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Empirical Mode Decomposition-based filtering for fatigue induced hand tremor in laparoscopic manipulation

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ABSTRACT

Fatigue induced hand tremor (FIT) is an unavoidable phenomenon, which substantially limits the accuracy of the surgical manipulation for long duration laparoscopic surgeries. Filtering intended motion from tremor is a challenging task as the properties of tremor change with increasing muscle fatigue levels. Muscle fatigue induced hand tremor has highly nonlinear and nonstationary characteristics that need a filtering strategy different from the conventional filters. Empirical Mode Decomposition (EMD) based filters have become popular in the recent past for its enhanced nonlinear signal handling capability. EMD based filtering strategy is case specific in nature as the EMD does not have any general analytical formulation unlike other (Kernel based) popular filtering techniques. In this work, we have addressed the tremor filtering issue with the help of EMD and the probability distribution characteristics analysis of Intrinsic Mode Functions (IMF) of the tremulous laparoscopic tool trajectory. A modified distribution asymmetry measure was employed to find out the threshold IMF for reconstruction of tremor free motion at different fatigue levels. In order to find the robustness of the proposed technique, the compensation strategy has been tested extensively on synthetic signal and experimentally acquired signals. Filtering threshold at different fatigue levels was also demonstrated for various subjects. Despite the time-varying properties of tremor, the proposed filtering strategy substantiates its efficacy to diminish the effect of tremor which was not possible by the conventional fixed cut-off filtering techniques.

1. Introduction

Minimally invasive surgery has its unique advantages over the conventional surgery for patients, as it offers reduced incision, quick recovery, and reduced hospital stay [1]. However, it is challenging from the surgeons' perspective as they have to manipulate specialized tool for prolonged timespan in an uncomfortable posture [2]. Hand tremor severely limits the quality of laparoscopic manipulation in minimally invasive surgery (MIS), where highly accurate movements are of primary interest [3,4]. Fatigue induced tremor (FIT) is a high frequency oscillating movement which adheres to the low frequency intended hand motion [5]. FIT frequency vary between 4Hz and 25Hz, depending upon the muscle fatigue level [6,5]. In Manual Laparoscopic Surgery (MLS) the surgical tool is directly manipulated by the doctor, and in Robot Assisted Laparoscopic Surgical (RALS) systems the surgeons' hand movement is reproduced by a slave manipulator inside the patient body. As the RALS has an intermediate controller, it is possible to employ a tremor compensation system for an accurate reproduction of intended surgical motion [7]. Implementation of tremor compensation is challenging in RALS since the characteristics of FIT changes significantly with the course of time with the increasing muscle fatigue [5,8,6].

The tremor signal is comprised of both deterministic and stochastic components [9,5], as a consequence the probability distribution changes with time. This makes the task of FIT compensation difficult for a filtering technique with the conventional Fourier based approach having a fixed *a priory basis*. A linear, fixed cut-off filtering with conventional Finite Impulse Response (FIR) or Infinite Impulse Response (IIR) structure based filters are incompetent to filter out the tremor from the intended motion as the tremor characteristics changes dynamically [10]. Even though wavelet based filtering can handle non-stationarity of signal to some extent, it fundamentally relies upon varying window *Fourier Spectral Analysis*, which essentially is a linear method [11]. Moreover, the wavelet thresholding process presumes that signal magnitude is significantly higher than the noise magnitude which is grossly discarded

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in case of tremor affected surgical manipulation [10]. Essentially, hand tremor compensation requires a signal processing scheme that can handle FIT without the assumption of linearity and stationarity.

EMD is a well celebrated method which can address the above mentioned issues of FIT compensation in an elegant manner [9]. It is a signal decomposition technique which works essentially in time domain, and sequentially decomposes the signal into various sub components known as IMF [12]. Though EMD has been extensively used for analysing hand movements [13,14], it has never been employed as a tool for minimizing the effect of FIT in dynamic scenarios where the tremor characteristics changes at different fatigue level. In this work EMD is used primarily as a tremor compensatory tool, in order to reduce the effect of tremor in laparoscopic tool manipulation (LTM) in dominant axis of tremor [8]. As the name suggests, EMD is a data driven decomposition process that depends upon numerical values of the signal. Since EMD assign the basis posteriorly, the temporal variation of the signal defines the number of basis; these basis are known as Intrinsic Mode Function (IMF) of the signal [12]. As a consequence, the high frequency activities are preserved with intact superior details in different IMFs without the prior assumption of linearity and stationarity [15,16]. The original signal can be reconstructed by summing up all the IMFs along with its residue. Partial cumulative sum of the IMFs makes the EMD based framework suitable for the current filtering scenario. Filtering capability of such strategies already has been established, although setting up the accumulation limit is unique and depends upon the nature of the application [17].

The objective of the present work is reconstruction of the FIT free intended laparoscopic manipulation trajectory by deciding a limiting reconstruction threshold on the IMFs. The idea of partial reconstruction was tried previously by a number of research groups [10,18], and the criteria for selection of reconstruction threshold in different scenarios were studied. Some of them are distribution dissimilarity based i.e. Kullback–Leibller Divergence (KLD) [19], and pattern recognition based approach, i.e. Hausdorff Distance [20], whereas few other works relied upon inferential statistics based criterion to find the limit [10]. Despite of its directional dependency, KLD is well accepted for its direct relation with the distribution mean, while the directional dependencies needs to be taken care of [19,20]. The critical factor of the current problem is the poor availability of information about the intended motion of the surgeon which varies with time, and relating fatigue level information for reducing tremor effects in a plausible manner. Primary backbone of the proposed approach is that the intended motion of the LTM is contributed by the higher order IMFs which have a lower frequency [15] and the lower order IMFs containing the high frequency components. It was assumed that the intended motion can occupy higher frequency modes depending upon the frequency content of LTM, i.e. a sudden fast movement in the case of a delicate suturing task performed in MLS is very common.

Muscle fatigue levels give the physiological perspective of tremor as the tremor changes due to the inability of producing sufficient torque with increasing fatigue in the associated muscle [21]. In this work, hand tremor at different fatigue level has been analyzed for all the experimental data. Assessment of muscle fatigue was carried out using the Mean Frequency (MF) analysis of Surface ElectroMyoGraphy (SEMG) signal recorded from the concerned prime mover muscle [22]. With the increasing fatigue level, MF drops down due to decreased conduction velocity of the neural excitation and increased synchronization of motor unit firing [23,6]. In this paper, we have demonstrated that the EMD based filtering works efficiently even though the tremor characteristics changes with increased muscle fatigue. The reconstruction thresholds for filtering were selected based on the Symmetric Kullback–Leibller Divergence (SKLD). Variation of the reconstruction threshold depending upon the varying tremor is demonstrated with hand tremor-like synthetic signal and the real tremor signal as well. Finally, the compensation strategy is verified with the experimentally acquired fatigue induced hand tremor data in laparoscopic manipulation.

2. Methods and conceptual framework

2.1. EMD based tremor filtering strategy

A significant advantage of employing EMD is its inherent adaptive nature, as the method resolves the signal to a set of posteriori defined basis (IMF), that are essentially derived from the data itself [15]. The IMFs ($IMF_n(t)$), are generated sequentially through the shifting process under some pre-determined criteria [12]. After the EMD of the tremulous signal, the resulting IMFs contains different amplitude and frequency values while having a identical time scale ($t = [1 : T]$) for all of them [17]. In this sequential decomposition procedure the frequency content of the IMF decreases gradually to a minimum value in the final IMF. Resulting IMFs always ensure that in terms of frequency $IMF_{n+1}(t) < IMF_n(t)$. This property of IMF drives the proposed tremor filtering framework as shown in Fig. 1.

Contribution of additive high frequency FIT varies with the changing muscle fatigue levels at different experimental task epochs. MF variation of the SEMG signal signifies the change in fatigue level of the associated muscle. Selective accumulation of the resolved $IMF_n(t)$ leads to a low frequency intended motion at different muscle fatigue level. Selection of the threshold was accomplished at each fatigue level on the basis of the consecutive IMFs' probability distribution asymmetry.

Symmetric Kullback–Liebler Divergence (SKLD) values at each fatigue level were used to determine the threshold of the reconstruction of the tremor free signal at different experimental task epoch. SKLD differentiates the IMF from a stochastic perspective as discussed in Section 4.3. Here the SKLD was used for detecting the distribution dissimilarity among $IMF_n(t)$ and $IMF_{n+1}(t)$ for all n. Since it is not possible to have a reference tremor signal for using it as a conventional filter, unlike the previous attempts with synthetic signals [20,24], different threshold was found at different stage of increasing fatigue level. After the threshold selection, reconstruction of the tremor free signal was accomplished by partial accumulation with the threshold bounded IMFs. This hierarchical filtering approach experimentally exhibited an efficient means to reduce the effect of FIT in LTM.

2.2. Detection of tremulous movement using wearable inertial sensors

Tremor compensation framework described in Section 2.3 requires the detection of the tremulous movement in LTM which can be carried out in various ways (i.e. optically, magnetically, or using inertial sensors) [25,26]. In this work, the trajectory of the tremulous tool manoeuvering in the sagittal plane was recorded with wearable inertial sensors (tri-axial accelerometer) as in the line diagram shown in Fig. 2. An elbow rest was provided in order to create the experimental scenario similar to the RAS [27,28,26].

Here we have used an accelerometer based joint angle measurement, where sagittal plane movement of forearm and palm with the elbow rest can be modeled as an inverted pendulum [29]. This approach of limb pose detection is appropriate in current scenario because tracking of the tool gripping point using other method often is not easy in the case of laparoscopic tool movement [26]. In order to deal with the high frequency tremor, the data acquisition rate has to be considerably high, which can be easily achieved with the current approach of inertial motion based sensing.