



IEEE ICMA 2006 Tutorial Workshop

Iterative Learning Control

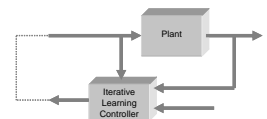
Algebraic Analysis and Optimal Design

Presenters: Kevin L. Moore, Colorado School of Mines, USA
YangQuan Chen, Utah State University, USA

Contributor: Hyo-Sung Ahn, ETRI, Korea

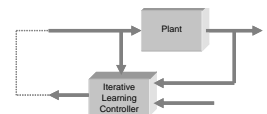
IEEE 2006 International Conference on Mechatronics and Automation
LuoYang, China

25 June 2006



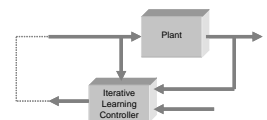
Further Research on ILC, If Any?

Y_d	D	N	C	H	
$Y_d(z)$	0	0	$\Gamma(w - 1)^{-1}$	H_p	Classical Arimoto algorithm
$Y_d(z)$	0	0	$\Gamma(w - 1)^{-1}$	$H_p(w)$	Owens' multipass problem
$Y_d(z)$	$D(w)$	0	$C(w)$	H_p	General (higher-order) problem
$Y_d(w)$	$D(w)$	0	$C(w)$	H_p	General (higher-order) problem
$Y_d(w)$	$D(w)$	$N(w)$	$C(w)$	$H_p(w) + \Delta(w)$	Most general problem
$Y_d(z)$	$D(z)$	0	$C(w)$	$H(w) + \Delta(w)$	Frequency-domain uncertainty
$Y_d(z)$	0	$w(t), v(t)$	$\Gamma(w - 1)^{-1}$	H_p	Least quadratic ILC
$Y_d(z)$	0	$w(t), v(t)$	$C(w)$	H_p	Stochastic ILC (general)
$Y_d(z)$	0	0	$\Gamma(w - 1)^{-1}$	H^I	Interval ILC
$Y_d(z)$	$D(z)$	$w(t), v(t)$	$C(w)$	$H(z) + \Delta H(z)$	Time-domain H_∞ problem
$Y_d(z)$	$D(w)$	$w(k, t), v(k, t)$	$C(w)$	$H(w) + \Delta H(w)$	Iteration-domain H_∞ ILC
$Y_d(z)$	0	$w(k, t), v(k, t)$	$\Gamma(k)$	$H_p + \Delta H(k)$	Iteration-varying uncertainty and control
$Y_d(z)$	0	\tilde{H}	Γ	H_p	Intermittent measurement problem
\vdots	\vdots	\vdots	\vdots	\vdots	\vdots



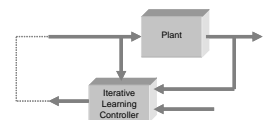
Further Research on ILC, If Any?

- ILC relatively matured.
- Inherently “robust”, less model-based, tolerant to slight nonlinearities.
- Transient and monotonic issues were not well handled but are now gaining attention.
- Applications to PDE systems not well understood.
- ILC for fractional order dynamic systems (polymer/piezo/silicon gel etc)
- ILC for large-scale uncertain spatial-temporal interconnected systems.
- ILC in network control systems (NCS) setting (telepresence/tele-training)
- Nonlinear updating laws? Why bother? Nonlinear feedback takes care of it.
- Repetitive control obeys the “waterbed effect”. ILC may not, due to the resetting operation, but ILC must obey the waterbed effect in the iteration domain.



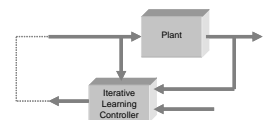
Other Ideas

- Intermittent ILC? (intermittent sensing, actuation, learning updating)
- ILC with nonuniform sampling, asynchronous ILC?
- Joint time-frequency domain ILC (techniques: wavelet, TFR, even fractional order Fourier transformation – our IEEE CIRA01 paper “Frequency-domain adaptive learning feedforward control”)
- Cooperative ILC with over-populated (or densely distributed) sensors and actuators, possibly networked, each with dynamic neighbors under uncertain communication topologies.
- Iterative learning consensus building for collective iterative learning control
- Memory and communication are getting cheaper and cheaper: can envision “ubiquitous collaborative iterative learning”.
- ...
- ...



Thank you!

- ILC web: www.csois.usu.edu/ilc
 - Maintained by Prof. YangQuan Chen
 - Links to presentations from 2003 ILC Summer School organized by Prof. Kevin Moore
 - Many other links
- Hyo-Sung Ahn's 2006 Ph.D. Dissertation:
 - <http://www.csois.usu.edu/people/hyosung/phd.pdf> (324 pages, 586 references cited.)
- Forthcoming new ILC monograph on robust ILC, Springer 07 (expected)





References by the Presenters

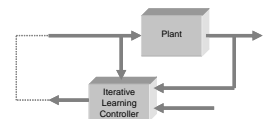


Books and Surveys

- “Iterative learning control: brief survey and categorization 1998 – 2004,” Hyo-Sung Ahn, YangQuan Chen, and Kevin L. Moore, accepted to appear, *IEEE Transaction on System, Man, and Cybernetics*.
- “Editorial: Special Issue on Iterative Learning Control,” Kevin L. Moore and Jian-Xin Xu, *International Journal of Control*, Vol. 73, No. 10, 819-823, July 2000.
- Iterative Learning Control: Convergence, Robustness and Applications*, Yangquan Chen and Changyun Wen, Springer-Verlag, Lecture Notes Series on Control and Information Science, vol. LNCIS-248, 1999.
- “Iterative Learning Control – An Expository Overview,” Kevin L. Moore, invited paper in *Applied and Computational Controls, Signal Processing, and Circuits*, vol. 1, pp. 151-214, 1999.
- Iterative Learning Control for Deterministic Systems*, Kevin L. Moore, Springer-Verlag Series on Advances in Industrial Control, Springer-Verlag, London, January 1993.
- “Iterative Learning Control: A Survey and New Results,” Kevin L. Moore, Mohammed Dahleh, and S.P. Bhattacharyya, *Journal of Robotic Systems*, vol. 9, no. 5, pp. 563-594, July 1992.

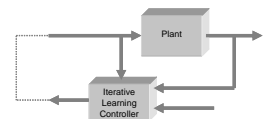
Other Workshops

- “Iterative Learning Control International Summer School: Tutorial Presentations,” collected presentation packet prepared for and distributed at the 2003 International Summer School on Iterative Learning Control, Logan, Utah, June 9-13, 2003.
- “Iterative Learning Control: Theory, Design, and Application, A CDC 2000 Tutorial Workshop,” collected presentation packet prepared for and distributed at a workshop presented at the IEEE 2000 Conference on Decision and Control, Sydney, Australia, Dec. 2000.
- “Iterative Learning Control Workshop and Roundtable: Extended Summaries,” collection of extended summaries of papers presented at the ILC Workshop and Roundtable, Tampa, FL, December 14-15, 1998.
- “Iterative Learning Control Workshop and Roundtable: Workshop Presentations,” collection of presentations given at the ILC Workshop and Roundtable, Tampa, FL, December 14-15, 1998.



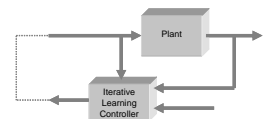
Robust ILC

- “Stability analysis of iterative learning control systems with interval uncertainty,” Hyo-Sung Ahn, Kevin L. Moore, and YangQuan Chen, accepted to appear in *Automatica*.
- “Monotonic Convergent Iterative Learning Controller Design Based on Interval Model Conversion,” Hyo-Sung Ahn, Kevin L. Moore, and YangQuan Chen, *IEEE Transactions on Automatic Control*, vol. 51, no. 2, pp. 366-371, February 2006.
- “A Robust Schur Stability Condition for Interval Polynomial Matrix Systems,” Hyo-Sung Ahn, Kevin L. Moore, and YangQuan Chen, in *Proceedings of 2006 IEEE Int. Conference on Mechatronics and Automation*, Luoyang, China, June 2006.
- “Maximum Singular Value and Power of an Interval Matrix,” Hyo-Sung Ahn, YangQuan Chen, and Kevin L. Moore, in *Proceedings of 2006 IEEE Int. Conference on Mechatronics and Automation*, Luoyang, China, June 2006.
- “Kalman Filter Augmented Iterative Learning Control on the Iteration Domain,” H.-S. Ahn, Y.Q. Chen, and K.L. Moore, *Proceedings 2006 American Control Conference*, Minneapolis, MN, June 2006.
- “Stability Analysis of Iterative Learning Control System with Interval Uncertainty,” H-S Ahn, KL Moore, and YQ Chen, in *Proceedings of 2005 IFAC World Congress*, Prague, Czech. July 2005.
- “Algebraic H-Infinity Design of Higher-Order Iterative Learning Controllers,” K.L. Moore, H.-S. Ahn, and Y.-Q. Chen, in *Proceedings 2005 IEEE International Symposium on Intelligent Control*, Cyprus, Greece, June 2005.
- “Monotonic Convergent Iterative Learning Controller Design Based on Interval Model Conversion,” H.-S. Ahn, K.L. Moore, and Y.-Q. Chen, in *Proceedings 2005 IEEE International Symposium on Intelligent Control*, Cyprus, Greece, June 2005.
- “Schur Stability Radius Bounds for Robust Iterative Learning Controller Design,” H-S Ahn, K L. Moore, and YQ Chen, in *Proceedings of 2005 American Control Conference*, Portland, Oregon, June 2005.
- “Robust Iterative Learning Control Design with the Iteration-Varying Uncertainty,” H-S Ahn, KL Moore, and YQ Chen, in *Proceedings of 2005 International Conference on Mechatronics and Automation*, Niagra Fall, Ontario, Canada. July 2005.



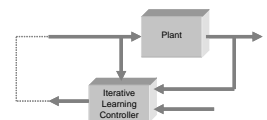
Monotonic and Optimal ILC

- “LMI Approach to Iterative Learning Control Design,” Hyo-Sung Ahn, K.L. Moore, and Y.Q. Chen, *Proceedings of 2006 IEEE Mountain Workshop on Adaptive and Learning Systems*, Utah State University, Logan, Utah, July 2006.
- “Monotonically Convergent Iterative Learning Control for Linear Discrete-Time Systems,” Kevin L. Moore, YangQuan Chen, and Vikas Bahl, *Automatica*, vol. 41, pp. 1529-1537 2005.
- “An Algebraic Approach to Iterative Learning Control,” Jari Hatonen, David H. Owens, and Kevin L. Moore, *International Journal of Control* vol. 77, no. 10, pp. 45-54, January 2004.
- “A Separative High-Order Framework for Monotonic Convergent Iterative Learning Controller Design,” Kevin L. Moore and YangQuan Chen, in *Proceedings of the 2003 American Control Conference*, Denver, Colorado, June 4 to 6, 2003.
- “Harnessing the Repetitiveness in Iterative Learning Control,” YangQuan Chen and Kevin L. Moore, in *Proceedings of 2002 IEEE Conference on Decision and Control*, Las Vegas, NV, Dec 22-14, 2002.
- “An Optimal Design of PD-type Iterative Learning Controller With Monotonic Convergence,” YangQuan Chen and Kevin L. Moore, in *Proceedings of the 17th IEEE International Symposium on Intelligent Control*, IEEE ISIC'02, Vancouver, British Columbia October 27-30, 2002.
- “An Algebraic Approach to Iterative Learning Control,” Jari Hatonen, David H. Owens, and Kevin L. Moore in *Proceedings of the 17th IEEE International Symposium on Intelligent Control*, IEEE ISIC'02, Vancouver, British Columbia October 27-30, 2002.
- “Feedback Controller Design to Ensure Monotonic Convergence in Discrete-Time, P-Type Iterative Learning Control,” Kevin L. Moore, YangQuan Chen, and Vikas Bahl in *Proceedings of 4th Asian Control Conference*, Singapore, Sept 2002.



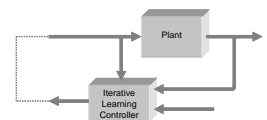
Monotonic and Optimal ILC (cont.)

- “An Investigation on the Monotonic Convergence of an High-Order Iterative Learning Update Law,” Kevin L. Moore and YangQuan Chen, in *Proceedings of the 2002 15th IFAC World Congress*, Barcelona, Spain, July 21-26, 2002.
- “Analysis of Linear Iterative Learning Scheme using Repetitive Process Theory,” D. Owens, E. Rogers, and Kevin L. Moore, *Asian Journal of Control* vol. 4, No. 1, Mar. 2002, pp. 90-98.
- “PI-type Iterative Learning Control Revisited,” YangQuan Chen and Kevin L. Moore in *Proceedings of the 2002 American Control Conference*, Anchorage, Alaska, May 8-10, 2002.
- “On D^{α} -type Iterative Learning Control,” YangQuan Chen and Kevin L. Moore, in *Proceedings of IEEE Conference on Decision and Control*, pp. 4451-4456, Orlando, FL, Dec. 3-7, 2001.
- “An Observation about Monotonic Convergence in Discrete-Time, P-Type Iterative Learning Control,” Kevin L. Moore, in *Proceedings of 2001 IEEE International Symposium on Intelligent Control*,” Mexico City, Mexico, September 2001.
- “Improved Path Following for an Omni-Directional Vehicle via Practical Iterative Learning Control Using Local Symmetrical Double-Integration, YangQuan Chen and Kevin L. Moore, in *Proceedings of the 3rd Asian Control Conference*, p. 1878-1883, Shanghai, China, July 2000.



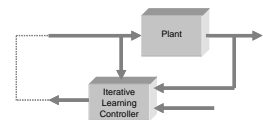
Foundations

- “Unified Formulation of Linear Iterative Learning Control,” Minh Q. Phan, Richard W. Longman, and Kevin L. Moore, in *Proceedings of AAS/AIAA Flight Mechanics Meeting*, Clearwater Florida, January 2000.
- “A Matrix-Fraction Approach to Higher-Order Iterative Learning Control: 2-D Dynamics through Repetition-Domain Filtering,” Kevin L. Moore, in *Proceedings of 2nd International Workshop on Multidimensional (nD) Systems*, pp. 99-104, Lower Selesia, Poland, June 2000.
- “Iterative Learning Control for Multivariable Systems with an Application to Mobile Robot Path Tracking Control,” Kevin L. Moore and Vikas Bahl., in *Proceedings of the 2000 International Conference on Automation, Robotics, and Control*, Singapore, December 2000.
- “An Iterative learning Control Algorithm for Systems with Measurement Noise,” (invited) Kevin L. Moore, in *Proceedings of the 1999 Conference on Decision and Control*, pp. 270-275 Phoenix, AZ, Dec. 1999.
- “Multi-Loop Control Approach to Designing Iterative Learning Controllers,” (invited) Kevin L. Moore, in *Proceedings of the 37th IEEE Conference on Decision and Control* pp. 666-671, Tampa, FL, December 1998.
- “Some Results on Iterative Learning,” Kevin L. Moore, S.P. Bhattacharyya, Mohammed Dahleh, in *Proceedings of 1990 IFAC World Congress*, Tallin, USSR, vol. 7, pp. 152-157, August 1990.
- “Iterative Learning for Trajectory Control,” Kevin L. Moore, Mohammed Dahleh, and S.P. Bhattacharyya, in *Proceedings of 1989 IEEE Conference on Decision and Control*, Tampa, Florida, pp. 860-865, December, 1989.
- “Learning Control for Robotics,” Kevin L. Moore, Mohammed Dahleh, and S.P. Bhattacharyya, in *Proceedings of 1988 Int. Conference on Communications and Control*, Baton Rouge, LA, pp. 976-987, October 1988.



New Directions

- “Iterative Learning Control Approach to a Diffusion Control Problem in an Irrigation Application,” Kevin L. Moore and YangQuan Chen, in *Proceedings of 2006 IEEE Int. Conference on Mechatronics and Automation*, Luoyang, China, June 2006.
- “Intermittent Iterative Learning Control” Hyo-Sung Ahn, YangQuan Chen, and Kevin L. Moore, in *Proceedings of 2006 IEEE Int. Symposium on Intelligent Control*, Munich, Germany, October 2006.
- “Iterative Learning Control of Perspective Dynamic Systems,” Lili Ma, Kevin L. Moore, YangQuan Chen, in *Proceedings of 2006 IEEE Int. Symposium on Intelligent Control*, Munich, Germany, October 2006.
- “Spatial-Based ILC for Motion Control Applications,” Kevin L. Moore, Mohua Ghosh, and YangQuan Chen, submitted to *Mechanica*.
- “Learning Feedforward Controller Using a Dialated B-Spline Network: Frequency Domain Analysis and Design,” YangQuan Chen, Kevin L. Moore, and Vikas Bahl, *IEEE Transactions on Neural Networks*, vol. 15, no. 2, March 2004.
- “Iterative Learning Control with Iteration-Domain Adaptive Feedforward Compensation,” YangQuan Chen and Kevin L. Moore, in *Proceedings of 2003 IEEE Conference on Decision and Control*, Hawaii, USA, Dec. 2003.
- “Frequency Domain Adaptive Learning Feedforward Control,” Y.Q. Chen and Kevin L. Moore, in *Proceedings of 2001 IEEE International Symposium on Computational Intelligence in Robotics and Automation*, Bamff, Alberta, Canada, pp. 396-401, July 29-August 1, 2001.
- “A Non-Standard Iterative Learning Control Approach to Tracking Periodic Signals in Discrete-Time Nonlinear Systems,” Kevin L. Moore, *International Journal of Control*, Vol. 73, No. 10, 955-967, July 2000. “A Period is a Repeated Iteration,” Kevin L. Moore, in *Iterative Learning Control Workshop and Roundtable: Extended Summaries*, unpublished collection of extended summaries of papers presented at the ILC Workshop and Roundtable, pp. 89-94, Tampa, FL, December 14-15, 1998.
- “Iterative Learning Control for Systems with Non-Uniform Trial Length with Applications to Gas Metal Arc Welding,” (invited) Kevin L. Moore and A. Mathews, in *Proceedings of 2nd Asian Control Conference*, Seoul, Korea, July 1997.



Other

- “A Practical Iterative Learning Path Following Control of an Omni-Directional Vehicle,” YangQuan Chen and Kevin L. Moore, *Asian Journal of Control*, vol. 4, No. 1, Mar. 2002, pp. 68-89.
- “Improved Path Following of USU ODIS by Learning Feedforward Controller Using Dilated B-Spline Network, Y.Q. Chen, Kevin L. Moore, and Vikas Bahl, in *Proceedings of 2001 IEEE International Symposium on Computational Intelligence in Robotics and Automation*, Bamff, Alberta, Canada, pp. 59-64, July 29-August 1, 2001.
- “Comments on United States Patent 3,555,252 -- Learning Control of Actuators in Control Systems,” Yangquan Chen and Kevin L. Moore, in *Proceedings of the 2000 International Conference on Automation, Robotics, and Control*, Singapore, December 2000.
- “On the Relationship Between Iterative Learning Control and One-Step-Ahead Minimum Prediction Error Control,” Kevin L. Moore, in *Proceedings of the 3rd Asian Control Conference*, pp. 1861-1865, Shanghai, China, July 2000.
- “An Iterative Learning Control Technique for Mobile Robot Path-Tracking Control,” Kevin L. Moore and Vikas Bahl, in *Proceedings of SPIE International Symposium on Intelligent Systems and Advanced Manufacturing: Mobile Robots XIV*, pp. 240-251, Boston, MA, Sept. 1999.
- “Neural Networks for Iterative Learning Control,” Mark A. Waddoups and Kevin L. Moore, in *Proceedings of 1992 American Control Conference*, Chicago, Illinois, pp. 3049-3051, June 1992.
- “A Reinforcement-Learning Neural Network for the Control of Nonlinear Systems,” Kevin L. Moore, in *Proceedings of 1991 American Control Conference*, Boston, Mass., pp. 21-22, June 1991.
- “Adaptive Gain Adjustment for a Learning Control Method for Robotics,” Kevin L. Moore, Mohammed Dahleh, S.P. Bhattacharyya, in *Proceedings of 1990 IEEE Conference on Robotics and Automation*, Cincinnati, Ohio, pp. 2095-2099, May 1990.

