Tremor acquisition system based on UWB Wireless Sensor Network

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Abstract—**This work suggest to quantify and analyze tremor using Ultra Wide-Band (UWB) Wireless Sensor Network (WSN). WSN based on UWB technology, provides a new technology for non contact tremor assessment with extremely low radiation and penetration through walls. Tremor is the target symptom in the treatment of many neurological disorders such as Parkinson's disease (PD), midbrain tremor, essential tremor (ET) and epilepsy. The common instrumental approaches for the assessment of tremor are motion capture devices and video tracking systems. The new tremor acquisition system is based on transmission of a wideband electromagnetic signal from couple of sensor nodes placed in different locations in a home and analysis of the received signal in each sensor node. The sensors can exchange information between each other with a coded transmission or send the raw data to a UWB hub for further analysis. The data can be then sent by internet gateway to any health care center for monitoring and for medical care. In this paper we describe the basic system and give some fundamental detection technique. For a feasibility test we built an UWB acquisition system 1-D UWB sensor node and examined the performance with an arm model that fluctuated in the range of clinical tremor frequencies (3-12 Hz). A future development of this work can lead to a low cost monitoring system installed at any home, hospital or school to continuously asses and report tremor conditions during daily life activities.**

Keywords-component; Tremor, UWB, Wireless Sensor Network, Parkinson.

I. Introduction

Tremor is the target symptom in the treatment of numerous neurological disorders such as Parkinson's disease (PD), midbrain tremor, and essential tremor (ET) [1]. Quantification and analysis of tremor is significant for diagnosis and establishment of treatments. For clinical research purposes, a number of scales have been developed for semi-quantitative assessment of frequency and magnitude [2] of tremor. Motion capture devices such as accelerometers [2] or gyroscopes [3], are the most popular for tremor assessment. But must be attached to patient's body and have limited capabilities on giving precise tremor amplitude due to amplitude drift [3]. Video recording is another popular technology for tremor assessment in gait analysis laboratories [4], but requires the patient to be inside the range of the video camera lens and consequently cannot be used for continuous assessment of tremor during daily life activities.

A Wireless Sensor Network (WSN) consists of spatially distributed autonomous sensors to cooperatively monitor physical conditions and is widely used in healthcare applications [5]. Each node in a sensor network is typically equipped with a radio transceiver (wireless communications device), a small microcontroller, and an energy source, usually a battery. Size and cost constraints on sensor nodes result in corresponding constraints on resources such as energy, memory, computational speed and bandwidth. IEEE 802.15.4-2006 [6] is the standard which specifies the physical layer and media access control for low-rate wireless personal area networks (LR-WPANs.

Ultra-wideband (UWB) is a radio technology that can be used with very low energy levels for short-range high-bandwidth communications, by using a large portion of the radio spectrum. The potential strength of the UWB radio technique lies in its use of extremely wide transmission bandwidths, which result in accurate position location and ranging, and material penetration. Most recent applications target sensor data collection and locating and tracking applications such as [7]. [8] suggests the use of biomedical applications of UWB radar for cardiac bio-mechanic assessment and chest movements assessment, OSA (obstructive sleep apnoea), and SID (sudden infant death syndrome) monitoring.

WSN based on UWB radio PHY is specified in IEEE 802.15.4a [9]. It has the advantage over other WSN based on 802.15.4 or Bluetooth that it can be used for transferring in low radiation and high data rate and penetrate through walls. The principle interest is in providing communications and high precision ranging / location capability (1 meter accuracy and better), high aggregate throughput, and ultra low power; as well as adding scalability to data rates, longer range, and lower power consumption and cost. In [10] implementation of efficient UWB low data-rate transceiver suitable for battery-less operation are presented. UWB based WSN can further be used in the same time as wireless body sensor network and as a system for range and location estimation [11]. These additional capabilities over the existing 802.15.4

standard are expected to enable significant new applications and market opportunities.

We suggest in this paper to quantify and analyze tremor with WSN network based on radar technology. Each sensor node has UWB radar capabilities and can use the UWB radar for wireless communication. The technology is based on transmission of a UWB signal, analysis of the received signal reflected from the patient to assess tremor characteristics using the sensor node processing capabilities and, send the data to a UWB hub and then send the data to remote medical care for tremor analysis. We provide data analysis tools for the UWB tremor acquisition system based on wireless sensor and give preliminary results for a UWB tremor acquisition based on one sensor node prototype we built.

This paper is organized as follows. Section II describes the UWB WSN system, a criterion to derive multi-dimensional tremor characteristics from all the UWB sensor nodes. Section III describes the experimental set-up which consists of an arm model with tremor and an one UWB sensor node. We performed a series of experiments with different distances in the range of 1-2 meters between the sensor and the arm with different sources of disturbance. Section IV analyzes the performance of the UWB sensor node and high light the advantages and disadvantages of the technology. Section V concludes the work and gives suggestions for future research.

II. System and Methods

A. System model

The system we propose is composed of a set of a set of Q UWB wireless sensor nodes, a UWB hub to collect the data from the UWB sensor nodes and an internet gateway to send the tremor assessment to a medical care center. Each UWB sensor node is placed in a different position in a home or walking laboratory and continuously assesses the tremor. A natural choice for positioning the sensor is in Cartesian coordinates of (x,y,z). The tremor analysis from each sensor node is sent to a UWB hub, using the UWB sensor node tranciever. The sensor nodes information is integrated to give multi dimensional analysis of the tremor either locally or in a remote medical care unit. Fig. 1 describes a typical tremor acquisition system based on UWB WSN. The sensore nodes are orthogonal to each other and located in the x, y and z axis.

Each UWB sensor node is equipped with a radio transceiver, a processing unit with storage and a power source. The UWB radio transceiver includes a transmitter and a receiver each equipped with antennas that can support the high band bandwidth, typically in size of 10 cm. Thus each sensor node functions as a small UWB.

The transmissions are synchronized in time and can be coded in different Multiple-Access methods to avoid exclusion and allow each sensor node to work independently. We choose Time-Division Multiple Access (TDMA) which is the a centralized scheme in which only one sensor node transmits at any given time interval. The transmission is divided into discrete non overlapping transmission intervals

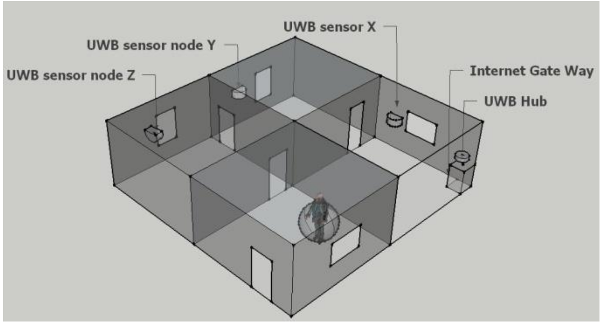

Figure 1. An UWB radio based 3-D tremor acquisition system is composed of 3 sensors. Each sensor transmits an UWB radio signal. We can assess the tremor according to the signal reflections. The raw data or the tremor features can be sent by internet Gate way to a medical care centre.

assigned to data or the processed data can be sent from the UWB sensor each sensor. In the end of every observation period, the raw node to the UWB hub as a packet through UWB data transmission.

From each sensor node an UWB pulse is transmitted into the medium where the patient is located at the node slot. The signal that has propagated through a wireless channel consists of multiple replicas (echoes, mainly caused by reflections from objects in the medium) of the originally transmitted signal, named Multipath Components (MPCs). Each MPC is characterized by attenuation and a delay. The received signal at sensor node i at time instance t is:

$$r_i(t) = \sum_{m,k} \beta_k(t - mT)\,p\big(t - mT - T_i - \tau_{m,k}\big) + n(t) \quad (1)$$

Where p(t) is a pulse with typical duration around 10 ns, m is the pulse index and T is the pulse repetition time, T_i is the sensor node i time slot, $\tau_{m,k}$ is the k'th MPC delay in the m'th pulse, β_k is its related attenuation factor which is assumed constant for a short observation time, n(t) is an additive noise component. The noise includes thermal and amplifier noise which can be modeled by white Gaussian processes, distortion from non linearity of amplifiers and interference from other radio signals from narrow band systems. The received signal can be further separated to desired MPCs reflected from Tremorring Body Parts (TBPs), non desired MPCs from other reflectors in the medium, and the noise.

We sample the received signal in (1) every period of T_S. The received signal for M consecutive pulses, are stored in an observation matrix r. The column dimension of r represents the time dimension of pulse repetition. The row dimension represents delay, which is equivalent to the spatial dimension since for a given MPC, multiplying the MPC's delay by the speed of light c gives us twice the distance the transmitted pulse propagated in space from the reflecting object to the acquisition system

B. Data Analysis

Data analysis can be divided to 4 stages: (1) Location of the patient in the room; (2) UWB Sensor nodes activation to obtain tremor displacement; (3) Collection, transmission and aggregation of UWB raw data for processing; (4) Extract tremor characteristics from the tremor displacements.

1) Location of the patient in the room.

UWB tracking algorithms based on UWB sensor network e.g. [7], can give patient location in time in accuracy in range of a meter. After patient location, we analyze only reflection from patient surrounding. We denote by N the number of samples in observation matrix related to each pulse transmission.

2) UWB Sensor node tremor displacement assessment.

We extract from the received signal MPCs' delays. From the delays we can obtain the TBP's displacements. If we choose an observation period small enough so that the patient is stationary and the TBP's displacements are around center location, the MPCs related to the TBP differ in time mainly by a weight time shift. This weight time shift is in a range that is determined by the tremor amplitude and the frequency of the change of the weight time shift in the observation period is determined by tremor frequency. A Linear Minimum Mean Square Error (MMSE) criterion for each TBP and i'th sensor node with the tremor amplitude and frequency constraints is:

$$\{\hat{\mathbf{w}}_i, \hat{\boldsymbol{\tau}}_i\} = \operatorname{argmin}_{w,\tau} E\left\{\sum_{m=1}^{m=M}\left(\mathbf{w}_{\tau_m}^T \mathbf{r}_m - s_i\right)^2\right\} \quad (2)$$

$$\text{s.t.} \quad -\frac{A_t}{2c} < \tau_m < \frac{A_t}{2c}, 2\text{Hz} < argmax_f|FFT(\tau)| < 12Hz$$

Where $\mathbf{r}_m$ is an N length vector of the sampled received signal for pulse index m, $1 \le m \le M$, s_i is a scalar representing the signal energy reflected from the TBP surface in the i'th sensor axis, τ_m is the m'th weight time shift, $\mathbf{w}_{\tau m}$ is an N length weight vector w shifted by τ_m , $\mathbf{w}_{\tau m}=\mathbf{w}(n-\tau_m)$, τ_i is an M long vector that includes the weight time shifts, $\boldsymbol{\tau}_i = \{\tau_1,\tau_2\ldots\tau_M\}$, A_t is the maximal clinical tremor displacement (in range of 1-4cm) and E[◦] is the expectation operator in the observation period .

The first constraint in (2) operates on observation matrix rows and limits the solution to the clinical tremor amplitude range, this is a spatial constraint. The second constraint operates on observation matrix columns and limits the solution during observation period to changes in tremor in the range of clinical frequencies, this is a temporal constraint.

An MMSE optimal solution to (2) is based on match filtering of the received signal with the transmitted pulse shape and combining the result with an optimal MMSE weights. It can be shown that the constraints can be translated to ones that satisfy Karush–Kuhn–Tucker (KKT) conditions. A solution derived by methods of nonlinear programming (NLP) [12] is optimal. An optimal solution is cumbersome, requires nonlinear programming and unavailable statistics and is sensitive to distortion in pulse shape.

A suboptimal solution to the problem, with no significant sacrifice in performance, is to apply to the matched filter outputs, the constraints in (2) one after another. A further efficient approximation uses instead of the MMSE weights, the Maximal Ratio Combining (MRC) weights, which combine the MPCs according to their Signal-to-Noise Ratios (SNRs), and is optimal if MPCs are well separated [13]. MRC has the advantage that it does not require the usually unavailable a-priory statistical information.

3) Tremor characteristics approximation.

The data from each sensor node is initially processed, stored in each sensor node memory and then transmitted through UWB communication to the UWB hub for aggregation. The transmission can be done, either by allocating part of frames for data transfer or as part of the PHY services. The aggregated data is then can be processed either locally or be sent thorough internet gate way to central processing utility.

4) Tremor characteristics approximation.

By multiplying the i'th sensor node weight delay shift related to each TBP by speed of light c, we obtain the displacement related to the i'th sensor axis:

$$\hat{\mathbf{d}}_i = c\hat{\boldsymbol{\tau}}_i \quad (3)$$

A set of tremor frequencies and amplitudes is obtained by Fourier transform of all the sensors $\hat{\mathbf{d}}_i$. For a single dominant tremor frequency the estimated tremor frequency and amplitude are:

$$\hat{A}_{t,i} = max|FFT(\hat{\mathbf{d}}_i)|, \hat{f}_{t,i} = argmax_f|FFT(\hat{\mathbf{d}}_i)| \quad (4)$$

A reasonable assumption is that the tremor frequency is the same in each axis. As a result, we can exploit the measurements diversity from all the sensors and approximate the tremor frequency by:

$$\hat{f}_t = \frac{1}{Q}\sum_i \hat{f}_{t,i} \quad (5)$$

Tremor amplitude is different for each sensor node. Still we can obtain an approximation of the average amplitude by:

$$\hat{A}_t = \sqrt{\sum_i A_{t,i}^2} \quad (6)$$

More advanced pattern matching algorithms based of the spectrum of known tremor patterns pathologies over time can be applied in the future.

In the common case of multiple TBPs we need to map the MPCs to the different TBPs. One way to map is according to the proximity of the MPCs where paths with similar delays are more likely to be related to the same TBP. This mapping is not accurate in a medium rich with scatterers that has no direct paths. Another way to map is according to MPCs pattern change in time. With a metal marker attached to the TBP of interest, the related MPCs amplitudes are enhanced and become more distinct then MPCs related to other TBPs.

III. Expiremental Setup

The experimental setup consisted of one UWB sensor node prototype and an arm model. The experiment was performed in a room size 10x7 meters. The arm model fluctuated in a range of frequencies and amplitudes similar to a clinical tremor of Parkinson patients. The arm surface was moving back and forth from and toward the UWB sensor node prototype in a single axis parallel to one wall in the room.

For modeling arm tremor we used a conduction coil, an AC generator source and a solid arm model with a small magnet attached. The AC generator induced periodic electrical current. The generator was wired to a transformer, which created a varying magnetic field in its core that induced a varying electromotive force. The force acted on a magnet attached to the solid arm model and generated periodic movement of the arm in the AC generator frequency. We attached to a metal strip to magnify the UWB reflection from the arm. Fig. 2 shows the arm model prototype.

The UWB sensor node prototype consisted of a transmitter, a receiver, a processing unit and a storage unit. The transmitter was based on pulse generator (Picosecond Pulse Labs 4015D). The Pulse width T_p was 100ps, the pulse amplitude was 1.35V, the pulse repetition frequency was 85 Hz, and the bandwidth was 8GHz, similar to commercial UWB dongles. The pulse generator was connected to an omni-directional antenna (EM-6865 Elector Metrix) via an 30 dB amplifier (Herotek AF2 1828A). The transmission power was extremely low with peak power of 52mWatt/cm^2 and average power of 105µWatt/cm^2 measured at distance of 1 meter from the antenna. The UWB signal was received by an omni-directional antenna (EM-6865 Elector Metrix) with an amplifier (Herotek AF2 1828A) and then fed to the receiver. The receiver was based on an oscilloscope (Agilent DSO81304A) with sampling rate T_s of 20GS/s. The receiver was synchronized to the transmitter by a trigger from the pulse Generator. The raw data was sent to a storage unit. To enhance antenna gain and improve directionality, we added a metal cover structure over both transmit (Tx) and receive (Rx) antennas. We isolated the received a nd transmit antenna with a Carton board wrapped by aluminum foil to avoid a direct path. We used the segmented memory oscilloscope memory for storage. The processing unit was a common notebook computer (Lenovo T61) and the SW we used for processing was Matlab.

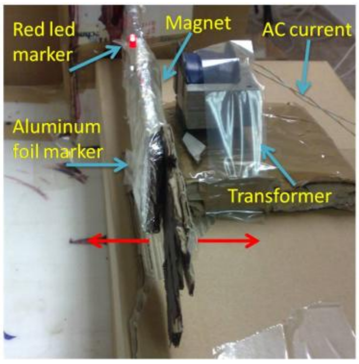

Figure 2. The arm model fluctuated in frequencies and amplitudes in similar range to the one in clinical tremor. A metal strip was attached to the arm to magnify the UWB reflection.

Figure 3. UWB sensor node prototype prototype and arm model in the back. The arm model in the back was moving back and forth from and to the UWB acquisition system in a way that maximized the reflection surface.

The UWB sensor node prototype antennas were placed in an optimal orientation to capture the maximal reflection from the arm model. The arm model was placed in 1 to 2 meters from the acquisition system. Fig. 3 shows the UWB sensor node prototype, the arm model can be seen in the back.

We performed two sets of experiments. The first set was performed with different distances between the arm and the acquisition system. For each distance, the arm model trembled with a single frequency which varied from 3 to 12Hz. The second set of experiments was performed with different disturbers. We recorded for 20 seconds with relatively stationary channel conditions (arm fixed to one place, no change in environment).

IV. RESULTS

For each experiment we followed the steps that are described in Section II-B. The arm model distance from the UEB sensor node was obtained by simple measurements. Fig. 4 shows the received signal r and its time-space spectrogram in the case of after locating the arm in resolution of 1 meter. The colors in the spectrogram represent the received signal amplitude in volts. MPCs related to the tremor can be detected in range of 10-20 cm from the central location by the pattern of fluctuations in the spectrogram. The MPCs related to tremor fluctuates in amplitudes of up to 1.5 cm.

Then we approximated the matched filtering to pulse shape by a simple peak detector. Then the constraints in (2) were applied one after another to the approximated matched filtered outputs. The approximated weight time shifts related to the arm (having similar frequency content) were combined with MRC weights. From the weight time shifts $\hat{\tau}$ we estimated the displacements according to (3). Then we estimated the tremor amplitude and frequency according to (4) and (5), respectively. Fig. 5 shows the estimated amplitude as a function of tremor frequency for distances between the arm and the sensor of 1, 1.5 and 2 meters. The approximated amplitude decreases with frequency. Near the frequency of 5Hz there is a peak which indicates the arm model resonance frequency. The amplitude estimations for the different distances are correlated with correlation factor of 0.97 and the average deviation from a video reference estimation was 0.1cm. The amplitude estimation at distance of 1.5meters was lower by factor of 2 than the other amplitude estimations. This difference is explained by the variation of tremor amplitude along the arm as the tremor's amplitude near the body is lower. With a smaller marker surface, the amplitude variation of the TBP can be minimized and the amplitude estimation variance can be improved. The average tremor frequency estimation error was 0.01Hz. The accuracy achieved by the tremor frequency estimation is explained by the single tremor frequency present in our arm model (unlike the tremor amplitude that varied along the arm).

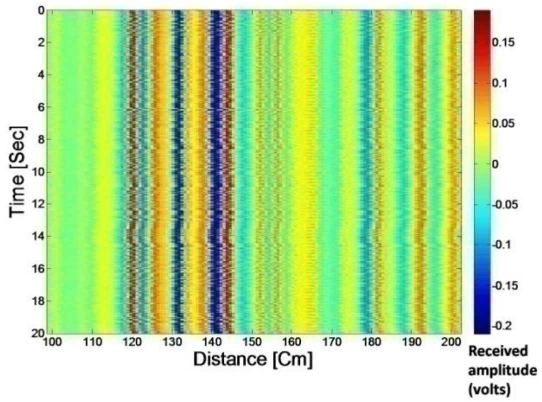

Figure 4. Signal time-space spectrum for the arm model. The for distance between the UWB sensor node and the arm model was fixed to 1.5 meter and the induced frequency was 5 Hz. The colors indicate the intensity of the received signal. Flactuations of the different MPCs can be seen in the spectrum.

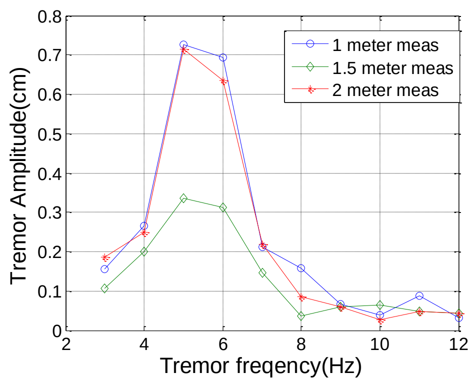

Figure 5. Tremor amplitude approximation for distances of 1, 1.5 and 2 meters between the UWB sensor node and the arm model. The tremor amplitude declines with tremor frequency but near 5 Hz, the resonance frequency, there is an increase in amplitude. The amplitude estimation at a distance of 1.5meters is lower by factor of 2 due to the variation of tremor amplitude along the arm surface.

We verified system performance with different noise sources. We used the following noise sources: static metal reflectors, a wooden partition that separated the arm model from the acquisition device and a person with his hand covered with metal in the background. We tested the system at a distance of 1.5 meter with tremor frequency of 5 Hz. The system has shown tolerance to all noise sources. In all cases the frequency estimation was excellent with absolute error of less than 0.03Hz. Amplitude estimation error from a video reference was less than 1 mm.

V. CONCLUSIONS AND FUTURE WORK

We suggested in this work to quantify and analyze tremor using Ultra Wide-Band (UWB) Wireless Sensor Network (WSN). Each sensor node is used as a small radar system to capture tremor in one dimension with data transfer capabilities. The sensors can send the raw data to a UWB hub for further analysis. The data can be then sent by internet gateway to any health care center for monitoring and for medical care. We provided data analysis tools for each sensor node and for the all WSN system.

For a feasibility test we built one UWB sensor node prototype to asses tremor in one axis. We examined the performance of the system with an arm model that fluctuated in the range of clinical tremor frequencies (3-12 Hz). We performed experiments with different disturbers like walls with moving objects in the medium, and showed the sensor node still capture the tremor characteristics. The frequency estimation was accurate with average estimation error of 0.01Hz. It seems that for tremor frequency estimation, one sensor seems to be adequate. The amplitude estimation was less accurate with average deviation from a video reference estimation of 0.1cm. To asses correct image of tremor amplitude in multi-dimensions, multiple sensors placed at different locations are needed.

In future, a system with small dimension UWB sensor nodes should be built operating in 802.15.4a standard. More research should be performed at different environments with thick walls and non Line of Sight (LoS) conditions. Directional antennas, higher sampling rates, higher bandwidth, higher radiation power, smaller marker size and more advanced equalization techniques can all improve the system performance. A future development of this work can lead to a low cost non contact tremor assessment system, utilizing extremely low radiation that can penetrate walls, work in any light condition, and can collect accurate data continuously. This WSN based on UWB radio technology will be installed at any home, hospital or school to continuously asses and report tremor conditions during daily life activities.

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