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14. ABSTRACT
The aim of this project was to (i) detect and classify personnel and their activities in an indoor environment monitored by different sensors, and (ii) develop novel signal processing approaches for networked sensors. During the course of this project, we have considered the case of video surveillance and have shown improved tracking performance using quality based fusion of data from multiple video sensors. We developed a copula based approach to heterogeneous sensor fusion. The proposed approach also applies information theoretic measures to

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FINAL PROGRESS REPORT

A. Statement of the problem studied

The aim of this project was to detect and classify personnel and their activities in an indoor environment monitored by different sensors as well as to develop novel signal processing approaches for networked sensors. During the course of this project, we have studied the following problems:

1. Video surveillance using multiple video sensors.
2. Heterogeneous sensor fusion problem using the theory of copulas.
3. Collaborative target detection in clutter and noise.
4. Channel aware physical layer design for wireless sensor networks.
5. Personnel detection using seismic sensors.

B. Summary of the most important results

The following paragraphs summarize the key results that have been established during this project period. Details are available in the cited papers.

1. *Video Surveillance using multiple video sensors.* The problem of improving tracking accuracy through multiple visual sensors in a distributed framework has been addressed for an outdoor video surveillance application [1]. A data fusion approach has been proposed to adaptively combine, according to the performance of each sensor, the position of a target resulting in a unified estimate. Sensor reliability is explicitly considered and a confidence function has been defined to automatically weight redundant estimates of the location of the targets in the fusion process. This is performed through a function that adjusts the measurement error covariance associated with the position information of each target according to the quality of its segmentation. In this way, localization errors due to incorrect segmentation of the blobs have been reduced, as well as the errors due to homographic transformations. Experimental results on video sequences of outdoor environments have shown the effectiveness of the proposed approach in terms of tracking accuracy in comparison with single camera systems.

2. *Copula based heterogeneous sensor fusion.* We designed a parametric framework for the joint processing of heterogeneous (multimodal) data. We showed how copula theory can be exploited to model heterogeneous signals [2], [3]. We identified the issues involved when modeling heterogeneous data and showed that copula functions possess properties that circumvent these difficulties. They provide an attractive approach as they allow one to define dependence separate from the choice of the marginal. A binary hypotheses test was formulated and a log-likelihood ratio test was derived for heterogeneous inputs. The copula approach allows us to separate the cross-modal terms from the unimodal terms in the likelihood ratio thus allowing intra-modal vs. inter-modal analyses. Detection performance analysis in the asymptotic regime proves the intuitive result that when inter-modal dependence is accounted for in the test statistic, the ability to discriminate between the two competing hypotheses increases over the product rule by a factor exactly equal to the multi-information between the multiple modalities. The important problem of model mismatch errors due to copula misspecification and its effect on detection performance was also studied. The theory was also applied to a multi-sensor detection application where each of the deployed sensors has different sensing capabilities [4].

3. *Closed-form performance for location estimation based on fused data in a sensor network.* For a large and dense outdoor sensor network, the impact of sensor density and signal to noise ratio (SNR) are investigated on the performance of a maximum likelihood (ML) location estimation algorithm [5]. The ML estimator fuses data, in the form of signal amplitudes, transmitted from local sensors to estimate the location of a source. A Gaussian-like isotropic signal decay model is

adopted to make the problem tractable and meaningful. This model is suitable for situations such as passive sensors monitoring a target emitting acoustic signals. The exact Cramer-Rao lower bound (CRLB) on the estimation error has been derived. In addition, an approximate closed-form CRLB by using the Law of Large Numbers is obtained. The closed-form results indicate that the Fisher information is a linearly increasing function of the product of the sensor density and the SNR. Even though the results are derived assuming a large number of sensors, numerical results show that the closed-form CRLB is very close to the exact CRLB for both high and relatively low sensor densities.

4. *Channel aware target localization in wireless sensor networks.* We proposed a new maximum-likelihood (ML) target localization approach which uses quantized sensor data as well as wireless channel statistics in a wireless sensor network [6], [7]. The novelty of our approach comes from the fact that statistics of imperfect wireless channels between sensors and the fusion center along with some physical layer design parameters are incorporated in the localization algorithm. We call this approach "channel-aware target localization." We derived three different channel-aware ML target localization algorithms along with their corresponding Cramér-Rao lower bounds (CRLBs). The first localization algorithm employs a hard-decoding link design and incorporates the bit error probabilities of the channel which is modeled as a binary channel (BC), whereas the second and the third localization algorithms are specifically developed for soft-decoding link designs assuming Rayleigh fading channels with phase coherent and phase non-coherent reception, respectively. Simulation results show that the performance of the channel-aware ML location estimators are quite close to their theoretical performance bounds even with relatively small number of sensors and their performance is superior compared to that of the channel-unaware ML estimators.

5. *Channel aware particle filtering for tracking.* A new framework for target tracking in a wireless sensor network using particle filters was proposed [8]. Under this framework, the imperfect nature of the wireless communication channels between sensors and the fusion center along with some physical layer design parameters of the network are incorporated in the tracking algorithm based on particle filters. We call this approach "channel-aware particle filtering." Channel-aware particle filtering schemes are derived for different wireless channel models and receiver architectures. Furthermore, we derived the posterior Cramér–Rao lower bounds (PCRLBs) for our proposed channel-aware particle filters and present a methodology to compute PCRLBs using Monte Carlo techniques. Similar to the localization scenario, the first tracking algorithm is developed for a hard-decoding link design. It incorporates the bit error probabilities of the channel which is modeled as a binary channel (BC). The second and the third tracking algorithms are specifically developed for soft-decoding link designs assuming Rayleigh fading channels with phase coherent and phase non-coherent reception, respectively. Simulation results demonstrate that the tracking performance of the channel-aware particle filters can reach their theoretical performance bounds even with relatively small number of sensors and they have superior performance compared to channel-unaware particle filters.

6. *Field estimation in sensor networks.* We proposed a conceptual framework for a novel diversity technique for WSNs monitoring spatially correlated processes has been proposed [9]. The effect of transmission packet losses on parameter estimation at the sink has been mitigated by field estimation along with bootstrap sampling techniques. The results show significant performance improvement. Importantly, the proposed algorithm runs completely at the sink and imposes very little additional computational and communication burden on the resource constrained sensor nodes. Also, the approach developed in this effort neither requires prior model assumption nor large sample assumption which make it suitable for complex real-life applications.

7. *False discovery rate (FDR) based target detection.* We proposed and explored for the first time an FDR based approach for the detection of targets in clutter and noise [10], [11]. The proposed

approach controls the FDR (defined as the ratio of the number of false alarms to the total number of detections) for an entire surveillance area, unlike the conventional approach of controlling the probability of false alarm for each surveillance cell. This results in a scheme which is adaptive to the number of targets and provides an opportunity to increase the detection performance in target rich environments while controlling the probability of false alarm at a single pre-defined target density. To obtain better control of the system level probability of false alarm, a distributed framework consisting of two or more sensors has also been formulated and analyzed. In the distributed setting with two or more sensors, the system-level probability of detection may be improved in target-rich environments while achieving strict control on the system-level probability of false alarm at two or more target fractions. Also, a modified FDR algorithm based on an estimate of the target fraction which can limit the increase of the probability of false alarm after a pre-specified level has been proposed. This scheme may be adopted both for the single sensor and multiple sensor formulations. Finally, to obtain a lower bound on the system level probability of false alarm, a hybrid detector which involves fusion of the decisions of a family-wise testing algorithm (with control of FDR) and a per-cell testing algorithm (with control of the probability of false alarm per cell) has been developed. Thus, our approach which is based on the control of a region-based statistic, as opposed to the conventional approach based on the control of a cell-based statistic, can distinguish between target-rich and target-starved regions and provides a more efficient and robust system design.

8. *Distributed target detection in wireless sensor networks.* In most realistic wireless sensor network applications, the sensors in the network receive non-identical signals. Under such conditions, the design of decision rules both at the local sensor and at the fusion center for distributed detection is an open and very challenging research problem. The FDR based detection framework (introduced above) addresses this important problem and shows significant improvement in performance over the classically used identical decision threshold approach [12], [13]. This is the first work on non-identical sensor threshold design for the distributed detection problem with fusion of the local sensor decisions in WSNs. For the proposed framework, various performance metrics like system level probability of detection and system level probability of false alarm have been derived. Our results are based on simulation and show excellent agreement with the analytically obtained results.

9. *Personnel detection using seismic sensors.* We proposed a data-driven signal processing scheme for footstep detection [14]. We presented an analysis of experimental data collected at Syracuse University and showed that the data exhibits significant nonlinearity when tested using the surrogate data method. We used a detector based on unprocessed data as a benchmark and showed that our detector is able to achieve significant improvements. We use a data driven decomposition scheme called empirical mode decomposition (EMD). EMD is able to decompose the signal in terms of oscillation modes present in the signal. This means that the amplitude of the analytic function of one or more modes will carry the footstep envelope information. Therefore, this signal processing scheme, in principle, can also be used with acoustic sensors.

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