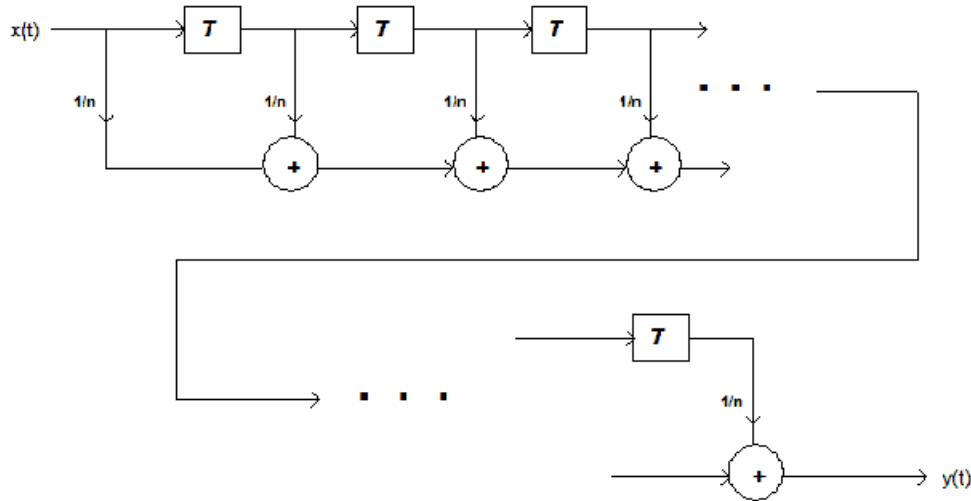
The wireless SIDSense monitor server software also uses a dynamic sized (ordered) Finite Impulse Response (FIR) filters based on profiling requirements that are implemented using n^{th} -order moving average convolution filters whereby the filter coefficients are found via:

$$\mathbf{B(i)} = 1/(\mathbf{P + 1}) \text{ for } i = 0, 1, 2, \dots, \mathbf{P}$$

Where $P = n - 1$ for creating the n^{th} -order filter[5]. The impulse response for the resulting filter is:

$$h(t) = d(t)/n + d(t - 1)/n + d(t - 2)/n + \dots + d(t - n)/n$$

The following Figure 10 illustrates the block diagram of this n^{th} -order filter:



The moving average convolution filter size is a function of the application that would run above the wireless SIDSense monitor server software layer[6]. The application could be an SIDS development infant mobility profiler, or a monitor for epileptic infants with seizures to help correlate their anti-epileptic drug schedules to name a few. These application have their own specialized requirements based on mobility dynamics to monitored and profiled.

IV. Conclusions

Our SIDSense system has allowed us to create a wireless smart MEMS sensor node that is approximately the size of a quarter that leverages an ad-hoc "self-healing" mesh network of detector and monitor nodes for broad premise coverage. Further work will in the areas of analyzing an infant's gait (lying, sitting, standing, falling, crawling, walking, or running) in real-time and time stamping this data and archiving this for future event and correlation analysis. Additionally, total three dimensional distance covered by infant over any time interval and location detection will be added.

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