Multivariate Sensing for Injection Molding Process Monitoring and Quality Prediction

This research, supported by NSF under grants DMI-0428366, CMMI-9988757, and CMMI-1000816, aims to test the hypothesis that improved observability in manufacturing processes correlates with higher product quality and productivity, using polymer processing as an example. As result of this research, a multivariate sensor (MVS) for direct structural integration into the cavity of an injection mold for in-situ quantification of several parameters that are critical to the quality attribute of injection molded parts, has been conceptualized, designed, characterized, prototyped, and installed within the mold cavity of a production grade injection molding machine (see **Fig. 1**). The MVS is able to quantify the rapidly changing dynamics of the pressure and temperature of the polymer melt, from which the melt flow velocity and melt viscosity are derived. The embedded sensing capability is realized by a piezoelectric stack that serve as both a pressure sensor and a power generator, an infrared photodetector for temperature measurement, and an application-specific integrated circuit (ASIC) chip with a microcontroller for high-speed acquisition of the four process parameters. By means of coded acoustic waves (**Fig. 2**), the four process parameters are wirelessly transmitted through the mold steel to a data receiver outside of the mold where space constraint is relaxed. The coded acoustic signals are de-coded on the receiver's end using wavelet transform, and processed by means of a mechanistic model for in-situ estimation of co-states such as injection energy and residual stress.

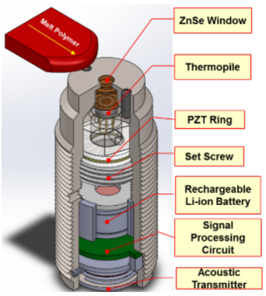

Fig. 1 Overview of MVS

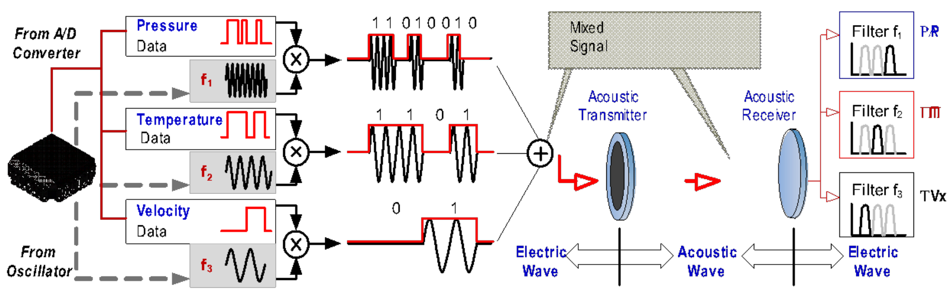

Fig. 2 Working principle of acoustic-based wireless multi-physics sensing data transmission out of mold cavity

Comparing to commercial sensors that measure only one parameter per sensor unit and need cable connection drilled through the mold structure for power supply and signal output, the in-mold MVS sensor is self-powered and uses coded ultrasound waves as the wireless carrier for signal transmission. The multi-modality nature of the MVS has resulted in up to 21.6% higher accuracy in the prediction of quality attributes of the molded part (e.g., part dimensions).

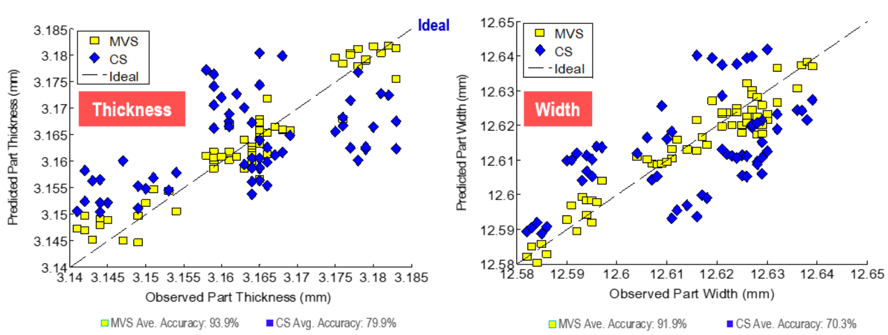

Fig. 3 Comparison of part quality prediction between multivariate sensor (MVS) and commercial sensors

Considering that more than 30% of plastic products worldwide are produced by injection molding, that the plastics industry is the third largest manufacturing industry in the United States operating over 17,000 facilities and providing nearly $374 billion in annual shipments, as well as the tight industry standards for maintaining part dimensional variances at the micrometer level, the quality prediction method enabled by MVS has provided the materials basis for significantly improved quality assurance and waste reduction.

Representative Publications

[1] R. X. Gao, Z. Fan, and D. Kazmer, "Method and System for Multivariate Remote Monitoring of Polymer Processing", U.S. Patent No. 9,446,544, September 20, 2016.

[2] P. Wang, Z. Fan, D. O. Kazmer, and R. X. Gao, "Orthogonal Analysis of Multisensor Data Fusion for Improved Quality Control," *Journal of Manufacturing Science and Engineering*, vol. 139, no. 10, p. 101008, Oct. 2017, doi: 10.1115/1.4036907.

[3] G. Gordon, D. O. Kazmer, X. Tang, Z. Fan, and R. X. Gao, "Quality control using a multivariate injection molding sensor," *Int J Adv Manuf Technol*, vol. 78, no. 9–12, pp. 1381–1391, Jun. 2015, doi: 10.1007/s00170-014-6706-6.

[4] S. P. Johnston, D. O. Kazmer, and R. X. Gao, "Online simulation-based process control for injection molding," *Polym. Eng. Sci.*, vol. 49, no. 12, pp. 2482–2491, Dec. 2009, doi: 10.1002/pen.21481.

[5] R. X. Gao, Z. Fan, and D. O. Kazmer, "Injection molding process monitoring using a self-energized dual-parameter sensor," *CIRP Annals*, vol. 57, no. 1, pp. 389–393, 2008, doi: 10.1016/j.cirp.2008.03.055.

[6] L. Zhang, C. B. Theurer, R. X. Gao, and D. O. Kazmer, "Analytic Wavelet-Based Ultrasonic Pulse Differentiation for Injection Mold Cavity Pressure Measurement," *Journal of Manufacturing Science and Engineering*, vol. 128, no. 1, pp. 370–374, Feb. 2006, doi: 10.1115/1.2123048.

[7] Li Zhang, C. B. Theurer, R. X. Gao, and D. O. Kazmer, "Design of ultrasonic transmitters with defined frequency characteristics for wireless pressure sensing in injection molding," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 52, no. 8, pp. 1360–1371, Aug. 2005, doi: 10.1109/TUFFC.2005.1509795.

[8] L. Zhang, C. Theurer, R. X. Gao, and D. O. Kazmer, "Frequency design of an ultrasonic transmitter for injection molding pressure measurement," *Transactions of the North American Manufacturing Research Institution*, Society of Manufacturing Engineers, Vol. 31, pp. 579-586, 2003.