Advances in Waveform-Agile Sensing for Tracking

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SYNTHESIS LECTURES ON ALGORITHMS AND SOFTWARE IN ENGINEERING #2

MORGAN & CLAYPOOL PUBLISHERS

ABSTRACT

Recent advances in sensor technology and information processing afford a new flexibility in the design of waveforms for agile sensing. Sensors are now developed with the ability to dynamically choose their transmit or receive waveforms in order to optimize an objective cost function. This has exposed a new paradigm of significant performance improvements in active sensing: dynamic waveform adaptation to environment conditions, target structures, or information features.

The manuscript provides a review of recent advances in waveform-agile sensing for target tracking applications. A dynamic waveform selection and configuration scheme is developed for two active sensors that track one or multiple mobile targets. A detailed description of two sequential Monte Carlo algorithms for agile tracking are presented, together with relevant Matlab code and simulation studies, to demonstrate the benefits of dynamic waveform adaptation.

The work will be of interest not only to practitioners of radar and sonar, but also other applications where waveforms can be dynamically designed, such as communications and biosensing.

KEYWORDS

Adaptive waveform selection, waveform-agile sensing, target tracking, particle filtering, sequential Monte Carlo methods, frequency-modulated chirp waveforms.

Bibliography

[1] A. Drozd, "Waveform diversity and design," IEEE EMC Society Newsletter, Summer 2006. [Online]. Available: http://www.ieee.org/organizations/pubs/newsletters/emcs/summer06/cover_story.pdf

[2] D. Cochran, "Reducing complexity for defense," *DARPATech 2002 Symposium*, Jul. 2002. [Online]. Available: http://web-ext2.darpa.mil/DARPATech2002/presentations/dso_pdf/speeches/COCHRAN.pdf

[3] Y. Bar-Shalom and T. E. Fortmann, *Tracking and Data Association*. Boston: Academic Press, 1988.

[4] R. L. Mitchell and A. W. Rihaczek, "Matched filter responses of the linear FM waveform," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 4, pp. 417–432, May 1968.

[5] D. F. DeLong and E. M. Hofstetter, "On the design of optimum radar waveforms for clutter rejection," *IEEE Trans. Inform. Theory*, vol. IT-13, no. 3, pp. 454–463, Jul. 1967. DOI: 10.1109/TIT.1967.1054038

[6] R. McAulay and J. Johnson, "Optimal mismatched filter design for radar ranging, detection, and resolution," *IEEE Trans. Inform. Theory*, vol. 17, pp. 696–701, Nov. 1971. DOI: 10.1109/TIT.1971.1054722

[7] M. Athans and F. C. Schweppe, "Optimal waveform design via control theoretic principles," *Information and Control*, vol. 10, pp. 335–377, Apr. 1967. DOI: 10.1016/S0019-9958(67)90183-0

[8] F. C. Schweppe and D. L. Gray, "Radar signal design subject to simultaneous peak and average power constraints," *IEEE Trans. Inform. Theory*, vol. IT-12, pp. 13–26, Jan. 1966. DOI: 10.1109/TIT.1966.1053853

[9] M. R. Bell, "Information theory and radar waveform design," *IEEE Trans. Inform. Theory*, vol. 39, pp. 1578–1597, Sep. 1993. DOI: 10.1109/18.259642

[10] K. T. Wong, "Adaptive pulse-diverse radar/sonar waveform design," in *IEEE Radar Conference*, pp. 105–110, May 1998. DOI: 10.1109/NRC.1998.677985

[11] N. Wang, Y. Zhang, and S. Wu, "Radar waveform design and target detection using wavelets," in *CIE International Conference on Radar*, pp. 506–509, Oct. 2001. DOI: 10.1109/ICR.2001.984758

[12] R. J. Bonneau, "A wavelet packet basis optimization approach to radar waveform design," in *IEEE International Symposium on Antennas and Propagation*, vol. 4, pp. 814–816, Jul. 2001. DOI: 10.1109/APS.2001.959589

[13] S. M. Sowelam and A. H. Tewfik, "Waveform selection in radar target classification," *IEEE Trans. Inform. Theory*, vol. 46, pp. 1014–1029, May 2000. DOI: 10.1109/18.841178

[14] D. Garren, M. Osborn, A. Odom, J. Goldstein, S. Pillai, and J. Guerci, "Enhanced target detection and identification via optimised radar transmission pulse shape," *IEE Proceedings-Radar Sonar and Navigation*, vol. 148, no. 3, pp. 130–138, 2001. DOI: 10.1049/ip-rsn:20010324

[15] S.-M. Hong, R. J. Evans, and H.-S. Shin, "Control of waveforms and detection thresholds for optimal target tracking in clutter," in *Proceedings of the 39th IEEE Conference on Decision and Control*, vol. 4, pp. 3906–3907, Dec. 2000. DOI: 10.1109/CDC.2000.912323

[16] S.-M. Hong, R. J. Evans, and H.-S. Shin, "Optimization of waveform and detection threshold for target tracking in clutter," in *Proceedings of the 40th SICE Annual Conference*, pp. 42–47, Jul. 2005. DOI: 10.1109/SICE.2001.977803

[17] D. J. Kershaw and R. J. Evans, "Optimal waveform selection for tracking systems," *IEEE Trans. Inform. Theory*, vol. 40, no. 5, pp. 1536–1550, Sep. 1994. DOI: 10.1109/18.333866

[18] D. J. Kershaw and R. J. Evans, "Waveform selective probabilistic data association," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 33, pp. 1180–1188, Oct. 1997. DOI: 10.1109/7.625110

[19] C. Rago, P. Willett, and Y. Bar-Shalom, "Detection-tracking performance with combined waveforms," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 34, pp. 612–624, Apr. 1998. DOI: 10.1109/7.670395

[20] R. Niu, P. Willett, and Y. Bar-Shalom, "Tracking considerations in selection of radar waveform for range and range-rate measurements," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 38, no. 2, pp. 467–487, Apr. 2002. DOI: 10.1109/TAES.2002.1008980

[21] S. D. Howard, S. Suvorova, and W. Moran, "Waveform libraries for radar tracking applications," *International Conference on Waveform Diversity and Design*, Edinburgh, UK, Nov. 2004. DOI: 10.1109/CISS.2006.286688

[22] S. P. Sira, A. Papandreou-Suppappola, and D. Morrell, "Dynamic configuration of time-varying waveforms for agile sensing and tracking in clutter," *IEEE Trans. Signal Processing*, vol. 55, no. 1, pp. 3207–3217, Jun. 2007. DOI: 10.1109/TSP.2007.894418

[23] S. M. Hong, R. J. Evans, and H. S. Shin, "Optimization of waveform and detection threshold for range and range-rate tracking in clutter," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 41, no. 1, pp. 17–33, Jan. 2005. DOI: 10.1109/TAES.2005.1413743

[24] B. F. L. Scala, W. Moran, and R. J. Evans, "Optimal adaptive waveform selection for target detection," in *International Conference on Radar*, pp. 492–496, 2003. DOI: 10.1109/RADAR.2003.1278791

[25] A. Doucet, N. de Freitas, and N. Gordon, Eds., *Sequential Monte Carlo Methods in Practice*. Springer-Verlag, 2001.

[26] M. S. Arulampalam, S. Maskell, N. Gordon, and T. Clapp, "A tutorial on particle filters for online nonlinear/non-Gaussian Bayesian tracking," *IEEE Trans. Signal Processing*, vol. 50, pp. 174–188, Feb. 2002. DOI: 10.1109/78.978374

[27] E. Kalman, Rudolph, "A new approach to linear filtering and prediction problems," *Transactions of the ASME–Journal of Basic Engineering*, vol. 82, no. Series D, pp. 35–45, 1960.

[28] R. van der Merwe, N. de Freitas, A. Doucet, and E. Wan, "The Unscented Particle Filter," in *Advances in Neural Information Processing Systems 13*, Nov. 2001.

[29] S. Julier and J. Uhlmann, "A new extension of the Kalman filter to nonlinear systems," *International Symposium on Aerospace/Defense Sensing, Simulation and Controls*, 1997. DOI: 10.1117/12.280797

[30] L. J. Ziomek, *Underwater Acoustics: A Linear Systems Theory Approach*.Orlando, FL: Academic Press, 1985.

[31] R. O. Nielsen, *Sonar Signal Processing*. Artech House, 1991.

[32] M. I. Skolnik, *Radar Handbook*, 2nd ed., M. I. Skolnik, Ed. New York: McGraw Hill, 1990.

[33] A. Papandreou-Suppappola, R. L. Murray, B. G. Iem, and G. F. Boudreaux-Bartels, "Group delay shift covariant quadratic time-frequency representations," *IEEE Trans. Signal Processing*, vol. 49, pp. 2549–2564, 2001. DOI: 10.1109/78.960403

[34] A. Papandreou-Suppappola, *Time-Varying Processing: Tutorial on Principles and Practice in Applications in Time-Frequency Signal Processing*, A. Papandreou-Suppappola, Ed. Florida: CRC Press, 2002.

[35] R. A. Altes and E. L. Titlebaum, "Bat signals as optimally Doppler tolerant waveforms," *Journal of the Acoustical Society of America*, vol. 48, pp. 1014–1020, Oct. 1970. DOI: 10.1121/1.1912222

[36] H. L. Van Trees, *Detection Estimation and Modulation Theory, Part III*. New York: Wiley, 1971.

[37] L. G. Weiss, "Wavelets and wideband correlation processing," *IEEE Signal Processing Mag.*, pp. 13–32, Jan. 1994. DOI: 10.1109/79.252866

[38] L. Cohen, *Time-Frequency Analysis*. Englewood Cliffs, New Jersey: Prentice-Hall, 1995.

[39] D. W. Ricker, *Echo Signal Processing*. Kluwer Academic Publishers, 2003.

[40] P. L'Ecuyer, "An overview of derivative estimation," *Proceedings of the 1991 Winter Simulation Conference*, pp. 207–217, Dec. 1991. DOI: 10.1109/WSC.1991.185617

[41] G. Pflug, *Optimization of Stochastic Models: The Interface Between Simulation and Optimization*. Kluwer Academic Publishers, 1996.

[42] J. C. Spall, "Multivariate stochastic approximation using a simultaneous perturbation gradient approximation," *IEEE Trans. Automat. Contr.*, vol. 37, pp. 332–341, Mar. 1992. DOI: 10.1109/9.119632

[43] J. Kiefer and J. Wolfowitz, "Stochastic estimation of a regression function," *Annals of Mathematical Statistics*, vol. 23, pp. 462–466, Sep. 1952. DOI: 10.1214/aoms/1177729392

[44] P. Sadegh and J. C. Spall, "Constrained optimization via stochastic approximation with a simultaneous perturbation gradient approximation," *Automatica*, vol. 33, no. 5, pp. 889–892, 1997. DOI: 10.1016/S0005-1098(96)00230-0

[45] S. P. Sira, D. Morrell, and A. Papandreou-Suppappola, "Waveform design and scheduling for agile sensors for target tracking," *Asilomar Conference on Signals, Systems and Computers*, vol. 1, pp. 820–824, Nov. 2004. DOI: 10.1109/ACSSC.2004.1399251

[46] B. D. Anderson and J. B. Moore, *Optimal Filtering*. New Jersey: Prentice-Hall, 1979.

[47] S. P. Sira, A. Papandreou-Suppappola, and D. Morrell, "Time-varying waveform selection and configuration for agile sensors in tracking applications," *IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. 5, pp. 881–884, Mar. 2005. DOI: 10.1109/ICASSP.2005.1416445

[48] D. A. Swick, "A review of wideband ambiguity functions," Naval Research Laboratory, Washington, D.C., Tech. Rep. 6994, Dec. 1969.

[49] Q. Jin, K. M. Wong, and Z.-Q. Luo, "The estimation of time delay and doppler stretch of wideband signals," *IEEE Trans. Signal Processing*, vol. 43, no. 4, pp. 904–916, Apr. 1995. DOI: 10.1109/78.376843

[50] Y. Doisy, L. Deruaz, S. P. Beerens, and R. Been, "Target doppler estimation using wideband frequency modulated signals," *IEEE Trans. Signal Processing*, vol. 48, no. 5, pp. 1213–1224, May 2000. DOI: 10.1109/78.839970

[51] C. E. Cook and M. Bernfeld, *Radar Signals, An Introduction to Theory and Application*. Boston: Artech House, 1993.

[52] S. P. Sira, A. Papandreou-Suppappola, and D. Morrell, "Waveform scheduling in wideband environments," *IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. 1, pp. I–697 – I–700, May 2006. DOI: 10.1109/ICASSP.2006.1661477

[53] S. P. Sira, A. Papandreou-Suppappola, and D. Morrell, "Characterization of waveform performance in clutter for dynamically configured sensor systems," *Waveform Diversity and Design Conference*, Lihue, Hawaii, Jan. 2006.

[54] R. Niu, P. Willett, and Y. Bar-Shalom, "Matrix CRLB scaling due to measurements of uncertain origin," *IEEE Trans. Signal Processing*, vol. 49, no. 7, pp. 1325–1335, Jul. 2001. DOI: 10.1109/78.928687

[55] T. Fortmann, Y. Bar-Shalom, M. Scheffe, and S. Gelfand, "Detection thresholds for tracking in clutter - A connection between estimation and signal processing," *IEEE Trans. Automat. Contr.*, vol. 30, pp. 221–229, Mar. 1985. DOI: 10.1109/TAC.1985.1103935

[56] D. J. Kershaw and R. J. Evans, "A contribution to performance prediction for probabilistic data association tracking filters," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 32, no. 3, pp. 1143–1147, Jul. 1996. DOI: 10.1109/7.532274

[57] S. P. Sira, A. Papandreou-Suppappola, and D. Morrell, "Waveform-agile sensing for tracking multiple targets in clutter," *Conference on Information Sciences and Systems*, Princeton, NJ, pp. 1418–1423, Mar. 2006. DOI: 10.1109/CISS.2006.286687

[58] C. Kreucher, K. Kastella, and Alfred O. Hero, III, "Multitarget tracking using the joint multitarget probability density," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 41, no. 4, pp. 1396–1414, Oct. 2005. DOI: 10.1109/TAES.2005.1561892

[59] J. A. Simmons and R. Stein, "Acoustic imaging in bat sonar: Echolocation signals and the evolution of echolocation," *Journal of Comparative Psychology*, vol. 135, no. 1, pp. 61–84, Mar. 1980. DOI: 10.1007/BF00660182

[60] J. A. Simmons, P. A. Saillant, and S. P. Dear, "Through a bat's ear," *IEEE Spectrum*, vol. 29, pp. 46–48, Mar. 1992. DOI: 10.1109/6.123330