

IREE REPORT for KIRA BARTON

NSEC: Center for Nano-Chemical-Electrical-Mechanical-Manufacturing Systems/Nano-CEMMS

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ABSTRACT: As design requirements and machining capabilities advance, the demand for the development of improved methods for precision motion control (PMC) continues to increase. The goal of the work proposed for the IREE project was to combine the theory and analysis techniques from the Eindhoven University of Technology (TU/e) and the University of Illinois at Urbana-Champaign (UIUC) to produce a novel control method. This report details research that was carried-out at TU/e in the area of Iterative Learning Control (ILC) as a direct result of the NSF travel grant. The research conducted at TU/e included collaboration with the research groups of Professor Maarten Steinbuch and Professor Okko Bosgra. These groups have extensive experience in the theoretical and practical aspects of learning systems. The stability and analysis techniques employed by these groups differ from the analysis techniques used in Professor Andrew Alleyne's group at UIUC. Through collaboration efforts with Prof. Steinbuch, Prof. Bosgra, and a few of their grad students, researchers from the two universities were able to define a new area of research in PMC by combining the TU/e research framework with the UIUC control algorithm.

INTRODUCTION

In the fall of 2007 (Aug. 12th – Dec. 30th), Kira Barton, a current graduate student at the University of Illinois at Urbana-Champaign (UIUC), traveled to the Eindhoven University of Technology (TU/e) in The Netherlands on a National Science Foundation (NSF) IREE travel grant. The goal of the work for the IREE project was to combine the theory and analysis techniques from TU/e and UIUC to produce a novel control method. The research for the NSF travel grant was aligned with current research being conducted in Professor Andrew Alleyne's lab at UIUC through the NSF funded Center for Nanoscale-Chemical-Electrical-Mechanical-Manufacturing Systems (Nano-CEMMS), NSF Award DMI 032816. Current research includes the development of an improved method for PMC by combining individual axis Iterative Learning Control (ILC) and Cross-Coupled ILC (CCILC) into a single control input [1]. CCILC is a new method in which a multiaxis Cross-Coupled Controller (CCC) is reformatted into a single-input single-output (SISO) ILC approach. Applying the techniques of ILC to CCC enables learning of the cross-coupled error which leads to a modified control signal and subsequent improvements in the contour trajectory tracking performance [2]. This approach is good for coordinating the activities of multiple motion axes. Potential applications for this work include micro/nano-scale manipulation and placement, as well as, biological applications such as cell manipulation, classification, and structural identification.

TU/e is part of the ‘Federation of 3 Universities of Technology’ along with Delft University of Technology and the University of Twente in the Netherlands. TU/e profiles itself as a leading international university specializing in engineering science and technology. It is currently ranked as the number three scientific university within Europe. Current research being conducted in the Controls and Dynamics department at TU/e in the research groups of Professor Maarten Steinbuch and Professor Okko Bosgra includes theoretical and practical aspects of learning systems. These two groups focus on the use of Linear Quadratic Regulator (LQR) optimal control theory [3] for the design of the learning update scheme. This scheme has been shown to produce improved tracking performance with application to a wafer stage [4,5]. The research groups of Prof. Steinbuch and Prof. Bosgra at TU/e were logical choices for international collaboration due to their extensive experience in ILC with application to PMC systems, combined with stability and analysis techniques that differ from the techniques used in Prof. Alleyne’s group.

Collaborative efforts with Prof. Bosgra, Prof. Steinbuch, and a few of their grad students, resulted in a new area of research in PMC by combining the TU/e research framework with the UIUC control algorithm. This work has already led to one collaborative conference paper. In addition to the collaborative research, this experience has provided an opportunity to establish lasting research relationships abroad.

RESEARCH ACTIVITIES AND ACCOMPLISHMENTS OF THE INTERNATIONAL COOPERATION

The research conducted during the international cooperation program focused on developing a novel control technique that improves the precision motion control (PMC) of multiple input multiple output (MIMO) manufacturing systems that perform the same task repetitively. Current research in Prof. Alleyne’s group at UIUC introduced the use of Cross-Coupled Iterative Learning Control (CCILC) to improve the contour tracking in repetitive PMC applications [2], see Figure 1. CCILC combines feedback Cross-Coupled Control [6] with ILC [7,8] into a learning control design which focuses on minimizing the contour tracking of a given system.

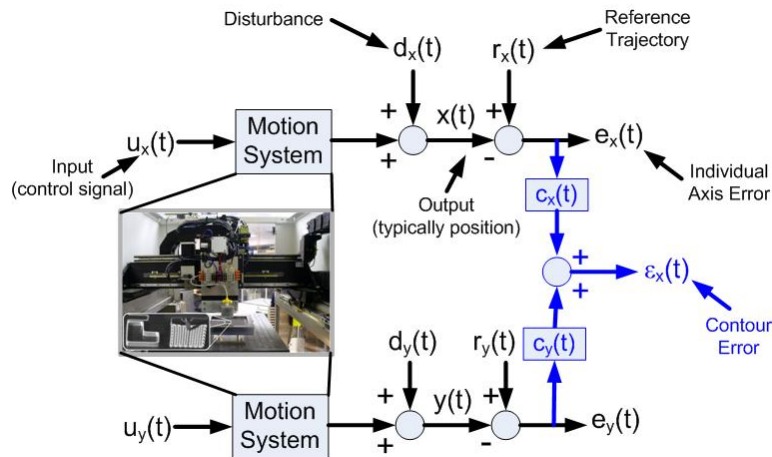


Figure 1. MIMO manufacturing system with individual axis and contour errors defined

Current research in the groups of Prof. Steinbuch and Prof. Bosgra at TU/e focuses on the use of LQL optimal control for designing the learning scheme [9,10]. The goal of the research carried out during the IREE project was to reformat the CCILC learning controller into the Norm Optimal (N.O.) framework utilized by the groups at TU/e. The N.O. framework gives a more structured approach for focusing on contour tracking, which results in a more intuitive design approach. The weighting approach of the N.O. framework also enables one to focus on individual axis or contour tracking as determined by the control designer. Figure 2 illustrates how the research conducted during the IREE project fits in with current research at UIUC and TU/e.

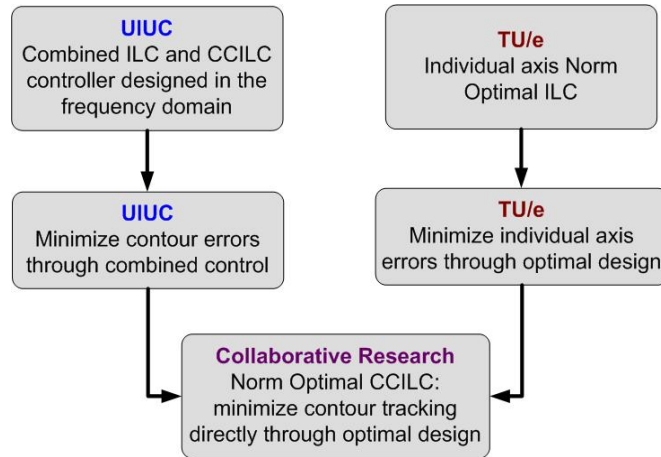


Figure 2. Illustration of how collaboration fits in with current research at each institution, respectively

Most of the collaboration between the researcher and the host laboratory was accomplished through general day-to-day interactions with grad students from the labs of Prof. Steinbuch and Prof. Bosgra, respectively. Occasionally, a more formal interaction was arranged with Prof. Steinbuch and Prof. Bosgra to discuss progress and future direction of the research. Maintaining a daily presence at a work station specifically assigned to the visiting researcher encouraged daily discussions and interactions between the researcher and host grad students. Working together, researchers from TU/e and UIUC were able to define a new area of research in which a novel learning controller for PMC was developed by combining the TU/e research framework with the UIUC control algorithm. Experimental results obtained by implementing the novel control scheme on an experimental testbed at UIUC are presented in Figure 3.

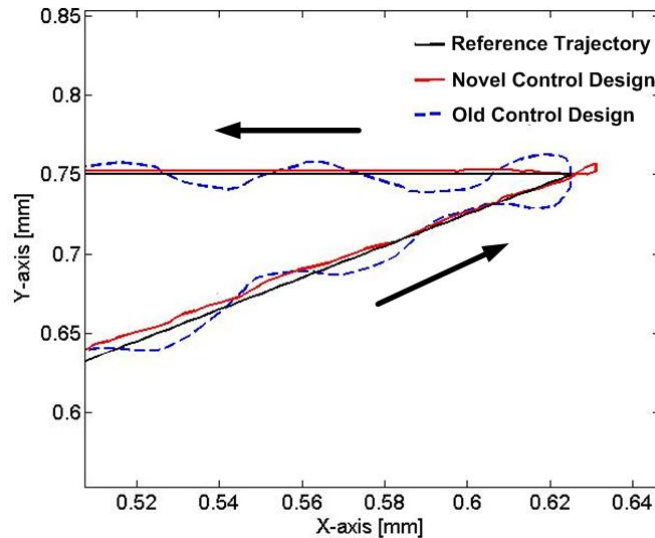


Figure 3. Experimental results obtained by implementing the novel controller on a testbed at UIUC

Along with daily discussions and the more formal meetings, the visiting researcher was expected to present the research accomplishments in the form of a peer-reviewed conference and formal presentation. The research conducted at TU/e in conjunction with the IREE travel grant was presented at the 47th IEEE Conference on Decision and Control in Cancun, Mexico on December 10th, 2008 [11].

BROADER IMPACTS OF THE INTERNATIONAL COOPERATION

The IREE supplemental travel grant provides a unique opportunity for a researcher to visit an international institution, collaborate with individuals to expand the knowledge and progress of a particular research area,

and foster closer future interactions between researchers from each institution. One of the most interesting aspects of visiting another university comes from observing the differences between the universities. While engineering is truly a universal field, the diversity in the means by which engineers learn, perform experiments, and conduct research becomes readily apparent. Attending several dissertation defenses at TU/e enabled the visiting researcher to observe an amazing tradition that is completely different from the dissertation defense process at UIUC. Through numerous university sponsored gatherings that encourage networking within the Controls and Dynamics group at TU/e, the visiting researcher made connections with several different researchers from TU/e in different areas of controls research. These connections provide a means of expanding one's research focus and lead to potential future collaborations.

Along with the more technical and research focused opportunities, living in another country for 5 months enables one to become familiar with a new language and culture, while also providing an enhanced international perspective. Europe is a very diverse continent with vast amounts of history and culture throughout. Given the location of the Netherlands, side trips to Belgium and Germany were a regular occurrence, allowing the researcher to experience several cultures. Transitioning from professional to personal relationships with individuals from the research groups at TU/e led to a more personal introduction to the Dutch lifestyle. Attending local activities in Eindhoven, such as local races, musical performances, holiday celebrations, and soccer games enhanced one's cultural experience.

While current research being conducted at UIUC within the NSF funded Nano-CEMMS Center involves researchers from various disciplines within the engineering and scientific community at UIUC, the experiences garnered from the international exchange, combined with potential collaborations with researchers from TU/e, make the supplemental award a highly valuable contribution to the individual and the research project as a whole. Many of the personal and professional connections made during the international research experience have been maintained since the researcher returned to her home university. Major conferences focusing on controls research provide a venue for continued collaborations between researchers due to the diversity at these conferences and the prevalence of international and national students.

DISCUSSION AND SUMMARY

The international research experience program provides a unique opportunity to visit an international institution and collaborate with colleagues working in similar areas of research. From August 12th – December 30th, 2007, Kira Barton, a current graduate student at the University of Illinois at Urbana-Champaign (UIUC), traveled to the Eindhoven University of Technology (TU/e) in The Netherlands as part of the IREE program. Current research conducted within the Controls and Dynamics group at TU/e, headed by Professor Maarten Steinbuch, is closely aligned with Ms. Barton's research at UIUC in Professor Andrew Alleyne's lab. Collaborative efforts with Prof. Steinbuch, Professor Okko Bosgra, and a few of their graduate students at TU/e, resulted in a new area of research in precision motion control (PMC). Combining the research analysis and framework from TU/e with the control algorithm developed at UIUC produced a novel controller which focuses on minimizing tracking errors in PMC systems. This work has led to a collaborative conference paper that was presented at the 47th IEEE CDC conference in December, 2008. Along with the collaborative research, this experience has provided an opportunity to establish lasting research relationships abroad.

Engineering is a highly dynamic field in which much of the forward progress builds on existing theorems and accepted algorithms. Collaboration between different institutions and researchers would enhance the knowledge in any given area of research. The IREE program facilitates collaboration and fosters international exchange by providing an opportunity for researchers to visit an international institution. This is a highly valuable experience and would benefit most researchers. Despite current economic challenges, the engineering field would benefit from a continuation of the IREE program. As more researchers travel abroad, not only will the research profit, but the enhanced international perspective will improve international relations in general.

ACKNOWLEDGEMENTS

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BRIEF BIOGRAPHIES OF RESEARCHERS

Kira Barton received her B.S. from the University of Colorado at Boulder in 2001 and her M.S. from the University of Illinois at Urbana-Champaign in 2006, both in mechanical engineering. She is currently a Ph.D. candidate in mechanical engineering at the University of Illinois. Her research interests include micro- and nano- precision motion control, with a specialization in iterative learning control.

Andrew G. Alleyne received his B.S. in Engineering Degree from Princeton University in 1989 in Mechanical and Aerospace Engineering. He received his M.S. and Ph.D. degrees in Mechanical Engineering in 1992 and 1994, respectively, from The University of California at Berkeley. He joined the Department of Mechanical and Industrial Engineering at the University of Illinois, Urbana-Champaign in 1994 and is also appointed in the Coordinated Science Laboratory of UIUC. He currently holds the Ralph M. and Catherine V. Fisher Professorship in the College of Engineering, was awarded the ASME Dynamics Systems and Control Division's Outstanding Young Investigator Award in 2003, and was a Fulbright Fellow to the Netherlands where he held a Visiting Professorship in Vehicle Mechatronics at TU Delft. He is a Fellow of ASME. His research interests are a mix of theory and implementation with a broad application focus. In addition to research he has a keen interest in education and was recently awarded the UIUC College of Engineering's Teaching Excellence Award for 2008.

Jeroen van de Wijdeven received his M.Sc. degree (cum laude) in Mechanical Engineering at the Eindhoven University of Technology, The Netherlands, in 2004. From 2004 until 2008 he was a research assistant in the Control Systems Technology Group in the department of Mechanical Engineering at the Eindhoven University of Technology. He received his Ph.D. degree from the Eindhoven University of Technology in 2008. His research focused on Iterative Learning Control, with special attention to ILC design for time-windowed and uncertain systems. Since October 2008 he has been working as a mechatronics development engineer at ASML.

Maarten Steinbuch is a full professor in Systems & Control. He received the M.Sc. degree (cum laude) in Mechanical Engineering from Delft University of Technology, Delft, The Netherlands, in 1984. From 1984 until 1987 he was a research assistant at Delft University of Technology and KEMA (Power Industry Research Institute), Arnhem, The Netherlands. In 1989 he received the Ph.D. degree from Delft University of Technology. From 1987-1998 he was with Philips Research Labs, Eindhoven as a Member of the Scientific Staff, working on modelling and control of mechatronic applications. From 1998-1999 he was manager of the Dynamics and Control group at Philips Center for Manufacturing Technology. Since 1999 he is full professor of the Control Systems Technology group of the Mechanical Engineering Department of Eindhoven University of Technology. His research interests are modelling, design and control of motion systems and automotive powertrains. He was an associate editor of the IEEE Transactions on Control Systems Technology, of IFAC Control Engineering Practice, and of IEEE Control Systems Magazine. He was editor-at-large of the European Journal of Control. Since October 1, 2008, he is Editor-in-Chief of IFAC Mechatronics. In 2003 and 2005 he obtained the 'Best-Teacher' award of the Department of Mechanical Engineering, TU/e. Since July 2006 he is also Scientific Director of the Centre of Competence High Tech Systems of the Federation of Dutch Technical Universities.

Okko Bosgra obtained his M.Sc. degree in Mechanical Engineering from Delft University of Technology, Delft, The Netherlands, in 1968. From 1981-1985 he held a Professorship in the Department of Physics at the Agricultural University of Wageningen, The Netherlands. Since 1986 he has been a Full Professor in Control Engineering, heading the Mechanical Engineering Systems and Control Group of Delft University of Technology, The Netherlands. Since 2003 he has also been a part-time Professor in the Control Systems Technology Group of the Mechanical Engineering Department of Eindhoven University of Technology, The Netherlands. In July 2005 he joined the Control Systems group at the Department of Electrical Engineering as a part-time professor. His current research interests are in the theory of robust identification and control design and their application to industrial problems in the process control field and in the field of mechanical servo motion control. Prof. Bosgra is director of the graduate school Dutch Institute of Systems and Control and co-founder of the Dutch Systems and Control Theory Network.