Non-Contact UWB Radar Technology to Assess Tremor

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Abstract— **This work quantifies and analyzes tremor using Ultra Wide Band (UWB) radio technology. The 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 with extremely low radiation, and analysis of the received signal composed of many propagation paths reflected from the patient and its surroundings. An efficient UWB radar detection technique adapted to tremor detection is developed. Periodicity in the time of arrival of the received signal is detected to obtain tremor characteristics. For a feasibility test we built an UWB acquisition system and examined the performance with an arm model that fluctuated in the range of clinical tremor frequencies (3-12 Hz). A development of this work can lead to a monitoring system installed at any home, hospital or school to continuously asses and report tremor conditions during daily life activities.**

Keywords— **Tremor, UWB, human radar signature, detection techniques.**

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 narrow band radar has been used [5] for the detection and classification of people's movements and location based on the Doppler signatures. When humans walk, the motion of various components of the body including the torso, arms, and legs produce a characteristic Doppler signature. Fourier transform techniques were used to analyze these signatures and identified key features representative of the human walking motion. [6] uses a classifier on the human body radar signature to characterize gait, in particular step rate and mean velocity. Radar techniques based on Doppler cannot detect tremor as the signal bandwidth they use, and correspondingly the temporal and spatial resolution, is usually too low to detect typical tremor.

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 biomechanics assessment and chest movements assessment, OSA (obstructive sleep apnea), and SID (sudden infant death syndrome) monitoring.

We suggest to quantify and analyze tremor with UWB radar technology. The UWB radar technology is based on transmission of a wideband electromagnetic signal and analysis of the received signal reflected from the patient to assess tremor characteristics. We provide data analysis tools for the UWB tremor acquisition system and give preliminary results for an UWB tremor acquisition system prototype we built.

This paper is organized as follows. Section 2 describes the UWB tremor acquisition system and efficient algorithms to assess tremor characteristics. Section 3 describes the experimental set-up which consists of an arm model with tremor and an UWB tremor acquisition system. We performed a series of experiments with different distances in the range of 1-2 meters between the acquisition systems and the arm with different sources of disturbance. Section 4 analyzes the performance of the UWB acquisition system. Section 5 concludes the work and gives suggestions for future research.

II. SYSTEM AND METHODS

A. System model

Our system is composed of a transmitter and a receiver. A high bandwidth pulse is transmitted into the medium where the patient is located. 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 Multi-path Components (MPCs). Each MPC is characterized by attenuation and a delay. The received signal at time instance t is:

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

Where p(t) is a pulse with typical duration around 10 ns, m is the pulse index and T is the pulse repetition time, $\tau_{m,k}$ is the k'th MPC delay in the m'th pulse, $\beta_{m,k}$ 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 Tremulous 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. Per each pulse, we reduce the observation period to N_h temporal samples that include only reflections from around the patient center body (torso) which can be obtained by any UWB tracking mechanism. The received signal for M consecutive pulses, are stored in an observation matrix r of size $M \times N_h$. 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 Algorithm

We divide the data analysis to two stages. First we extract from the received signal MPCs' delays which relate to TBP's displacements. Then we analyze the MPCs' delays and obtain tremor characteristics.

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 with the tremor amplitude and frequency constraints is:

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

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

Where $\mathbf{r}_m$ is an N_h length vector of the sampled received signal for pulse index m, 1≤m≤M, s_l is a scalar representing the signal energy reflected from the l'th TBP surface for pulse index m, τ_m is the m'th weight time shift, w_{τ_m} is an N_h length weight vector w shifted by τ_m, $w_{\tau_m}(n) = w(n - \tau_m)$, τ is an M long vector that includes the weight time shifts, $\boldsymbol{\tau} = \{\tau_1, \tau_2 .. \tau_M\}$, A_t is the maximal clinical tremor displacement (in range of 1-4cm) and $E[\cdot]$ 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) [9] 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 [10]. MRC has the advantage that it does not require the usually unavailable a-priory statistical information.

Full tremor characteristics can be derived by the approximated weight time shifts vector $\hat{\boldsymbol{\tau}} = \{\hat{\tau}_1, \hat{\tau}_2 .. \hat{\tau}_M\}$. A set of tremor frequencies and amplitudes is obtained by Fourier transform of $\hat{\boldsymbol{\tau}}$. For a single dominant tremor frequency the estimated tremor frequency and amplitude are:

$$\hat{A}_t = c(max|FFT(\hat{\tau})|), \hat{f}_t = argmax_f|FFT(\hat{\tau})| \quad (3)$$

Where c is the speed of light, $\hat{A}_t$ and $\hat{f}_t$ are the approximated tremor amplitude and frequency. 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 a UWB prototype system and an arm model to model a TBP of a patient.

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 a metal strip to the arm to magnify the UWB reflection.

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 and 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.

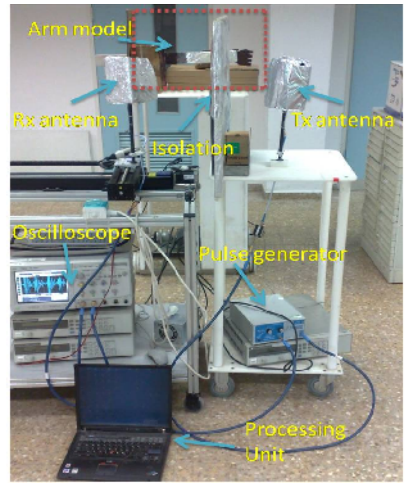

Fig. 1 UWB tremor acquisition system prototype and arm model. The arm model in the back was moving back and forth from and to the UWB acquisition system in a way that maximized the reflection surface.

The arm surface was moving back and forth from and toward the UWB acquisition system in a single axis. The UWB 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. Figure 1 shows the UWB tremor acquisition system 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. First 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 tremor frequency and amplitude according to (3). Figure 2 shows the estimated amplitude as a function of tremor frequency for distances between the arm and the acquisition system 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 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).

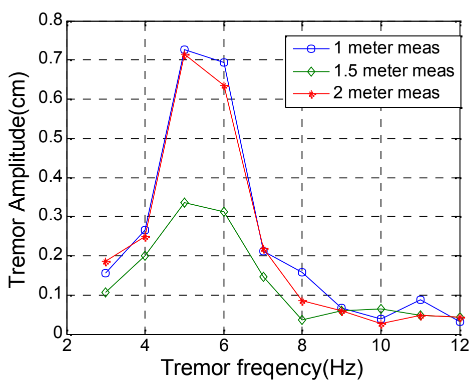

Fig. 2 Tremor amplitude approximation for distances of 1, 1.5 and 2 meters between the acquisition system and the arm model. The tremor amplitude declines with tremor frequency but near 5 Hz, the resonance frequency, there is an increase in amplitude. The amplitude estimation at a distance of 1.5meters 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 RESERACH

We suggested UWB technology to quantify tremor for diagnosis of different patient pathologies. We built a UWB tremor acquisition system prototype and provided data analysis tools for the acquisition system. A feasibility test that was performed showed accurate tremor frequency and amplitude estimations. The system used for feasibility test operated with low radiation of the wideband radar signals to stand the requirements of common standards like 802.15.4a PHY. As a result, the wideband signals used in this technology are low power enough to not influence everyday life and enable and will enable coexistence of other wireless signals related to cell phone or Wireless LANs.

In future this system should be tested with multiple body segments having different frequencies and with neurological diseases patients. Implementation of this technology in Wireless Sensor Network (WSN) will enable deployment in wide public places like elderly housing facilities.

This new technology can offer non contact tremor assessment, utilizing extremely low radiation that can penetrate walls, work in any light condition, and can collect accurate data continuously. This new technology can be utilized in the future to work at any home and transmit the collected data to a remote hospital for continuous tremor monitoring and analysis with minimum cost. Directional antennas, higher sampling rates, higher bandwidth, higher radiation power, smaller marker size and more advanced equalization techniques can all improve the system performance.

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