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Accurate tumor localization and tracking in radiation therapy using wireless body sensor networks

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ABSTRACT

Radiation therapy is an effective method to combat cancerous tumors by killing the malignant cells or controlling their growth. Knowing the exact position of the tumor is a very critical prerequisite in radiation therapy. Since the position of the tumor changes during the process of radiation therapy due to the patient's movements and respiration, a real-time tumor tracking method is highly desirable in order to deliver a sufficient dose of radiation to the tumor region without damaging the surrounding healthy tissues.

In this paper, we develop a novel tumor positioning method based on spatial sparsity. We estimate the position by processing the received signals from only one implantable RF transmitter. The proposed method uses less number of sensors compared to common magnetic transponder based approaches. The performance of the proposed method is evaluated in two different cases: (1) when the tissue configuration is perfectly determined (acquired beforehand by MRI or CT) and (2) when there are some uncertainties about the tissue boundaries. The results demonstrate the high accuracy and performance of the proposed method, even when the tissue boundaries are imperfectly known.

1. Introduction

1.1. Problem description

Radiation therapy (also called Radiotherapy) is an effective method to combat cancerous tumors by delivering high doses of radiation to the tumor to kill or control the growth of malignant cells by damaging their DNA [1]. A critical requirement of radiation therapy is to precisely delineate tumors and adjacent normal structures to avoid healthy tissues exposed under radiation. Recent specialized CT and/or MRI assisted techniques, such as three-dimensional conformal radiation therapy (3DCRT) and Intensity-Modulated Radiation Therapy (IMRT) [24], have significantly enhanced the ability to deliver an accurate radiation dose to the target volumes. In these methods, the radiation is split into hundreds of thin beamlets targeting the tumor from various angles to achieve a better focus on the cancerous region and reduce the damage to the surrounding healthy tissues [2]. In IMRT, beamlets can also have various radiation intensities and it helps to produce a treatment area that better conforms to the contour of the tumor [3].

Knowing the exact position of the tumor is one of the most essential prerequisites in radiation therapy, because any slight bias in the position of the tumor will cause the radiation to be delivered to the surrounding healthy tissues rather than the tumor area, which would not only degrade the performance of the treatment due to a lack of sufficient dose for the tumor treatment, but also may cause severe side effects such as tissue toxicity and secondary cancer [2,4]. It is important to note that the position of the tumor changes during radiation therapy because of respiration, gastro-intestinal, bladder filling, cardiac system or patient movements. Thus a *real-time* tumor tracking mechanism is highly desired in radiation therapy treatments in order to deliver and maintain a precise amount of radiation to the tumor region without damaging the surrounding healthy tissues [2,4].

1.2. Background and previous work

Various methods have been proposed in the literature for tumor tracking in radiation therapy treatments based on implanting several wired or wireless devices (called beacons) inside or in the vicinity of the tumor [2–13]. The Calypso localization system is one of the most prevalent methods that has been widely used for tumor positioning in prostate radiation therapy [7,8]. In the Calypso system, three magnetic transponders are implanted inside

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or in the vicinity of the target. Localization of the transponders is achieved using an electromagnetic array consisting of four electromagnetic coils to excite the transponders and 32 receiving coils to pick up the response from the transponders. Positions of the implanted transponders are estimated relative to the magnetic array based on the response measurements [4,7]. There are several other electromagnetic based localization systems such as the 3-dimensional magnetic tracking methods as proposed in [2,13] that use the similar idea to track the tumor positions during the radiation therapy.

Infrared camera with external marker has been also used for tumor tracking. In this method, the simultaneous motions of several external markers and an internal target are estimated using an infrared camera system [25–28]. Recently, radar sensor systems have also been attracting extensive attention for the purpose of tumor tracking [29–31].

1.3. *The proposed approach*

In this paper, we propose and develop a novel positioning method based on spatial sparsity in 3D space and convex optimization theory [17] to achieve accurate results. In the proposed method, we use only one wireless implantable RF transmitter implanted inside or in the vicinity of the tumor. The implant plays the role of an emitter by transmitting an RF signal. The signal will be received by a sensor array mounted in a known position beneath or above the patient's body. Then, the received signals will be processed to estimate the position of the implant (i.e., the emitter) relative to the sensor array, based on received signal strength (RSS), time-of-arrival (TOA), and phase shift parameters.

The classical localization methods usually include two stages. In the first stage, one or more location-dependant parameters (such as TOA or RSS) are estimated. Then in the second stage, these parameter estimates are used in statistical processing or finger printing methods to estimate the location of target. However the classic two-stage method is not necessarily optimal because in the first stage the parameter estimates are obtained by ignoring the fact that all measurements should be consistent with a single target location. In other words, each stage itself is optimal but the cascade of the two stages is not necessarily optimal [14].

Unlike classic RSS or TOA based localization approaches, we use convex optimization theory to solve the problem of location estimation directly without going through the intermediate stage of TOA or RSS estimation. In other words, there is no need to explicitly estimate the RSS or TOA for each of the sensors in a separate stage and the decision about the target location is made directly based on all received signals. Given all aforementioned features, the proposed method is much more accurate in positioning and very robust to multipath conditions caused by signal reflections at the boundaries of body organs compared to classic TOA/RSS based methods.

Some serious challenges exist for the in-body localization, compared to regular localization in other environments. The human body is made up of various organs that consist of different types of tissues; thus, the electrical characteristics of the body – such as power absorption, conductivity and relative permittivity – show significant anisotropy and heterogeneity. For example, the relative permittivity value varies according to the tissue type. Since the signal propagation velocity is expressed as a function of the relative permittivity, the propagation velocity and consequently the TOA highly depends on the specific tissue layers that the signal passes through from the implant (emitter) to the sensor (receiver) [15]. The path loss exponent and power absorption parameters also vary by tissue thickness [18]. Therefore, traditional in-body localization methods based on RSS or TOA are challenging and sometimes inaccurate unless we have *a priori* knowledge about the position of the implant. Even if this *a priori* information is available it is difficult to exploit it in the classical location methods. In this paper, we propose a novel tissue-adaptive approach, considering the propagation velocity and path loss exponent as location-dependent parameters that can be exploited to estimate the implant location more precisely.

In [15,16], we reported preliminary results for a proposed *2-dimensional* positioning method based on spatial sparsity. However, those studies suffer from various assumptions made for the purpose of simplification and ease of implementation. For instance, in [15] the human body is assumed to be uniformly made by only one tissue type. In [16], we addressed the tissue variety problem by simply calculating the weighted average of relative permittivity and then computing the average propagation velocity. In this paper, to achieve more precise results, we first estimate the exact interconnection points between the line-of-sight and the tissue boundary surfaces. Then, the accurate delay will be calculated as the summation of delays in each tissue layer. We will also expand the results by providing a detailed discussion on how the path loss and delay should be computed for each potential signal path including the method developed to estimate the interconnection points between line-of-sight and tissue boundary surfaces. Furthermore, we will derive new equations and algorithms for the *3-dimensional* localization.

The performance of the proposed approach was evaluated using Monte-Carlo computer simulation. The results demonstrate the high localization accuracy of our method (i.e., less than 2 mm error using only 4 receiver sensors), even in the case when the tissue configurations are not exactly known and the tissue boundaries are uncertain. The results also show the robustness of the proposed method to multipath conditions that are caused by massive signal reflections at the boundaries of human body organs.

The rest of the paper is organized as follows. In Section 2, we first give an overview of the concept of spatial sparsity, and how to achieve sparse solutions using convex optimization. Then, we discuss the received signals model and path-loss and TOA computation in human body consisting of various types of tissues. Next, we present the problem formulation and show how we exploit the sparsity and convex optimization theory to solve the location estimation problem based on both TOA and RSS. Then, we propose an alternative approach to reduce the computational complexity of the problem, especially for *3-dimensional* localizations. In Section 3, we evaluate the performance of the proposed method in two different cases: when the tissue configuration and boundaries are exactly known, and when a certain level of ambiguity and uncertainty of the tissue configuration exists. Finally, we provide some discussions about the results and performance of the proposed method.

2. Methods: tumor localization and tracking

2.1. *Spatial sparsity based approach*

If we consider the human body area of interest as a fine enough three-dimensional grid space, the number of grid points containing the implant(s) (i.e., the emitters) is much smaller than the number of all grid points in the space. Assume that we allocate a positive number (such as one) to the grid points that include an emitter and assign zero to the rest of the grid points. Now, by arranging those numbers into a vector, we obtain a very sparse vector including only one (or more if we have more than one implant) non-zero element. Since each element of this long vector corresponds to a grid point in the grid space, we are able to estimate the location of the implant by finding the position of the non-zero elements of the sparse vector.

In general, the ℓ_p-norm of a vector ν is defined as $||\mathbf{v}||_p = \sqrt[p]{\sum_i |v_i|^p}$. In many optimization problems (such as the least square