WAVEFORM-AGILE SENSING: OPPORTUNITIES AND CHALLENGES

Douglas Cochran

DARPA Defense Sciences Office

ABSTRACT

Continuing advances in device technologies are producing active sources that are increasingly agile in their waveform transmission capabilities. Additionally, modern receivers are generally designed to support adaptive processing. This combination presents rich opportunities for new sensing methodologies that exploit agility of both transmitter and receiver to yield improved performance in such applications as detection, classification, and tracking. This paper outlines some of these opportunities and sketches some challenges entailed in realizing these opportunities and approaches being brought to bear on these challenges.

1. INTRODUCTION

Much recent research in sensing has addressed the integration of sensing and processing. Traditionally, most sensing systems have been designed and operated as feed-forward chains of largely independent functions. A typical such chain begins with the transduction of a physical phenomenon into an electrical signal, proceeds through digitization, digital signal processing (DSP), and then statistical processing to support back-end operations such as detection, classification, and tracking (Figure 1). The increasing availability of agile and configurable sensing elements enables a first level of integration of sensing and processing in which feedback mechanisms are added to allow the configuration of upstream elements (e.g., the sensors and DSP stages) to be controlled by the dynamically evolving requirements of the downstream processing (Figure 2). A second level of integration (Figure 3) can occur when processing functionality is incorporated into the transduction and digitization procedures in such a way, for example, that the number of digital bits produced is reduced while the essential information is retained. When this is possible, the DSP burden is effectively attenuated by carrying out some portion of the processing by manipulation of the sensor configuration.

A particular situation in which feedback of the kind depicted in Figure 2 is viable occurs in active sensing where the transmitted waveform sequence can be designed (or selected from a library) in a closed-loop fashion based on feedback from the receiver. Waveform-agile transmitters and receivers with adaptive processing capabilities are increasingly available across most active sensing modalities, including optical, acoustic, and radio-frequency (RF) systems.

The remainder of this paper outlines some of the emerging technologies that are creating opportunities for waveform-agile sensing, describes some of the generic mathematical challenges entailed in closed-loop scheduling of waveforms for active sensing, and sketches a few of the approaches being investigated in response to these challenges. Because this paper represents an overview for an ICASSP 2005 special session entitled “Advances in Waveform Agile Sensor Processing,” special emphasis will be given to aspects of the general topic to which the papers in the session [1-5] pertain.

2. WAVEFORM-AGILE SENSORS

Continuing advances in sensor technology are providing active sensors that are increasingly agile both in their waveform transmission capabilities and receiver response characteristics. This is true to various degrees across all sensing modalities, as illustrated by the three key modalities discussed in this Section.

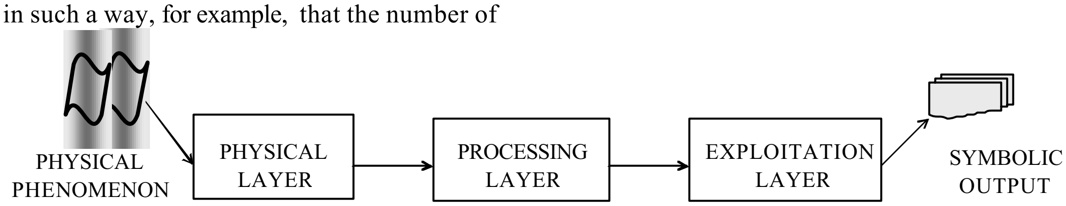

Figure 1. Traditional feed-forward sensor system structure.

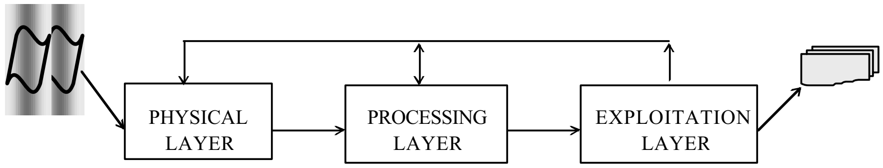

Figure 2. Integration of sensing and processing via feedback.

2.1. Optical sensing

Perhaps the most striking recent advances in device technologies directly relevant to active sensing are in the optical regime. Fast, high-resolution spatial light modulators (e.g., digital micromirror arrays) enable precision pulse shaping for waveform production at the transmitter (e.g., [6]) and can also be used as sensor-processor components at the receiver (e.g., [7]).

Figure 4 indicates how such a device might be used in an optical waveform source. Different wavelengths of white light are separated spatially by a prism and presented to the mirror array. The intensity of each wavelength in the scene illumination is controlled by the number of mirror elements receiving that wavelength that are tilted to reflect incident light toward the scene. The mirrors can often be pushed in and out to adjust phase as well as angle. Thus, if the array is presented by N spatially-separated coherent sources at wavelengths $\lambda_1, \ldots, \lambda_N$ then the scene $S(t)$ illumination can be designed as a Fourier series in the available wavelengths

$$S(t) = \sum_{n=1}^{N} A_n \cos(\omega_n t - \phi_n)$$

where the amplitudes A_n are controlled by the number of mirrors used to illuminate the scene (mirror tilt), the phases ϕ_n are controlled by the mirror displacement, and ω_n represents the frequency corresponding to wavelength λ_n.

In addition to high-speed, digitally-controlled spatial light modulators, new laser technology contributes opportunities for development of waveform-agile sources for active sensing. In particular, femtosecond pulse-shaped lasers of sufficient power to serve as sources for optical sensing at large standoff distances are in laboratory stages of development [8]. In addition to

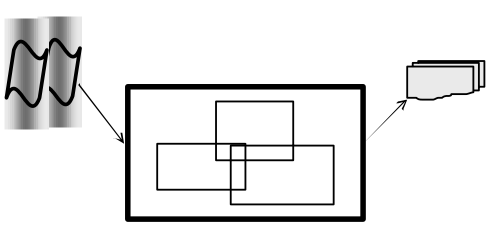

Figure 3. Integrated sensor/processor.

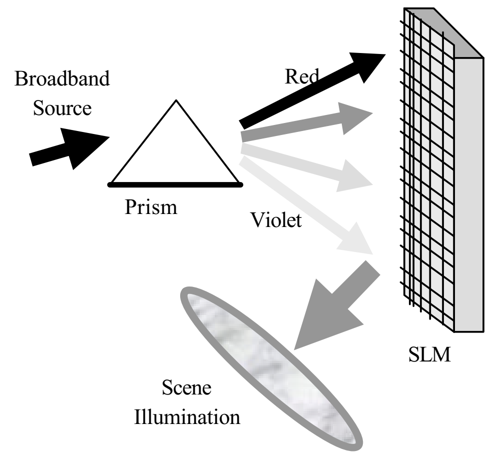

Figure 4. Use of a micromirror spatial light modulator in an optical source.

serving as sources for active optical sensing in their high-power manifestations, fast-pulse lasers can also be used to control sources of other kinds of radiation such as x-rays [9].

2.2. Radio-frequency sensing

Major thrusts in development of agile antennas and antenna arrays for radio-frequency (RF) sensing, both for active (i.e., radar) and passive (e.g., electronic intelligence gathering) applications have been undertaken in recent years by the U.S. Department of Defense as well as other government and commercial entities in several nations. Agile RF transmitters and receivers are also of great value for communications applications, and "waveform diversity" has become an important topic in both communications and sensing research. Development of multi-function transmitter and receiver systems (including apertures, amplifiers, and software-driven controller/processor suites) capable of performing both active and passive sensing functions as well as communications has been another focus of substantial recent research.

Development of new "agile" electronic materials has led to antennas whose spatial and frequency response characteristics are electrically tunable and highly nimble.

Electrical properties (e.g., dielectric constant) of such materials can be quickly adjusted through the application of an electrical stimulus signal. Ultimately, antennas constructed with such materials may have response characteristics that can electrically configured at practical real-time rates for RF sensing applications. At this time, however, such devices are still in the laboratory prototype phase of development.

The emergence of software-driven, digitally-controlled transmitter and receiver functions has led to much interest in new types of radar processing [10]. Such conceptually simple ideas as dynamically partitioning a source array as a configurable collection of virtual sub-arrays, possibly transmitting a different waveform from each element, have recently started to receive attention in view of the viability of sensor systems capable of supporting such approaches.

2.3. Acoustic sensing

In general, it is probably fair to say that waveform-agile source technology is not advancing as quickly in the acoustic regime as in the optical or RF domains. Air-coupled devices of certain types (e.g., speakers) have been capable of substantial agility for years; the advent of software-driven digital controller technology has been the main recent contributor to increasing the value of these components for active sensing applications.

Progress continues to be made in the development of coherent sources capable of sufficient transmission power for underwater sonar applications, but the engineering challenges are substantial and the versatility of sources in this regime is generally significantly less than in the RF and optical domains. Nevertheless, systems that provide limited libraries of selectable waveforms (e.g., constant-frequency pulses, linear and quadratic chirps with various parameters) are on the horizon and work on optimal scheduling with such libraries is being published (e.g., [4]).

3. CHALLENGES AND APPROACHES

Three essential challenges in developing practical waveform scheduling applications are quantification of criteria of importance in downstream processing, design of waveforms or waveform families that are optimal (or nearly optimal) with respect to these criteria, and computationally tractable identification of optimal (or nearly optimal) scheduling policies. Bodies of historical research apply to each of these challenges and they are individually and collectively receiving considerable current attention.

3.1. Quantification of downstream requirements

If one views closed-loop waveform scheduling in analogy with the game "Twenty Questions," the waveforms, perhaps in conjunction with receiver processing, are the questions. Deciding which is the best question to ask, even in a single-stage ("myopic" or "greedy") scheme, requires a metric of value for each waveform. In general, this metric will depend on the state of current knowledge; a waveform that is of great value in determining whether a unidentified target is bigger than a breadbox may be essentially useless once the target has been classified with confidence.

Past work has studied metrics based on rule-of-thumb performance criteria (e.g., expected impact of the measurement on the ambiguity function estimate) and on information-theoretic criteria (e.g., as in [11] and [12]). While current work continues along these lines, quantifying the relationship between waveform design and the downstream information most important to acquire (in the context of what is already known) remains a central challenge in waveform scheduling.

3.2. Waveform design

Design of waveforms for active sensing, particularly for radar and sonar, is a longstanding area of active research. For example, the desire to produce constant-power waveforms with desirable auto-ambiguity function characteristics or families of constant-power waveforms having desirable auto-ambiguity and cross-ambiguity function characteristics has motivated literally hundreds of papers over the past several decades. The key results of this body of work (e.g., Barker sequences, Welti codes, Welch bound) are household terms in sensing and communications circles. Design of waveform families with desirable generic characteristics continues to be important; methodology for dynamic tailoring of waveform design to specific downstream metrics is beginning to receive attention (as in [1] and [2]), but this remains a largely open challenge for waveform-agile sensing.

3.3. Multi-stage optimization

Dynamic, multi-stage resource allocation problems also have a rich history. Although some impressive results have been obtained (e.g., Gittens' proof of the existence of an index solution to the classical multi-arm bandit problem), few of these are computationally tractable for problems of practical size – even when the cost values required to implement them (e.g., metrics discussed above) can be computed. Computation of metrics is generally not a trivial matter, however. To apply a Bayesian approach with information-theoretic metrics, for example, it is typically necessary to propagate forward conditional density functions (or at least parameters thereof) in the presence of nonlinearities. The use of embedded simulation (e.g., particle filtering [13]) for this purpose has proven of value, though its use is computationally costly – especially for multi-stage problems.

Recent attacks on combinatorial and computational issues entailed in multi-stage scheduling problems (e.g., [3] and [5]) are showing considerable promise for obtaining approximate solutions, in some cases with error bounds, that are computationally viable for non-trivial problems. These approaches build on foundations from such established areas as optimal control theory, dynamic programming, and statistical design of experiments.

Despite recent encouraging results, obtaining algorithmic solutions compatible with the closed-loop sensing tempo supportable by many of the new transmitter technologies is still a tall order. Novel ideas, such as for scheduling of waveform blocks and for the use of novel analog or optical methods to physically encode performance criteria and adapt waveforms, have been discussed informally but even embryonic investigation of such possibilities remains to be undertaken.

4. CONCLUSIONS

Exploitation of waveform-agile sources is emerging as an important area of opportunity and challenge in the science, engineering, and practice of sensing. The papers [1-5] in this special session represent recent approaches to waveform design and scheduling for common applications; other applications spanning all aspects of sensing present prospects for integration of sensing and processing, in general, and waveform-agile sensing, in particular. While each of these will present specialized technical challenges, they will also benefit from the advancement of fundamental methodologies for multi-stage scheduling of resources, waveform design, and quantification of the relationship between downstream performance requirements and sensor configuration (including waveform and receiver processing, possibly among other parameters).

5. ACKNOWLEDGMENTS

The author is grateful to his DARPA colleagues Dennis Healy and Carey Schwartz for their ongoing collaboration on the area of this paper. He also thanks the researchers who have participated in the DARPA Integrated Sensing and Processing program.

6. REFERENCES

[1] G. Dietl, J. Wang, P. Ding, M.D. Zoltowski, D.J. Love, and W. Utschick, "Hybrid transmit waveform design based on beamforming and orthogonal space-time block coding," Proc. IEEE ICASSP, Philadelphia, April 2005.

[2] S.D. Howard, A.R. Calderbank, W. Moran, H.A. Schmitt, and C.O. Savage, "Relationships between radar ambiguity and coding theory," Proc. IEEE ICASSP, Philadelphia, April 2005.

[3] C. Kreucher and A.O. Hero III, "Non-myopic approaches to scheduling agile sensors for multistage detection, tracking and identification," Proc. IEEE ICASSP, Philadelphia, April 2005.

[4] S.P. Sira, A. Papandreou-Suppappola, and D. Morrell, "Time-varying waveform selection and configuration for agile sensors in tracking applications," Proc. IEEE ICASSP, Philadelphia, April 2005.

[5] S. Suvorova, D. Mušicki, B. Moran, and S. Howard, "Multi step ahead beam and waveform scheduling for tracking of manoeuvering targets in clutter," Proc. IEEE ICASSP, Philadelphia, April 2005.

[6] R. Belikov, C. Antoine-Snowden, and O. Solgaard, "Femtosecond direct space-to-time pulse with MEMS micromirror arrays," *Proc. IEEE/LEOS Int. Conf. Optical MEMS*, pp. 18-21, Aug. 2003.

[7] S.K. Nayar, V. Branzoi, and T.E. Boult, "Programmable imaging using a digital micromirror array," *Proc. IEEE Computer Society Conf. Computer Vision and Pattern Recognition*, vol. 1, pp. 436-443, June-July 2004.

[8] J. Garduño-Mejía, A.H. Greenaway, and D. T. Reid, "Designer femtosecond pulses using adaptive optics," *Optics Express,* vol. 11, no. 17, pp. 2030-2040, 25 August 2003.

[9] A. Egbert, B. Mader, C. Fallnich, A. Ostendorf, B.N. Chichkov, K. Eidmann, H. Stiel, and P.V. Nickles, "Compact, high-repetition rate, ultrashort hard-x-ray source driven by femtosecond laser pulses," *IEEE Lasers and Electro-Optics Conf. Technical Digest,* pp. 337-338, May 2002.

[10] M.C. Wicks and B. Hamid, "Four problems in radar," in J.S. Byrnes, ed., *Proc. NATO Advanced Study Institute on Computational Noncommutative Algebra and Applications,* Il Ciocco, Italy, July 2003, NATO Science Series II: *Mathematics, Physics and Chemistry* 136.

[11] M.R. Bell, "Information theory and radar waveform design," *IEEE Trans. Inf. Theory,* vol. IT-39(5), pp. 1578-1597, Sept. 1993.

[12] S.M. Sowelam and A.H. Tewfik, "Waveform selection in radar target classification," *IEEE Trans. Inf. Theory,* vol. IT-46(3), pp. 1014-1029, May 2000.

[13] M. Arulampalam, S. Maskell, N. Gordon, and T. Clapp, "A tutorial on particle filters for online nonlinear/non-Gaussian Bayesian tracking," *IEEE Trans. Sig. Proc.,* vol. SP-50, pp. 174-188, Feb. 2002.