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UWB Sensor Networks for Position Location and Imaging of Objects and Environments

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1. Introduction

Ultra-wideband (UWB) radio sensors promise interesting perspectives for position location and object identification in short range environments. Their fundamental advantage comes from the huge bandwidth which may be up to several GHz depending on the national regulation rules. E.g. frequency ranges of 3.1-10.6 and 1.99-10.6 GHz are deregulated for communication and wall penetrating radar, respectively, in the U.S. (FCC). Even 50 MHz to 18 GHz are envisaged for ground and wall penetrating radar in Europe (which will include specific protection measures of sensitive sites). Consequently, UWB access network infrastructure allows unprecedented spatial resolution in geolocalization of active UWB devices without range ambiguity [1], [2] and UWB radar sensors [3] allow high resolution in detection and localization of passive objects in short range distance. With the lower frequencies involved in the UWB spectrum, looking into or through nonmetallic materials and objects becomes feasible. This is of major importance for applications like indoor navigation, object recognition and imaging, through wall detection and tracking of persons, ground penetrating reconnaissance, wall structure analysis etc. UWB sensors preserve their advantages -high accuracy and robust operation- even in multi-path rich propagation environments. This all makes UWB a promising basis for autonomous navigation of mobile sensor nodes, -e.g. maneuverable robots- in an unknown or even hostile environment that may arise as result of an emergency situation. In this case UWB may help to identify hazardous situations such as broken walls, locate buried-alive persons, roughly check the integrity of building constructions, etc.

Despite the excellent range resolution capabilities of UWB, detection and localization performance of the sensor network can be significantly improved by cooperation between sensor nodes. Distributed sensor nodes will acquire comprehensive knowledge on the structure of the environment and perhaps construct an electromagnetic image. This approach takes advantage of information exchange between sensor nodes, distributed processing and sensor data fusion. It includes relative sensor-to-sensor localization and ad-hoc assignment of tasks to nodes. The nodes can act as deployable or moving anchor nodes determining a local coordinate system in an environment without existing reference infrastructure. They can also act as “scouts” to observe or illuminate certain areas for imaging or recognition applications for the purpose of the mission to be fulfilled and according to their sensing capabilities.

2. Relative Sensor-to-Sensor Node Localization

Since imaging of environments and objects in essence is a combination of sequential observations of one moving sensor or of a number of spatially distributed sensors, the knowledge of the precise location of each sensor node is a prerequisite. Whereas existing indoor navigation systems mostly rely on fixed reference beacons belonging to the infrastructure of some wireless access network, localization in unknown environment must be autonomous and self-contained. The nodes must at first establish their own local coordinate system by estimating their relative position. Then the structure of the unknown environment has to be recognized. This will be achieved by imaging and object recognition methods. When the structure of the environment is finally recognized, it will be related to the sensor network coordinate system. Autonomous localization of sensor nodes basically relies on relative sensor-to-sensor node localization. Since imaging may include coherent combining of multistatic signals, we should aim at cm-level location accuracy. With its high temporal resolution, time-based localization approaches (ToA, time of arrival) are the

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natural choice in case of UWB. This also avoids usage of expensive antenna arrays which we would need for AoA (angle of arrival) approach [1]. ToA, however, requires time base synchronization between nodes. This can be achieved by RToA (round trip time of arrival) approach which means that any sensor involved must be able to retransmit received signals. However, to reduce overall interference created by the UWB nodes, it makes sense that only some nodes act as active Tx/Rx nodes. These will play the role as deployable anchor nodes. Anchor nodes should be placed at “strategic” positions meaning that they span a large volume and ensure a complete illumination of the environment. Active Rx-only nodes can calculate their own position relative to the anchor nodes by applying TDoA (time difference of arrival) or related pseudo-range methods. Both methods require only one additional synchronised anchor node.

Mayor source of location error is non-line-of-sight (NLOS) propagation [2], [13]. NLOS can be avoided by selective anchor reference choice if there are redundant anchors. Advanced estimation and tracking techniques may further enhance location accuracy and robustness against outliers.

3. Imaging of Environments

To recognize the geometrical structure of an environment, it has to be explored by a number of spatially sensor nodes, perhaps roaming about on arbitrary tracks. The environment is illuminated by one or more Tx nodes. Rx nodes record the backscattered waves. Images of the environment are created by fusing the recorded data from different Rx nodes. Electromagnetic wave (EM) imaging uses some form of back propagation, back projection, or time-reversal for image reconstruction [4], [5], [6], Time domain imaging methods using broadband or UWB excitation signals are usually referred to as migration [7]. They basically apply linear operations and take into account a number of simplifying assumptions. An example is Kirchhoff migration which uses a ray optical model of wave propagation, neglects multiple reflections and assumes Rayleigh or specular scattering of waves from objects. The latter requires the size of the objects to be clearly smaller or larger than the wavelength of the excitation signal. However, in case of UWB, the relative span of wavelengths is very wide. If the object size is in the order of any wavelength involved, this gives rise to structural resonances or geometric induced dispersions of waveforms which causes image blurring but also may allow recognition of object shape. Moreover, Kirchhoff migration assumes a constant wave velocity, which must be a priory known. Despite of these limitations, Kirchhoff migration is widely used due to its relatively low computational complexity. If higher complexity can be accepted, nonlinear processing such as cross-correlated back projection algorithm [8] can be used to increase the quality of focused images. A measured example in an industrial environment is given in Figure 1. Rx1 and Rx2 in the left hand picture describe the position of two fixed anchor nodes that determine the local coordinate system (note that in this real-time experiment the anchor nodes where emulated by hardware-synchronized receivers). The black curve describes the random track of the moving illuminator sensor. The focused image indicates strong reflections by red hot spots. The arrows relate those hot spots to the details in the photo image on the right side.

Whereas the multistatic imaging approach mentioned above presumes a coherent data fusion of widely distributed sensors, a different approach arises if we assume sensor nodes that are equipped with (at least) one transmit and two receive channels. Since in this case, coherent data processing is inherently limited to local sensor node platform, synchronization requirement is relaxed at the expense of a more complex node architecture [12]. Cooperation between the nodes can still enhance the final result.

4. Detection and Localization of Time-Variant and Moving Objects

The detection of time-variant or moving objects requires a separation of time-variant and static signals. However, the waves scattered from static objects such as walls and furniture are in most cases much stronger than waves scattered from, e.g., humans beings. Therefore, removal of static background reflections my considerably enhance the dynamic range for detection of weak time variant signal features. An example is given if Fig. 2. The signal of interest is the through wall radar return of a person behind the wall. The first wall echo, background reflection, and antenna cross talk completely mask the interesting signal details. However, if we remove the static signal part from the dynamic one, we achieve a very clean response which clearly reveals even the respirators activity of the person as shown in Fig. 3. Background subtraction methods are well known from video surveillance. A review of these techniques can be found in [9]. Localization of time-variant and moving objects again requires distributed sensor observations and object tracking.

5. Conclusions

Imaging of environments and detection of unknown objects in the vicinity of UWB sensor networks can be achieved by sensor cooperation which includes coherent and noncoherent multistatic data fusion. Advanced signal processing allows recognition of the shape, orientation and other morphological features of the objects, identification of moving objects and detection of time variant object features. Further enhancement may be achieved by distributed inference methods [11]. Those include advanced multiple sensor data fusion, local and distributed decision, probability distribution and particle based soft decision methods, multiple hypothesis tests, tracking in case of time-variant observations etc. Object detection must be robust against various error sources and missing (incomplete) information. Knowledge based approach, distributed learning, and (distributed) iterative enhancement may help to optimize the cooperative detection performance. Since sensor cooperation may require considerable information exchange between nodes, optimization between local computational effort and vs. message distribution payload is necessary.

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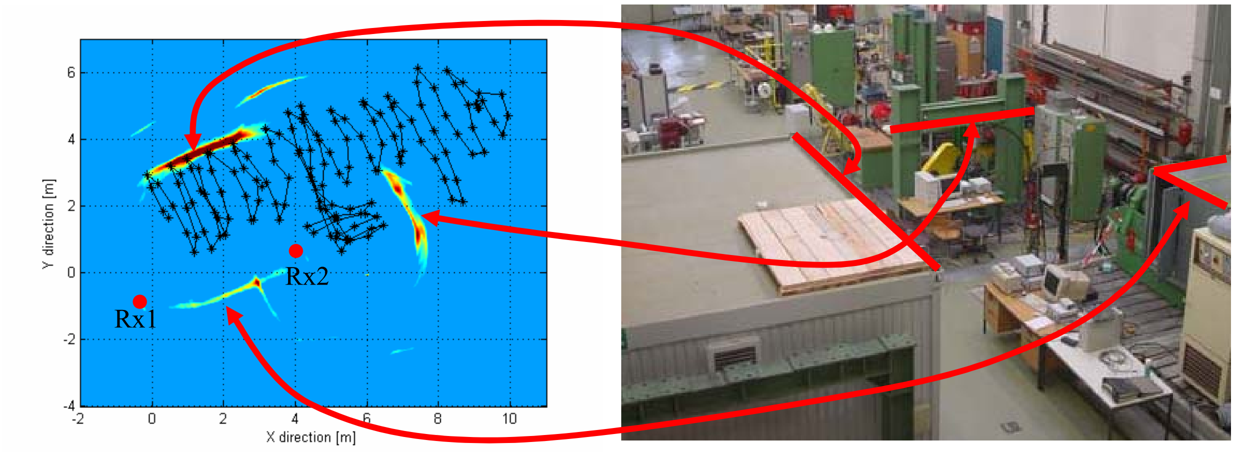

Figure 1. Multistatic imaging of a propagation environment

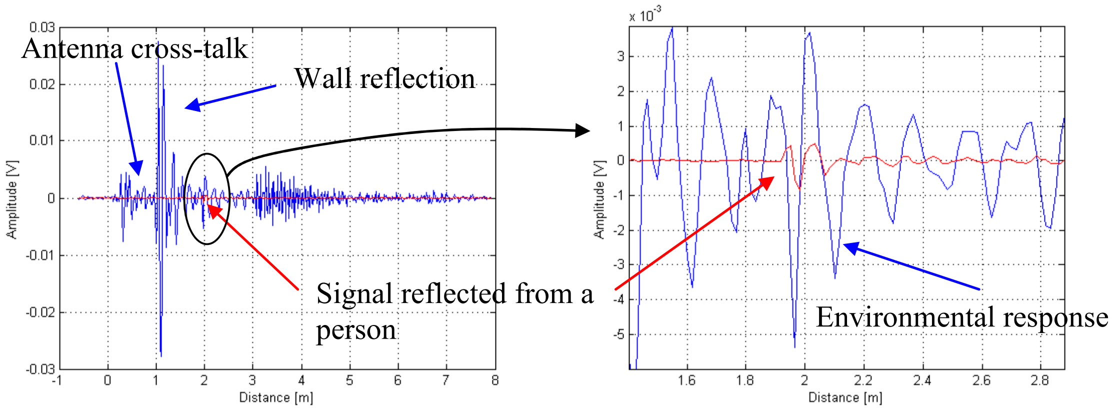

Figure 2. Time signal detection from through wall radar returns

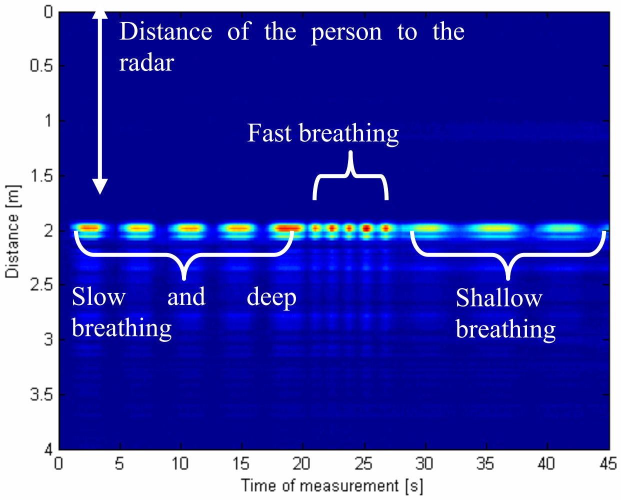

Figure 3. Human respiratory activity from radar returns with background subtraction