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Fundamental Bounds on Information Fusion with Focus on Waveform-based Intent Detection and Avoidance

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14. ABSTRACT

In radar systems one may have a priori knowledge of the scene or its statistics.
The supported research sought to exploit this additional knowledge available to a radar to improve its performance along two main lines:
1) past radar waveform returns and knowledge of scene statistics allows a radar to adapt its subsequent waveforms to these extra sources of information, and 2) knowledge of the geometry of the radar scene may allow one to exploit multi path reflections to improve radar performance such as target detection and localization. In our first direction, it is known that adapting radar waveforms to best extract information exploits prior scene knowledge - for example knowledge of multipath - and improves performance. How to ``best" design and adaptively select waveforms, however, remains an open question. Central to answering this is how to properly incorporate feedback, or ``close" the loop. In a more theoretical direction, we have proposed a novel, information

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1 Executive Summary

In radar systems one may have a priori knowledge of the scene or its statistics. The supported research sought to exploit this additional knowledge available to a radar to improve its performance along two main lines: 1) past radar waveform returns and knowledge of scene statistics allows a radar to adapt its subsequent waveforms to these extra sources of information, and 2) knowledge of the geometry of the radar scene may allow one to exploit multi path reflections to improve radar performance such as target detection and localization.

In our first direction, it is known that adapting radar waveforms to best extract information exploits prior scene knowledge - for example knowledge of multipath - and improves performance. How to "best" design and adaptively select waveforms, however, remains an open question. Central to answering this is how to properly incorporate feedback, or "close" the loop. In a more theoretical direction, we have proposed a novel, information theoretically optimal metric which properly incorporates feedback which will allow for the more efficient and effective scheduling of radar waveforms and shown the resulting designed or scheduled waveforms in simulations.In a second, more practical direction, we have proposed waveform design and waveform scheduling in the context of space time adaptive processing (STAP) for radar. It was shown that both the designed waveform and the scheduled waveforms will depend on the spatial and Doppler responses of the desired target; in particular, its spatial and temporal steering vectors.

In our second direction, we focussed on a particular type of scene prior knowledge - multipath. In the past, multipath has been associated with negative connotations in radar systems. We demonstrated that when prior information about the sources of multipath are known, then multipath can be exploited - rather than ignored or mitigated - to improve radar performance in several scenarios: we derived the Cramer-Rao lower bounds on target localization for several geometries in the presence and absence of line-of-sight components with single and multiple sensor systems. We furthermore considered localization exploiting multi path in passive scenarios with a single sensor.

Personnel involved. This project has supported the work of PI Assistant Professor Natasha Devroye for 3 summer months, of Ph.D. student Nathan Schneider (currently with General Electric) for 1 year, and of postdoctoral research associate Dr. Pawan Setlur (currently with Wright State Research Institute and Air Force Research Labs) for 1.5 years. We have furthermore collaborated with colleagues Professor Danilo Erricolo at the University of Illinois at Chicago, and his Ph.D. student Harun Hayvaci and Tadahiro Negishi. Dr. Devroye and Dr. Setlur visited the Wright Patterson Air Force Base, hosted by Dr. Murali Rangaswamy and Dr. Braham Himed, to give a talk entitled "Exploiting scene knowledge in radar systems," on February 28, 2013. This initiated a collaboration with Dr. Rangaswamy which resulted in the publication; the collaboration is ongoing and a journal submission is planned in fall 2013. This visit also initiated a collaboration with Dr. Alan O'Connor, who was then a National Research Council Postdoctoral Fellow at the Air Force Research Laboratory, and is currently with Lincoln Labs.

2 Topic 1: Closed loop radar waveform scheduling and design

PUT FIGURES!

Numerous defense applications rely on closed-loop, or adaptive, information gathering systems. Waveform scheduling and design hopes to achieve maximal information extraction of the radar scene, which typically changes from one measurement to the next, by exploiting prior statistics and waveform diversity. Such systems have traditionally been approached from a statistical signal processing perspective. We sought to develop new, *information theoretically* motivated ways of designing and scheduling radar waveforms in adaptive or cognitive radar systems. Such radar systems have the ability to adapt waveforms (on a pulse by pulse basis, or less frequently) to the sensed environment through either waveform selection from a library of waveforms, or through waveform design. Instead of designing with specific objectives in mind, we sought a surrogate metric for such closed loop information gathering systems, and used concepts from information theory to provide generic, objective-independent designs. We started our work with a theoretical, conceptual formulation in [1], and refined the ideas in a series of papers on information theoretic waveform scheduling and waveform design [2, 3], space-time adaptive processing closed loop waveform scheduling and design [4], and finally an information theoretic analysis of time-reversal in radar channels in [5, 6].

2.1 Information theoretic waveform scheduling and design

Some of the earliest connections between radar and information theory were made by Woodward and Davies [7, 8, 9], in which information theoretic arguments were used to quantify the amount of information a radar receiver may extract about a quantity of interest based on noisy measurements. Since then, the most profound connection between radar and information theory has been made by Bell [10, 11], where it is argued that to design waveforms for maximal information extraction, mutual information should be used as metric. This differed from more classical detection and estimation theoretic waveform design approaches [12, 13, 14, 15]. In Bell's seminal journal publication [10] and thesis [11] the radar targets are modeled as extended ones which exhibit interference and resonance effects, making waveform design relevant. The target impulse response is assumed not to be known a priori, and is thus modeled as a Gaussian random process. Bell seeks to design the input waveform to maximize the mutual information between the target and the received waveform (given the input waveform). This optimization led to a water-filling strategy over a combination of the target and noise power spectral densities. The work of Bell has been extended to multiple target detection and tracking [16], to signal-dependent clutter [17], and to the design of MIMO radar waveforms [18]. In these works, a single waveform was designed; the closed loop performance of a system with the ability to adapt is not explicitly addressed.

In our work [2, 3] the problem of adaptively selecting radar waveforms from a pre-defined library of waveforms, as well as that of designing waveforms for several steps in advance given knowledge of scene statistics, was addressed from an information theoretic perspective. Typically, radars transmit specifc waveforms periodically, to obtain for example, the range and Doppler of a target. Although modern radars are capable of transmit- ting different waveforms during each consecutive period of transmission, it was unclear how these waveforms should be designed or scheduled to best understand the dynamic radar scene.

First, a pre-dened waveform library is assumed to be given, or designed a priori. In our work, we proposed the information theoretic metric "directed information" – a metric more suitable than mutual information for characterizing systems with feedback – for waveform scheduling, which was shown to incorporate the past radar returns to effectively schedule waveforms. Past work had considered only greedy, one-step mutual information-based approaches to scheduling. Under certain conditions, we showed that optimizing the more traditional two-step mutual information is equivalent to maximizing the two-step directed information. However, whenever the clutter statistics are target dependent (which happens often in practice) we showed that the two are not equivalent and in this case maximizing the directed information is of more relevance to the closed loop information gathering problem.

Analog and discrete models were proposed; the former allows for a spectral domain interpretation, whereas, the latter permits analogies to Bayesian error metrics. We then formulated this waveform scheduling problem in a Gaussian framework, derived the corresponding maximization problem, and illustrated several special cases.

One may alternatively use the directed information not as a scheduling metric but as a waveform design metric. In this case, we investigated designing waveforms over two steps using the two-step directed information as metric. This is the subject of ongoing work; a journal submission including both directed information based waveform design and scheduling is anticipated in 2013 [19].

2.2 Space-time adaptive processing waveform scheduling and design

In collaboration with Dr. Murali Rangaswamy of AFRL, we considered waveform design and scheduling in a more practical context of space time adaptive processing (STAP) for radar. An air-borne radar with an array of sensors is assumed, which interrogates ground based targets. The designed waveform is assumed to be transmitted over one coherent processing interval. The waveform design and waveform scheduling problems were formulated with a cost function similar to the Minimum Variance Distortionless Response (MVDR) cost function as in classical radar STAP. Least-squared solutions for the designed waveform were obtained, and it was seen that both the designed waveform and the scheduled waveforms depended on the spatial and Doppler responses of the desired target; in particular, on its spatial and temporal steering vectors. We characterized the performance of the designed and scheduled waveforms for unknown correlation matrices which were estimated from the training data. We envision incorporating real-world data from AFRL in our planned journal submission in 2013 [20].

2.3 Information theoretic analysis of time-reversal radar systems

We next extended our information theoretic analysis of radar systems to time-reversal radar systems in [5] and [6]. Time-reversal (TR) techniques have been shown to lead to gains in detection and enable super-resolution focusing. These gains have thus far mainly been demonstrated for time invariant channels, where the channel remains constant between the initial and time-reversed signal transmissions. We sought to relax this assumption by studying the benets of TR over time-varying channels. To do so, we compared a time-reversed and a non time-reversed system by comparing the mutual information between the channel impulse response and channel outputs given the transmitted signals over two time slots of a radar system. Besides evaluating this mutual information, and showing that for this setup it is equal to directed information which might be of interest in feedback-like channels, we also provide a low-rank interpretation of this mutual information for Gaussian channels. We presented analytical results for a simple scalar problem which illustrates the impact of nonstationary channels on TR, and for general channels, numerically evaluated the difference in mutual informations, which demonstrated that, if the channels are nonstationary yet correlated, TR may still provide mutual information gains over non time-reversed systems.

3 Topic 2: Multipath exploitation in radar systems

To further understand the impact of side-information or additional a priori knowledge and how this may be incorporated in improving performance of a radar system, we considered a specific example of additional side-information: knowledge of scene geometry (i.e. of stationary buildings via prior surveillance or blue prints). We considered multiple aspects of the multi path exploitation problem, including better estimation of the accuracy of the direct path time delay (i.e. target localization), estimation of angle of arrival with a single sensor, localization in the absence of a line of sight delay, passive localization, and the derivation of fundamental bounds on the localization precision when exploiting multi path.

In [21], time delay estimation using the maximum likelihood principle was addressed for the multipath exploitation problem, and the corresponding Cramer-Rao bounds were derived. A single wideband radar, and a target in a known reecting geometry were assumed. If the multipath is indeed detectable and resolvable, it was shown that multipath exploitation, rstly, permits estimating the angle of arrival (AoA) of the target with a single sensor, and secondly, improves estimation accuracy of the direct path time delay. Both these are possible because the multipaths time delay is a deterministic function of the time delay of the direct path as well as its AoA. The multipath caused from reections from surfaces yields virtual radar sensors observing the target from different aspects, thereby allowing AoA estimation.

In [22] and [23] we considered single sensor localization in urban scenarios. In such urban scenarios, radar returns consist of a direct path return along with multipath returns from signal reections off surfaces such as building walls or oors. When multipath is resolvable, and given the knowledge of the geometry of the reecting surfaces, multipath returns create additional virtual radar sensors, thereby permitting target localization with a single radar sensor. Exploiting multipath, rather than viewing it strictly as a hindrance, is an emerging topic in the radar community whose potential is not yet fully understood. Towards this goal, we rst derived the Cramr-Rao and the Bayesian Cramr-Rao bounds on target localization using a single-sensor which exploits resolvable multipath. For a wide class of radar-target geometries, functions termed multipath preservers were derived which indicate when multipath is physically observable in the radar returns; these functions assisted in evaluating the potential of multipath exploitation in urban sensing. Given a reecting geometry, the obtained lower bounds allow the radar operator to anticipate blind spots, place condence levels on the localization results, and permit sensor positioning to optimally aid in exploiting multipath for target localization. It was shown that variance bounds on the location parameters improve with richer resolvable multipath generating mechanisms. We also discussed various practical issues that arose in that context, including the multipath association problem, clutter, and the impact of wall roughness.

In [24] we extended our understanding of how to exploit multi path in urban scenarios by considering scenes in which the targets that are hidden due to lack of line of sight (LOS) path in urban environments; we sought to image these targets. Conventional processing via synthetic aperture beamforming algorithms do not detect or localize the target at its true position. To ameliorate these shortcomings, we presented two multipath exploitation techniques to image a hidden target at its true location under the assumptions that the target multipath is resolvable and detectable. The first technique directly operates on the radar returns, whereas the second operates on the traditional beamformed image. Both these techniques mitigate the false alarms arising from the multipath while simultaneously permitting the shadowed target to be detected at its true location. While these techniques are general, they were examined for two important urban radar applications: detecting shadowed targets in an urban canyon, and detecting shadowed targets around corners.

Finally, in [25] we considered the problem of passive localization of RF emitters based on exploitation of the multipath interaction of the signal with environment, as again, is likely to be found in an urban environment. The times of arrival of the different multipath components were used to perform localization based on a constellation of virtual sensors. The feasibility of the approach was examined and the concept of geometric dilution of precision (GDOP), which was introduced to characterize the performance degradations experienced in GPS due to poor satellite configurations, is used to examine the effect of the relative geometry of emitter, scatterers, and receiver. In the context of a mobile receiver, as would be the case for an UAV, the analysis pointed to some counterintuitive results on what trajectories provide the best information about the emitter position.

4 Publications

Numerous publications have emerged from this work, as seen in the References. We would like to note all publications are publicly available, and are also available on the PI's website `http://www.ece.uic.edu/Devroye`

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