University of California, Berkeley

Mechanical Systems Control Laboratory

Research Booklet

MSC laboratory

August 2013

Dedicated to:

Cheryl Valentine
John Neerhout, Jr.

Preface

The Mechanical Systems Control Laboratory (together with its predecessors) has nearly 40 years of history. The laboratory has engaged in pioneering research in precision motion control, robot control, vehicle control and mechatronics. The laboratory typically has 15 to 20 graduate students and 5 to 10 visitors such as visiting student researchers, visiting scholars and visiting industrial fellows. The laboratory's current projects are described in this booklet to give readers a flavor of the research conducted by the laboratory members. During the past four decades, more than 100 students have completed their PhD degrees, and they are now leaders in academia and in industry. Their names and the titles of dissertations are listed at the end of this booklet.

Masayoshi Tomizuka

Cheryl and John Neerhout, Jr. Distinguished Professor
Department of Mechanical Engineering

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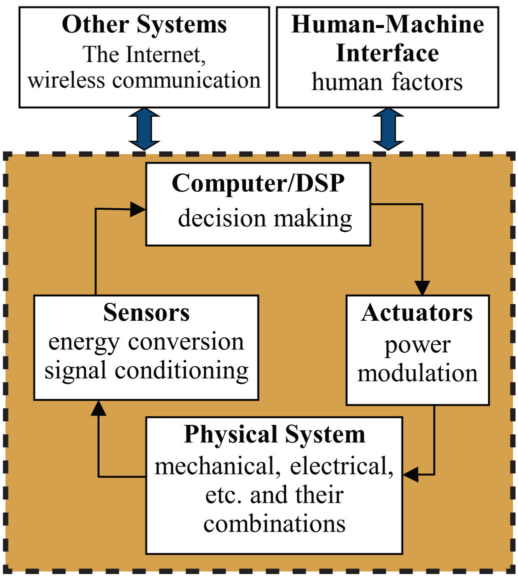
Research Overview

Research activities in the Mechanical Systems Control Laboratory range from fundamental control theory to its applications to various engineering systems. Our research is holistic and includes analysis, design and synthesis of control algorithms, and their implementation and verification based on simulation and experimentation. Furthermore, our research applies mechatronics considerations in many ways. Mechatronics is the synergistic integration of mechanical engineering with electronics and intelligent computer control in the analysis and design of engineering systems and system integration. Synergy is sought by designing physical systems for better controllability and observability, selecting sensors and actuators as well as their locations, designing control algorithms with minimal complexity, and so on. The figure below depicts a typical modern mechatronic system. Since digital devices are used in most of control implementation nowadays, the decision making box is labeled Computer/DSP. Decision making is accomplished by feedback control, feedforward control, high level logic, and so on. Research projects are supported by the National Science Foundation, FANUC Corporation, NSK, Applied Materials, Industrial Technology Research Institute, Agilent, Nikon Research Corporation of America, Western Digital, Computer Mechanics Laboratory, Toyota, Quanser, and King Abdulaziz City for Science and Technology. National Instruments has provided an array of hardware and software tools to facilitate our research.



Modern Mechatronic System

Researcher: Wenjie Chen (Postdoctoral researcher),
Pedro Reynoso-Mora (Graduate student), Michael Chan (Graduate student),
Cong Wang (Graduate student), Chung-Yen Lin (Graduate student),
Ernesto Solanes (Visiting student)

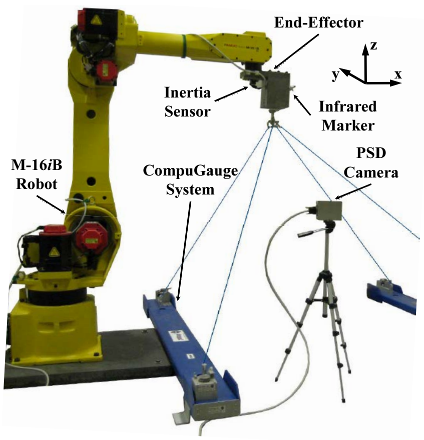
Recent Graduate: Cheng-Huei Han (GE Research, Germany),
Chun-Chih Wang (Formfactor),
Soo Jeon (University of Waterloo, Canada)

Sponsor: FANUC Corporation

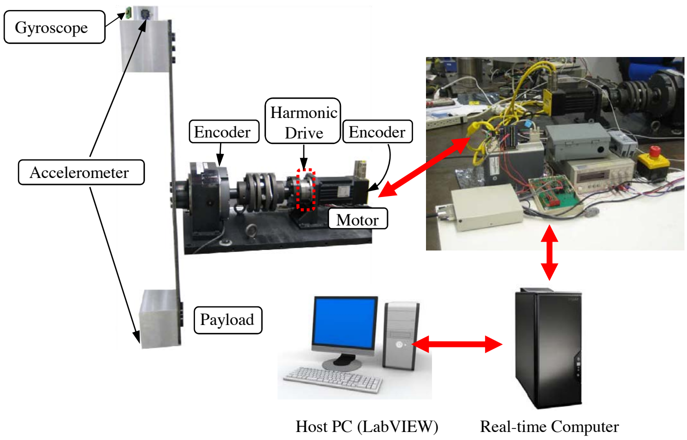
Introduction

Designing high-performance and low-cost robot manipulators is one of the ultimate challenges for engineers today. Key performance criteria for these robots are: 1) speed, 2) accuracy and repeatability, 3) vibration suppression, and 4) cost. In striving to meet these increasingly stringent performance goals, a mechatronic approach, which combines aspects from both mechanical hardware and servo software, is required. This research focuses on learning control, vision sensing dynamics compensation, kinematic visual servoing, and automatic sensor frame identification. The project utilizes an integrated analytical, simulation, and experimental effort to attain the objectives.

Experimental Setup



FANUC M-16iB robot system
(6 joint; motor encoders, end-effector 9-DOF IMU, CompuGauge 3D position sensor, PSD camera; MATLAB xPT Target)

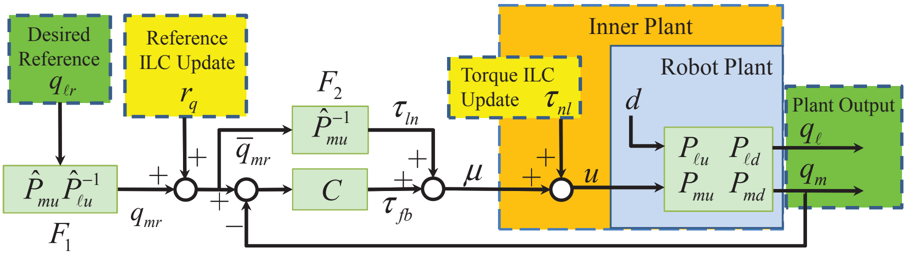


Single joint indirect drive robot setup
(servo motor, harmonic drive, payload; motor side and load side encoders, load side gyroscope and accelerometers; LabVIEW Real-Time and FPGA modules)

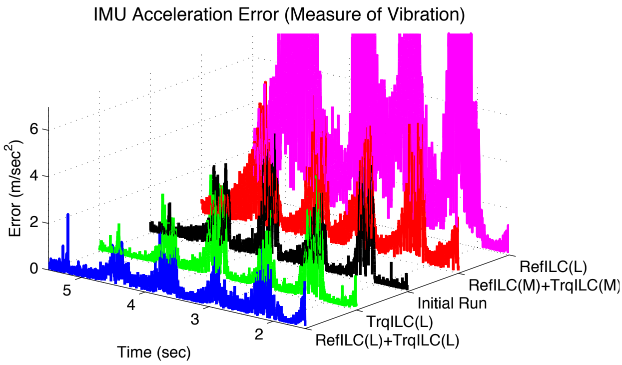
Iterative Learning Control (ILC)

Motivation and Approach

To compensate for the repetitive tracking error of automated systems in repetitive industrial applications, the feedforward control inputs ("τ_{nl}" and "r_q" below) are updated iteratively by processing the error information from previous iterations.



1) Model industrial robot (blue shaded area "Robot Plant") as a MIMO system, where
   a. disturbance "***d***" is in a different channel from the control input "***u***", and
   b. real-time feedback signal "q_m" is not the output of interest "q_l"
2) Design a <u>hybrid dual-stage</u> ILC scheme
   a. Torque ILC (TrqILC, yellow shaded area "τ_{nl}") to compensate for the model uncertainty & disturbances to make the inner plant (orange shaded area) behave as a nominal model
   b. Reference ILC (RefILC, yellow shaded area "r_q") to compensate for the joint flexibility
   c. Ad hoc hybrid scheme: iteration-varying gain for dual-stage transition



Main Results

1) Position tracking and vibration reduction: applications to both single-joint and multi-joint robots with joint elasticity [1, 4, 5] (right figure: proposed hybrid dual stage ILC scheme (RefILC(L)+TrqILC(L)) outperforms either single stage ILC (RefILC(L) or TrqILC(L)) or dual stage ILC with mismatched learning (RefILC(M)+TrqILC(M)) in the vibration suppression of FANUC M-16*i*B robot).
2) Considering link (beam) flexibility: application to large size LCD substrate transfer robot for vibration reduction [2].
3) Learning for general motions: train multiple neural networks for predicting the model following error in a multi-joint robot without further learning or sensing after training stage [3].

Recent Key Publications

[1] W. Chen, and M. Tomizuka, "Dual-Stage Iterative Learning Control for MIMO Mismatched System with Application to Robots with Joint Elasticity," *IEEE Transactions on Control Systems Technology*, DOI: 10.1109/TCST.2013.2279652

[2] C-S. Tsai, W. Chen, D-K. Yun, and M. Tomizuka, "Iterative Learning Control for Vibration Reduction in Industrial Robots with Link Flexibility," in *Proceedings of the 2013 American Control Conference (ACC)*, Washington, DC, June 17-19, 2013

[3] J. Asensio, W. Chen, and M. Tomizuka, "Robot Learning Control Based on Neural Network Prediction," in *Proceedings of the 2012 ASME Dynamic Systems and Control Conference (DSCC)*, pp. 1489-1497, October 17-19, 2012

[4] W. Chen, and M. Tomizuka, "Iterative Learning Control with Sensor Fusion for Robots with Mismatched Dynamics and Mismatched Sensing," in *Proceedings of the 2012 ASME Dynamic Systems and Control Conference (DSCC)*, pp. 1480-1488, October 17-19, 2012

[5] W. Chen, and M. Tomizuka, "A Two-Stage Model Based Iterative Learning Control Scheme for a Class of MIMO

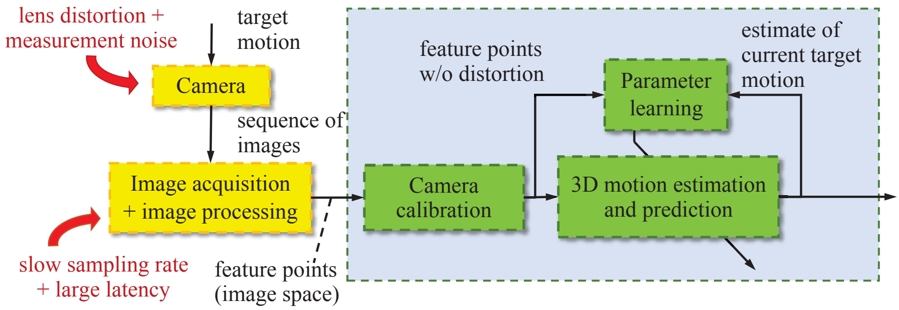
Mismatched Linear Systems," in *Proceedings of the 2012 ASME International Symposium on Flexible Automation (ISFA)*, paper No. ISFA2012-7199, June 18-20, 2012

Vision Sensing Dynamics Compensation (VSDC)

Motivation and Approach

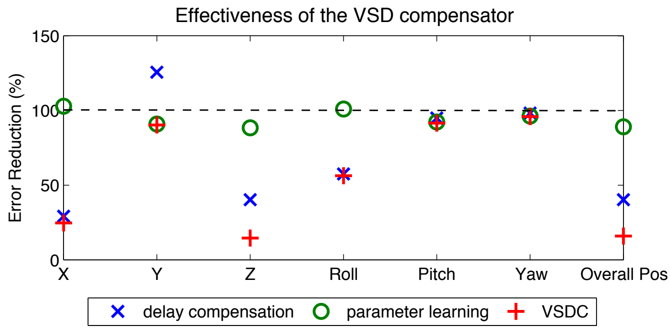
In order to compensate for the large feedback time delay, slow sampling rate, lens distortion, and measurement noise in industrial machine vision systems, a target motion (i.e., position and orientation) estimation scheme (blue shaded area), Vision Sensing Dynamics Compensation (VSDC) scheme, is developed.

1) A look-up table was built (green shaded area "Camera calibration") to map the feature information (contaminated by the lens distortion) from the sensing plane to a virtual plane where the nonlinear effects are fully corrected [1].
2) A Kalman filter based state estimator was designed (green shaded area "Motion estimation and prediction") to provide a real-time state feedback (i.e., target motion in Cartesian space) via delayed measurements in the image space.
3) The observer was optimized (model and gains, green shaded area "Parameter learning") to improve the estimation results.



Main Results

1) Learning target motion characteristics: combining the motion estimation block and the parameter learning block as an incomplete data Maximum Likelihood estimation problem [2].
2) VSDC in Position based visual servoing (PBSV): application to the multiple-marker-single-camera configuration. (upper figure: the proposed VSDC scheme greatly improves the estimation results by both compensating for the sensor dynamics (i.e., delay compensation) and correctly modeling the target motion characteristics (i.e., parameter learning))



Recent Key Publications

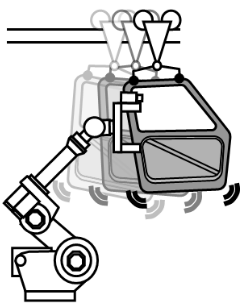
[1] C. Wang, W. Chen, and M. Tomizuka, "Robot End-effector Sensing with Position Sensitive Detector and Inertial Sensors," in *Proceedings of the 2012 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 5252-5257, 2012

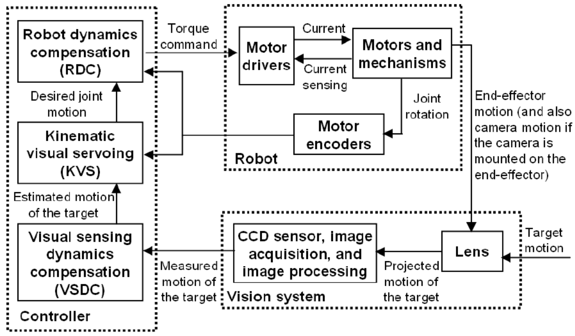
[2] C.-Y. Lin, C. Wang, and M. Tomizuka, "Visual tracking with sensing dynamics compensation using the Expectation-Maximization algorithm," in *Proceedings of the 2013 American Control Conference (ACC)*, Washington, DC, June 17-19, 2013

Kinematic Visual Servoing

Motivation and Approach

Currently, in most applications of vision guided industrial manipulators, the workpiece is either stationary (e.g., bin picking) or in simple motion (e.g., picking from a conveyor belt). In such applications, a simple look-then-move control strategy gives good performance. There are, however, desirable applications in which the workpieces are in more complex motion. Guiding the robot to approach and track a moving target based on vision feedback is often termed as visual servoing. Compared to conventional tasks (e.g. welding and palletizing) where reference trajectory is known in advance, the motion of the robot is planned in real-time.

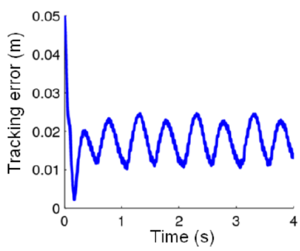




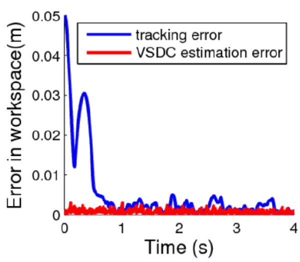
1) Rather than the look-then-move scheme, a real-time vision guidance control algorithm is desired.
2) Most industrial robots in use are controlled by trajectory tracking control algorithms. In order to improve usability for the end user, the conventional trajectory tracking control algorithm should be preserved and the vision guidance control algorithm should be designed to be an add-on.
3) In order to apply to real-world industrial robots, the limited sampling speed of the vision system and the limited dynamics response of the actuators should be fully considered.

Main Results

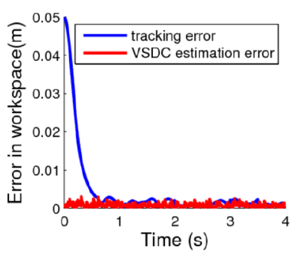
1) Based on the compensated vision feedback from the visual sensing dynamics compensation (VSDC) algorithm, a two-layer control strategy [1] consisting of kinematic visual servoing (KVS) and robot dynamics compensation (RDC) is developed using the theory of multi-surface sliding control. The KVS control law acts as an online motion planner, whereas the RDC control law preserves the structure of a conventional trajectory tracking controller.
2) Constrained optimal control is applied to address the limited dynamics capability of the robot.



only basic KVS
without VSDC
without torque saturation consideration



VSDC + KVS
without torque saturation consideration



VSDC + KVS with optimal constrained control

Recent Key Publications

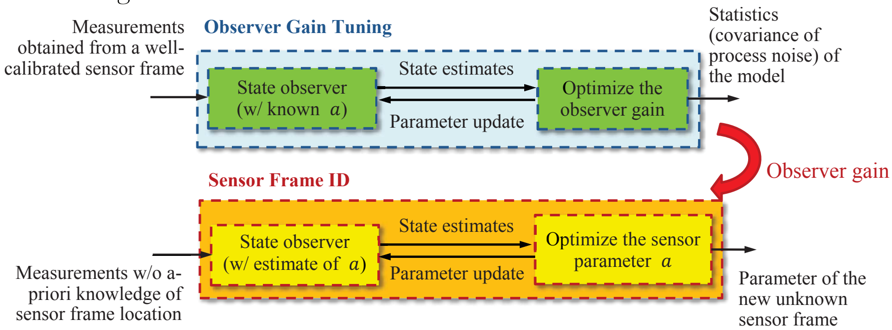
[1] C. Wang, C.-Y. Lin, and M. Tomizuka, "Visual Servoing Considering Sensing Dynamics and Robot Dynamics," in *Proceedings of the 6th IFAC Symposium on Mechatronic Systems*, pp. 45-52, 2013 **(Best Student Paper Finalist)**

Automatic Sensor Frame Identification

Motivation and Approach

In industrial applications, sensor mounting locations may vary due to task variations, which leads to frequent needs of sensor frame calibration. To simplify the calibration process, and to ensure the accuracy of the state estimation in robot manipulators, an automatic sensor frame identification process is developed. This process detects the sensor's mounting position and orientation by updating the estimate of the sensor parameter "$\boldsymbol{a}$" (i.e., the sensor frame location) using multiple sensor signals over a designed trajectory.

1) Design a nonlinear observer (blue shaded area) that provides accurate estimates of robot states.
2) Decouple the sensor frame identification problem (orange shaded area) as two separate problems:
   a. Estimate the robot states using an estimate of the sensor parameter.
   b. Optimize the sensor parameter by solving the Maximum Likelihood estimation problem using the estimates of robot states.



Main Results

1) Automation of the calibration process for load side accelerometer: applications to single-joint robot and multi-joint robots with joint elasticity [1].
2) Observer design for robot manipulators with joint elasticity: the extended Kalman filter (EKF) based [1] and the stochastic piecewise affine (PWA) model based approaches.

Recent Key Publications

[1] C.-Y. Lin, W. Chen, and M. Tomizuka, "Automatic sensor frame identification in industrial robots with joint elasticity," in *Proceedings of the 2013 ASME Dynamic Systems and Control Conference (DSCC)*, October 21-23, 2013

Additional Accomplishments to Date

1) **Sensor Development and Sensor Fusion**

   To better measure and/or estimate the desired robot states in the mismatched robotic systems, a fast and precise position measurement device called PSD camera was developed in [A4], and several dynamic and/or kinematic model based sensor fusion methods were developed in [A1-A6] to integrate the multiple sensor signals from both the motor side and the load side.

2) **Automatic Gain Tuning**

   In order to expedite the gain tuning/validation process, automatic gain tuning methods based on extremum seeking control algorithm [A7] or iterative feedback tuning scheme [A8] were investigated.

3) **Optimal Trajectory Planning**

Without proper compensation, highly accelerating/decelerating motions may induce undesirable vibrations. Thus, a time optimal approach was proposed in [A9, A10] to plan the robot trajectory such that it achieves accurate positioning while suppressing residual vibrations.

4) Other more specific control objectives such as **vibration suppression** and **friction compensation** were also studied for the robotic systems with indirect drive mechanisms in [A11-A13].

Recent Key Publications

[A1] W. Chen, and M. Tomizuka, "Direct Joint Space State Estimation in Robots with Multiple Elastic Joints," *IEEE Transactions on Mechatronics*, 2013, DOI: 10.1109/TMECH.2013.2255308

[A2] W. Chen, and M. Tomizuka, "Comparative Study on State Estimation in Elastic Joints," *Asian Journal of Control*, Vol. 16, No. 3, pp. 1-12, May 2014

[A3] W. Chen, and M. Tomizuka, "Load Side State Estimation in Robot with Joint Elasticity," in *Proceedings of the 2012 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, pp. 598-603, July 11-14, 2012

[A4] C. Wang, W. Chen, and M. Tomizuka, "Robot End-effector Sensing with Position Sensitive Detector and Inertial Sensors," in *Proceedings of the 2012 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 5252-5257, 2012

[A5] W. Chen, and M. Tomizuka, "Estimation of Load Side Position in Indirect Drive Robots by Sensor Fusion and Kalman Filtering," in *Proceedings of the 2010 American Control Conference (ACC)*, pp. 6852-6857, June 30-July 2, 2010

[A6] S. Jeon, M. Tomizuka, and T. Katou, "Kinematic Kalman Filter (KKF) for Robot End-Effector Sensing," *ASME Journal of Dynamic Systems, Measurement and Control*, Vol. 131, Iss. 2, February 2009 **(2010 Rudolf Kalman Best Paper Award)**

[A7] M. Chan, K. Kong, and M. Tomizuka, "Automatic Controller Gain Tuning of a Multiple Joint Robot Based on Modified Extremum Seeking Control," in *Proceedings of the 18th IFAC World Congress*, pp. 4131-4136, 2011

[A8] C-C. Wang and M. Tomizuka, "Sensor-based controller tuning of indirect drive trains," in *Proceedings of the10th IEEE International Workshop on Advanced Motion Control*, pp.188-193, 26-28 March 2008

[A9] P. Reynoso-Mora, W. Chen, and M. Tomizuka, "On the Time-optimal Trajectory Planning and Control of Robotic Manipulators Along Predefined Paths," in *Proceedings of the 2013 American Control Conference (ACC)*, Washington, DC, June 17-19, 2013

[A10] P. Reynoso-Mora, and M. Tomizuka, "LQ-Based Trajectory Tracking of Robotic Manipulators With "Near" Dynamically Feasible Time-Optimal Trajectory," in *Proceedings of the 2012 ASME International Symposium on Flexible Automation (ISFA)*, paper No. ISFA2012-7271, 2012 **(Best Theory Paper Award)**

[A11] W. Chen, K. Kong, and M. Tomizuka, "Hybrid Adaptive Friction Compensation of Indirect Drive Trains," in *Proceedings of the 2009 ASME Dynamic Systems and Control Conference (DSCC)*, pp. 313-320,October 12-14, 2009

[A12] C-H. Han, C-C. Wang, and M. Tomizuka, "Suppression of vibration due to transmission error of harmonic drives using peak filter with acceleration feedback," in *Proceedings of the10th IEEE International Workshop on Advanced Motion Control*, pp.182-187, 26-28 March 2008

[A13] S. Jeon and M. Tomizuka, "Stability of Controlled Mechanical Systems with Ideal Coulomb Friction," *ASME Journal of Dynamic Systems, Measurement, and Control*, vol.130, no.1, January, 2008

Control of Vacuum Wafer Handling Robot

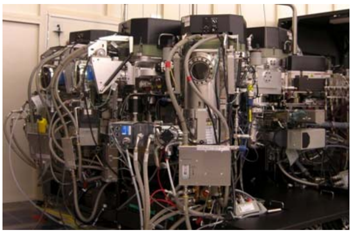
Researcher: Cong Wang (Graduate student), Xiaowen Yu (Graduate student)

Sponsor: Applied Materials, Inc.

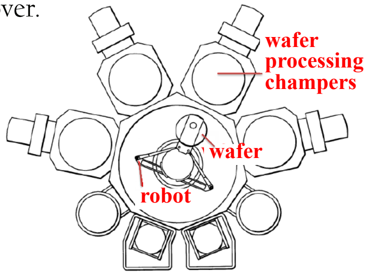
Motivation and Approach

Wafer handling robots are used to transport wafers inside the vacuum environment of IC fabrication tools. Major concerns for the robot performance are:

1) Speed and acceleration: Fast motion is desired to reduce production time, however, the wafer is placed on the end-effector of the robot without any fixture. Friction is the only force preventing sliding so acceleration has to be limited to avoid sliding.
2) Accuracy of tracking and positioning: the reference trajectory is designed to be smooth to avoid sliding. It is important to reduce tracking error to ensure the smoothness of the motion.
3) Vibration and oscillation may cause the sliding of wafers, which generates contaminating particles and even leads to wafer tip-over.



An IC fabrication tool



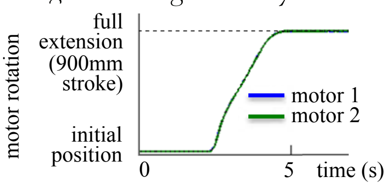
The wafer handling robot inside an IC fabrication tool

Our research aims at improving the robot control performance in above aspects. Meanwhile, the robustness, ease of implementation, and ease of tuning shall also be fully considered. Major approaches include:

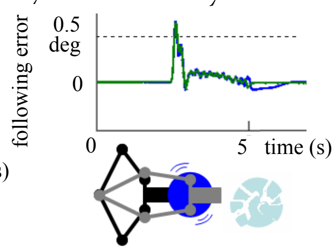
1) Model-based dynamics compensation.
2) Controller tuning using distributed auxiliary sensing.
3) Disturbance compensation based on adaptive modeling and identification.

Main Results

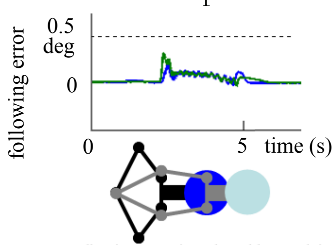
With the proposed approaches, the reference trajectory can be optimized for maximum smoothness, and the following error is significantly reduced by model-based dynamics and disturbance compensation.



The reference trajectory is optimized for maximum smoothness.



Overly large following error causes sliding, even tip-over and crash.



Following error is reduced by applying model-based dynamics and disturbance compensation.

Recent Key Publications

[1] X. Yu, C. Wang, Y. Zhao, and M. Tomizuka, "Dynamics Modeling and Identification of a Dual-blade Wafer Handing Robot," in *Proceedings of the Sixth ASME Dynamic Systems and Control Conference (DSCC)*, 2013

[2] C. Wang, X. Yu, and M. Tomizuka, "Fast Modeling and Identification of Robot Dynamics using the Lasso," in *Proceedings of the Sixth ASME Dynamic Systems and Control Conference (DSCC)*, 2013

Mechatronics for Human Assistance

Researcher: Wenlong Zhang (Graduate student), Chen-Yu Chan (Graduate student), Kan Kanjanapas (Graduate student)

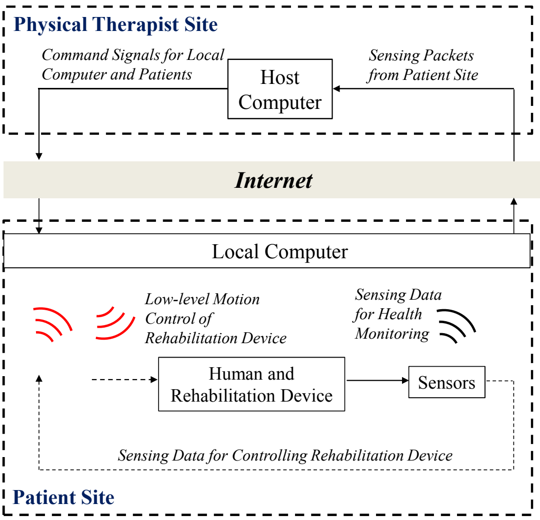
Recent Graduate: Joonbum Bae (UNIST, Korea), Kyoungchul Kong (Sogang University, Korea)

Sponsor: National Science Foundation (NSF)

Introduction

In this research, a networked mobile assistive system (NMAS) that integrates a physical assistive device with a high-speed wireless body sensor network is proposed. The proposed system provides a complete and active health care system to benefit the users (e.g. elderly people, patients with Parkinson's disease and stroke) and improve the management strategy of the health care provider (hospitals, physical therapists). Various research topics are under investigation, including sensor and actuator design, human motion capture and analysis, control of the rehabilitation device over real-time wireless network, and clinical test of the wireless human motion monitoring system. This is a joint research project with computer science researchers from University of Texas, Austin (UTA) and physical therapists from University of California, San Francisco (UCSF).

System Structure and Hardware



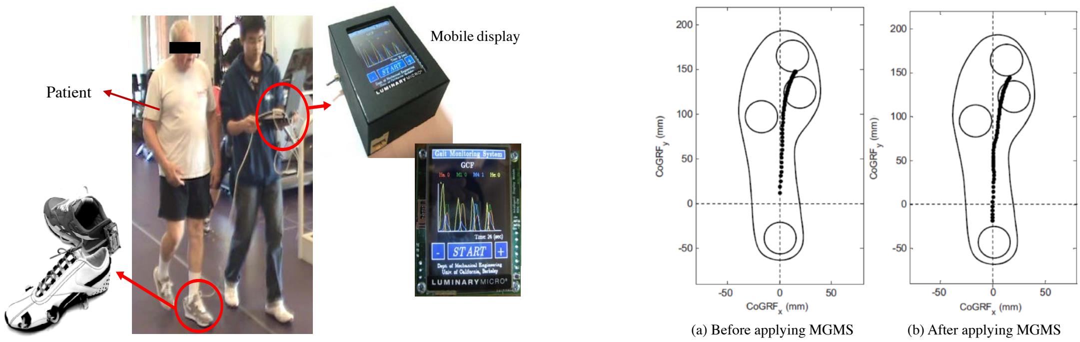
Structure of the NMAS
(two computers and two networks; internet to connect therapists and patients; a local wireless network to connect local computer and all local devices.)

Hardware developed for the NMAS
(upper left: wireless joint angle sensor; lower left: smart shoes for gait detection; right: compact rotary elastic actuator for knee joint assistance)

Development of Smart Shoes

Motivation and Approach

In the NMAS, gait analysis is employed as the major approach of disease diagnosis and evaluation. To provide accurate gait detection, four air pressure sensors were embedded in a shoe to measure ground reaction force (GRF). Based on raw force measurements, fuzzy logic was employed to estimate the current gait phase [1]. A mobile gait monitoring system (MGMS) was developed to provide real-time visual feedback to patients for gait correction. Clinical tests were run with patients at the UCSF rehabilitation clinic.



Clinical test of the MGMS (Left: the MGMS in a clinical test; Right: result of the clinical test)

Main Results

The smart shoes could provide real-time and accurate gait phase detection. With the help of visual feedback from the MGMS, all patients had improvement on their walking pattern in the clinical tests. The above results show the temporal track of the center of ground reaction force (CoGRF) [2].

Recent Key Publications

[1] K. Kong, and M. Tomizuka, "A Gait Monitoring System Based on Air Pressure Sensors Embedded in a Shoe," *IEEE/ASME Transactions on Mechatronics*, vol. 14, no. 3, pp. 359-370, 2009

[2] J. Bae, K. Kong, N. Byl and M. Tomizuka, "A Mobile Gait Monitoring System for Abnormal Gait Diagnosis and Rehabilitation: A Pilot Study for Parkinson Disease Patients," *ASME Journal of Biomechanical Engineering*, vol. 133, no.4, pp. 041005, 2011

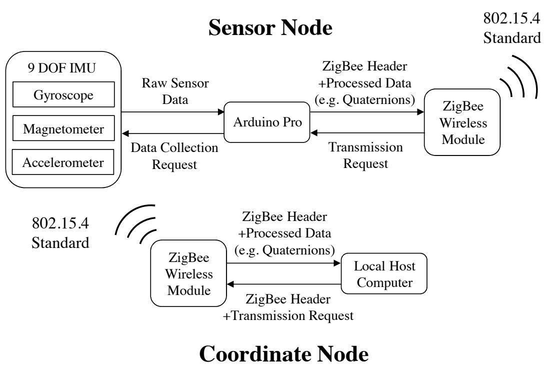
Development of Wireless Joint Angle Sensor

Motivation and Approach

In the NMAS, human motion capture plays an important role in kinematic analysis, and human joint kinematics is of great interest for abnormal walking detection. A 9-DOF inertial measurement unit (IMU) sensor was employed and programmed with an Arduino microprocessor based on direct cosine matrix (DCM) algorithm [1] and a time-varying complementary filter (TVCF) [2]. ZigBee technology was utilized to enable wireless communication between IMU sensor node and the local computer. A user interface was developed to provide visual feedback to patients [1].

Main Results

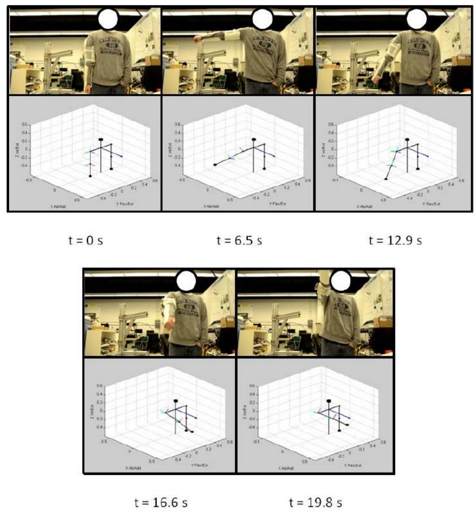
Three prototyped sensor nodes have been manufactured and they have been used for both upper-extremity and lower-extremity human motion capture and analysis. The wireless IMU sensor could provide accurate three-dimensional human joint angle estimation in real-time. The sensor could be configured to work at either wireless mode (up to 30Hz via ZigBee) [1]



Structure of the wireless joint angle sensor

or wired mode (100Hz via serial port) [2] for different applications.

Right figure: experimental results for human motion capture



Recent Key Publications

[1] J. Bae, K. Haninger, D. Wai, X. Garcia and M. Tomizuka, "A Network-Based Monitoring System for Rehabilitation," in *Proceedings of IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, pp. 232-237, 2012.

[2] K. Kanjanapas, Y. Wang, W. Zhang, L. Whittingham, and M. Tomizuka, "A Human Motion Capture System based on Inertial Sensing and A Complementary Filter," in *Proceedings of the Sixth ASME Dynamic Systems and Control Conference (DSCC)*, 2013.

Passive Exoskeleton Design for Human Motion Analysis

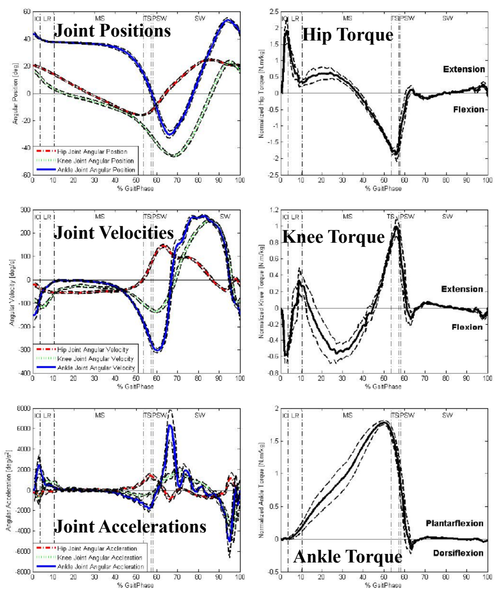
Motivation and Approach

In this research, a 7-DOF passive exoskeleton is designed to combine kinematic sensing and human joint torque estimation. The designed passive exoskeleton mainly allows motions in the sagittal plane. Several motion sensors and force sensors are utilized including encoders, gyroscopes, and smart shoes; therefore, the joint kinematics and ground contact forces can be measured. We also developed a dynamic model of human walking for estimating the human joint torque. Since the kinematic constraints of the lower-limb extremity during walking vary upon gait phases, the walking dynamic model is described by multiple sub-dynamic models derived using Lagrangian mechanics.

Main Results

The joint kinematics measurement and torque estimation were verified by experiments. A healthy male subject with a normal gait pattern wore the exoskeleton suit and walked on a treadmill with a constant speed. The proposed passive exoskeleton could measure joint kinematics and estimate joint torque accurately as shown in the figure on the right.

The 7-DOF passive exoskeleton and experimental results (Left: hardware development of the passive exoskeleton; Right: joint torque estimation results)



Recent Key Publications

[1] K. Kanjanapas and M. Tomizuka, "7 Degrees of Freedom Passive Exoskeleton for Human Gait Analysis: Human Joint Motion Sensing and Torque Estimation During Walking," in *Proceedings of IFAC Symposium on Mechatronic Systems*, pp. 285-292, 2013.

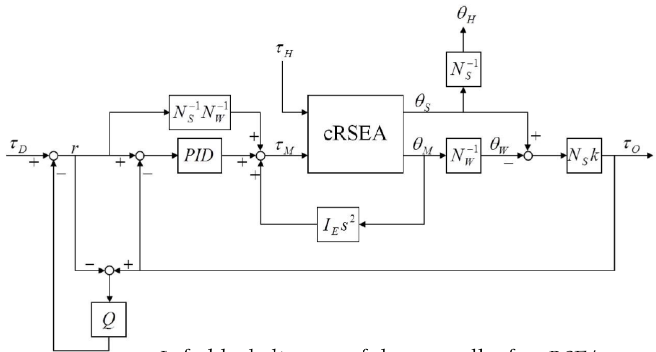
Design and Control of a Compact Rotary Series Elastic Actuator (cRSEA)

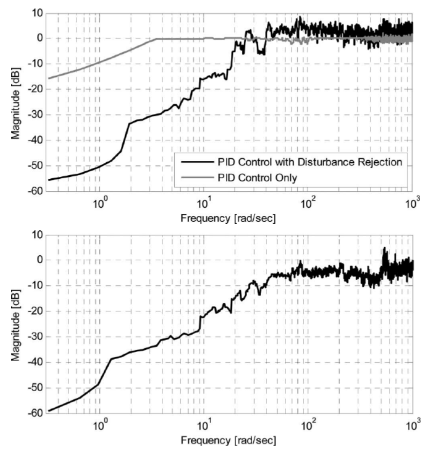
Motivation and Approach

In the NMAS, an actuator is essential for providing active assistance to users to facilitate their walking. Precise and large torque generation, back drivability, low output impedance, and compactness of hardware are important requirements for human assistive robots. Considering the requirements above, a compact rotary elastic actuator (cRSEA) was designed for knee joint assistance. To magnify the torque generated by an electric motor in the limited space of the compact device, a worm gear was utilized. There are backlash, friction, unmodelled dynamics, and disturbance from human-robot interactions in the control system of cRSEA, which makes the controller design challenging. A robust control technique was proposed for the cRSEA.

Main Results

With the worm gear mechanism, the cRSEA may generate assistive torque up to 10.86 Nm under normal situations and 130Nm under extreme situations for a short duration while achieving backdrivability. A PID control algorithm was combined with a disturbance observer (DOB) and torque feedforward control to provide robust and accurate torque control of the actuator [1]. Moreover, a fictitious gain method was proposed to calculate the desired assistive torque for the actuator to generate [1, 2]. The figures below show the controller structure and the frequency response of the torque error output, respectively.





Left: block diagram of the controller for cRSEA;
Right: (upper) frequency response from desired torque to torque error;
(lower) frequency response from human joint motion to torque error

Recent Key Publications

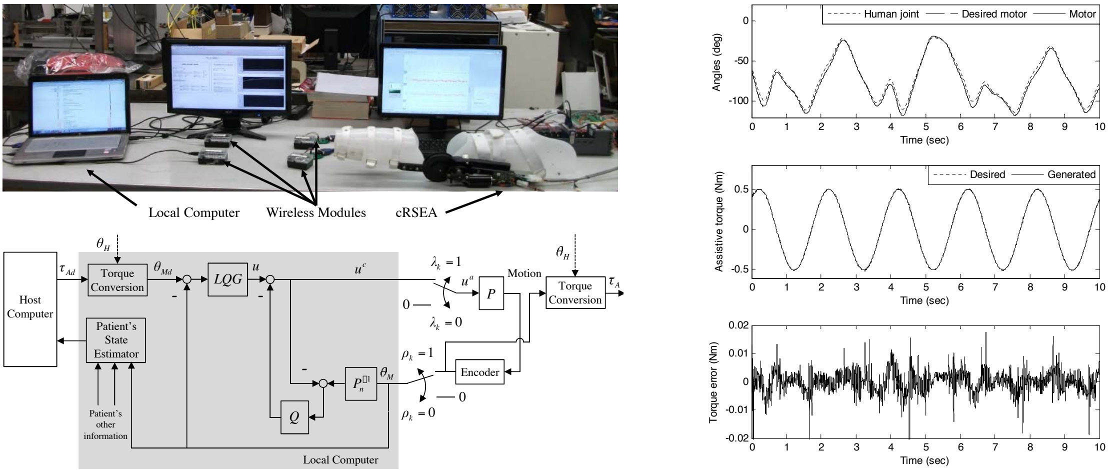
[1] K. Kong, J. Bae and M. Tomizuka, "A Compact Rotary Series Elastic Actuator for Human Assistive Systems," *IEEE/ASME Transactions on Mechatronics*, vol. 17, no. 2, pp. 288-297, 2012

[2] K. Kong and M. Tomizuka, "Control of exoskeletons inspired by fictitious gain in human model," *IEEE/ASME Transactions on Mechatronics*, vol. 14, no. 6, pp. 689–698, 2009

Control of the cRSEA over Wireless Network

Motivation and Approach

In the NMAS, the cRSEA is controlled over a wireless network for improved mobility. However, wireless control is less reliable than wired control due to packet loss, time delay, and packet disorder caused by wireless communication. A Bernoulli random process was used to model the possible packet loss. A modified LQG control with a disturbance observer (DOB) was proposed to control the cRSEA under packet loss [1]. Under the situation when future references can be previewed, the preview control technique was extended so that the previewed reference signal can be used for improved tracking performance [2]. To deal with time-varying delays, a communication disturbance observer (CDOB) was investigated [3]. A wireless control system was built using WirelessHART protocol to test the performance of proposed controllers [4].



Left Upper: experimental setup of the wireless control system; Left Lower: block diagram of the modified LQG controller; Right: experimental results with 30% packet loss

Main Result

All the algorithms proposed above have been tested and verified by simulations and experiments. For packet loss compensation, experimental results of the modified LQG controller are shown in the figure above. For the control system with 30% packet loss, the proposed controller can still guarantee that accurate assistive torque would be generated [1, 4]. Modified preview control could improve the tracking performance with previewed reference signals if the preview time is long enough [2]. The proposed CDOB could guarantee the stability of the wireless tracking control system under varying and unknown time delays [3].

Recent Key Publications

[1] J. Bae, W. Zhang, and M. Tomizuka, "Network-Based Rehabilitation System for Improved Mobility and Tele-Rehabilitation," *IEEE Transactions on Control Systems Technology*, to appear, 2013

[2] W. Zhang, J. Bae, and M. Tomizuka, "Modified Preview Control for a Wireless Tracking Control System with Packet Loss", in *Proceedings of 2012 ASME Dynamic System and Control Conference (DSCC)*, pp. 2524-2533, 2012 **(Semi-Plenary Paper Award Finalist)**

[3] W. Zhang and M. Tomizuka, "Compensation of Time Delay in a Network-based Gait Rehabilitation System with a Discrete-time Communication Disturbance Observer," in *Proceedings of IFAC Symposium on Mechatronic Systems*, pp. 555-562, 2013.

[4] W. Zhang, X. Zhu, S. Han, N. Byl, A. K. Mok, and M. Tomizuka, "Design of a Network-based Mobile Gait Rehabilitation System," in *Proceedings of IEEE International Conference on Robotics and Biomimetics (ROBIO)*, pp. 1773-1778, 2012.

Exoskeleton Design & Control for BMI Study

Researcher: Wenjie Chen (Postdoctoral researcher), Junkai Lu (Graduate student), Kevin Haninger (Graduate student)

Recent Graduate: Joonbum Bae (UNIST, Korea)

Sponsor: National Science Foundation (NSF)

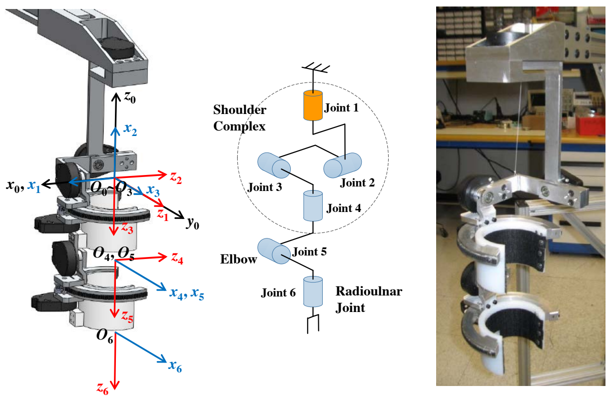
Introduction

The integration of a brain-machine interface (BMI) and an exoskeleton has the potential to promote the understanding of fundamental principles in the neural control of movements, as well as to motivate a new generation of rehabilitation or power augmentation exoskeleton systems. This research focuses on the design and control of a multiple degrees of freedom (DOF) upper limb exoskeleton for BMI macaques to achieve: 1) data acquisition (by torque control) and 2) motion actuation (by impedance/position control), providing proprioceptive feedbacks to help establish a closed-loop BMI system. Collaborators are researchers from the labs of Professor Jose Carmena and Professor Claire Tomlin at UC Berkeley working on, respectively, neural decoder design and hybrid system scheme identification and control. Our effort by now has been devoted to design and control of the upper-limb exoskeleton including kinematic design and analysis, torque reflecting actuator design, as well as hardware fabrication.

6-DOF Passive Exoskeleton for Macaque Upper-limb

Motivation and Approach

When operated in tracking mode where macaque's arm is free to do arbitrary motion, a singularity-free design of the shoulder complex is essential for both precise tracking and safety concerns. To achieve this, a 6-DOF passive prototype exoskeleton with 4 DOFs at the shoulder complex is proposed and fabricated.



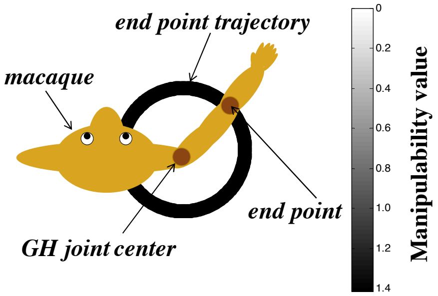
6-DOF passive upper-limb exoskeleton
(CAD model with coordinate frames; simplified joint model; physical hardware design implementation.)

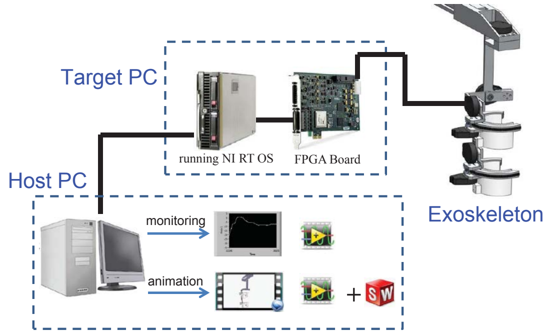
The following studies are further conducted:

1) Kinematics is analyzed for the proposed shoulder complex model
    a. Manipulability comparison is conducted with other designs of different DOF assignments
    b. Feasibility of singularity and joint limits avoidance during tracking task is verified based on backward reachability analysis
2) Home positions of incremental encoders are calibrated based on an external optical mocap system
    a. Encoder initial offsets are identified by solving a nonlinear least squares problem
    b. Cross-validations are completed using data sets from different experimental sessions

Main Results

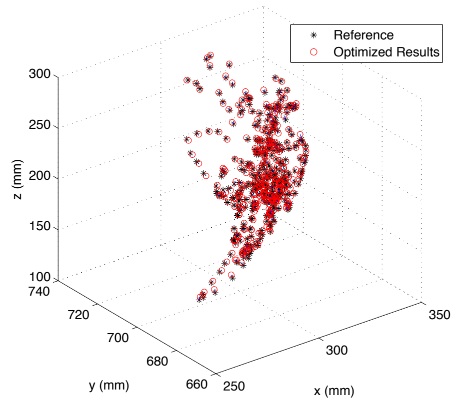
1) Each posture's possession of different levels of manipulabilities due to redundancy makes it possible to avoid singularities by properly planning the trajectories in tracking task. The figure below shows that the proposed model is able to achieve its maximum manipulability in each direction on the horizontal plane [1].





Structure of the real-time data acquisition system
(exoskeleton, encoders; target PC, LabVIEW Real-time and FPGA modules; host PC, LabVIEW and SolidWorks.)

2) By regarding unpredictable macaque's desired task space motion as disturbance, exoskeleton joint space trajectory as control input, game theory based backward reachability analysis demonstrates that there always exists a joint trajectory along which system will not enter unsafe neighborhood of singularity and joint limits for the normal BMI task workspace [1].



3) RMS error of the calibrated 3D end point position is approximately 2 mm. The above right is a plot of sampled marker positions in the mocap camera frame for both reference data and data generated with identified encoder parameters.

Recent Key Publications

[1] J. Lu, W. Chen, and M. Tomizuka, "Kinematic Design and Analysis of a 6-DOF Upper Limb Exoskeleton Model for a Brain-Machine Interface Study," in *Proceedings of the 6th IFAC Symposium on Mechatronic Systems*, pp. 293-300, 2013 **(Best Student Paper Finalist)**

Motorized Exoskeleton Design for Macaque Upper-limb

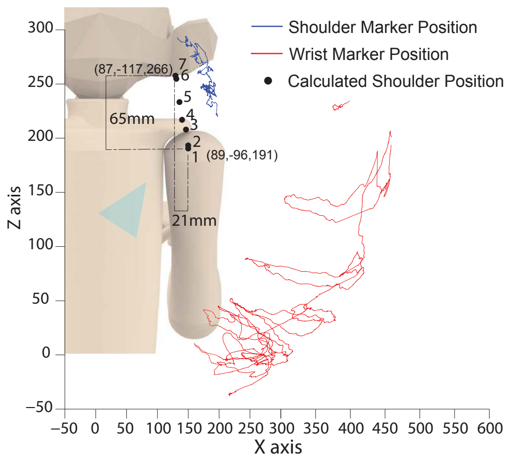
Motivation and Approach

The proposed motorized exoskeleton is able to work in three control modes: 1) torque control mode to passively collect kinematic data as the exoskeleton tracks macaques' voluntary arm movements; 2) position control mode to bring the arm and exoskeleton to spatial targets following decoded neural signals; and 3) impedance control mode to act as a source of mechanical perturbations that macaques should resist by stiffening their arms. To achieve safe, natural motion, the following two subtopics from kinematic and dynamic aspects of the exoskeleton design are conducted.

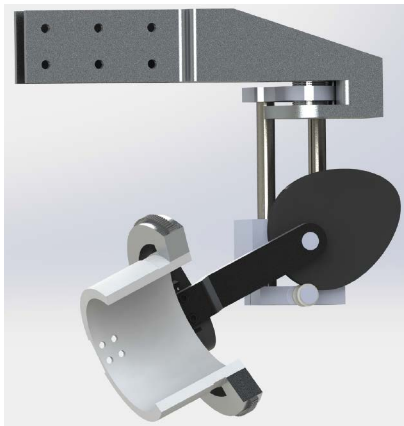
Kinematic Design

To allow for safe interaction between an external mechanism and biological joints, care must be taken to apply external torques along the axis imposed by the biological joint. Due to the structure of most biological joints, the instantaneous center of rotation (e.g., monkey's shoulder center) may vary according to the angle of the joint.

To characterize the behavior of the shoulder center in macaques, analysis was performed on the motion of the upper arm. Motion capture data was obtained for a sedated monkey (with markers along the upper arm and torso), as the arm was moved through a variety of postures. This data was partitioned according to the elevation of the arm (roughly speaking, the angle made between the humerus and the spine). The shoulder center was then found by comparing the position of arm markers in multiple frames, and finding the intersection of axes which describe the rigid body transformation between them. A kinematic design matching with this kinematic/morphological analysis is currently being investigated.



The approximate position of the shoulder center was found at various arm elevation ranges



A mechanism was designed which uses a cam to more closely follow the vertical motion of the shoulder

Actuator Design

Due to limited space at the macaque's joint side, a cable-driven mechanism is most ideal for lightweight and compact joint side design. To achieve back-drivability and torque-reflecting, serial elastic mechanisms will be adopted at each of the designed upper-limb joint sides. Bowden cables connecting from the joint side will be driven remotely by the geared DC motors. To reduce sensing complexity and cost at the motor side, friction characteristics of the transmission train will be first identified and then robust/adaptive controllers will be synthesized for output torque estimation and generation.

3D Target Presenting System

This device was designed and constructed to allow automatic arbitrary 3D placement of two targets in a 40x40x80 cm workspace to motivate the BMI subject (macaque) through a variety of reaching paths.

Variable Stiffness Actuators (VSAs)

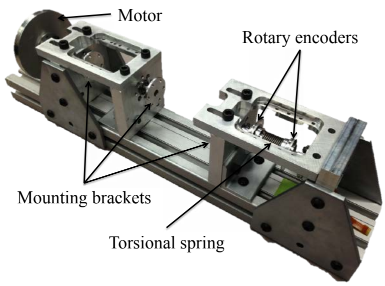
Researcher: Wenjie Chen (Postdoctoral researcher), Robert Matthew (Graduate student), Changliu Liu (Graduate student)

Introduction

As robotic devices are becoming more ubiquitous in the modern world, human-robot interaction is becoming a necessity. Human muscle's natural stiffness varies in different task scenarios. This biological feature motivates the development of a compliant actuator with adjustable stiffness to ensure the safety and comfort of human users while maintaining performance. In other words, Variable Stiffness Actuators (VSAs) and the corresponding intelligent control are desired to provide the flexibility by changing their compliance to suit the variable tasks given.

Experimental Setup

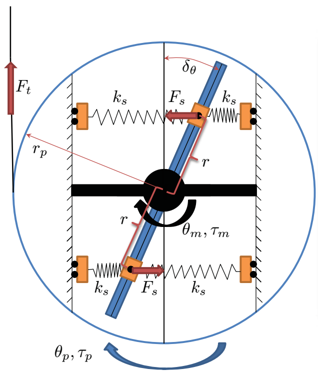
To perform this research, we have constructed a test rig capable of accurately measuring the position and torque of a VSA device. Using this setup we can test both the static and dynamic properties of such devices. The test device itself comprises of a set of standardized mounting brackets, to which high resolution optical indexing encoders are mounted. Motor control and data acquisition are performed using a real-time operating system.

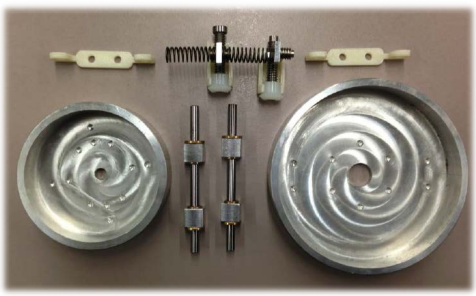


Test rig for VSA position and torque measurements

A Proposed VSA Design

One of the designs we are currently investigating uses a variable length fulcrum to change the effective stiffness of two linear springs. By varying the positions of these two springs, the effective rotational joint stiffness of the series elastic actuator can be changed continuously allowing for the dynamic properties to be tuned to suit the desired application.





Proposed VSA concept design

Control Strategy

We are currently investigating a hybrid system control strategy that fits the inherent characteristics of such devices and applications involving the stiffness changes. In a hybrid framework, the dynamics of each mode will be characterized for each task segmentation and a set of different controllers will be synthesized to provide optimal performance. By varying actuator stiffness, the system dynamics can be altered at a mechanical level, requiring the hybrid feedforward/feedback controllers with adaptation capabilities to be properly realized and switched for each segment.

Potential Applications

By varying the stiffness of an actuator, we are able to protect both the actuator and interfacing devices by allowing for flexibility in their movements. This can be of use in human assistive devices where it is important to not apply impulse loads to the user. These devices can also be used to tune the resonance of a device which stores /dissipates energy.

Safety for Human-Robot Collaboration

Researcher: Chi-Shen Tsai (Graduate student)

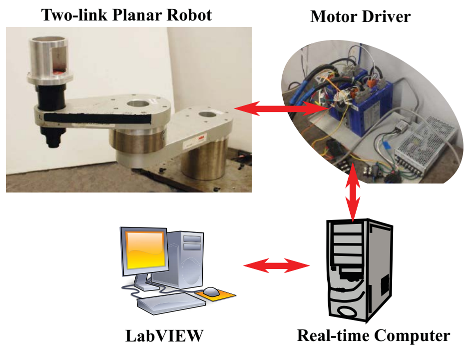
Recent Graduate: Shu-Wen Yu (Areva)

Sponsor: Industrial Technology Research Institute (ITRI), Taiwan

Introduction

With the growing need for humans and robots to share a workspace and/or task, the safety of human-robot collaboration/cooperation has been gaining increased research attention. To guarantee the safety of human workers, robot systems should be able to perceive the complex environment, react to any unexpected human workers on its planned trajectory, and continue on the task if possible. It involves on-line path planning and reactive control. Experiments on a two-link planar robot and simulations on an ITRI 7-DOF robot are conducted for validation. Furthermore, the algorithm may be applied with little change to the dynamic trajectory generation in robot-robot cooperation under a decentralized master-slave control structure.

Experimental Setup



Two-link planar robot setup (servo motor, LabVIEW Real-Time, and FPGA modules)

BI-Jacket & Potential Field Based Methods

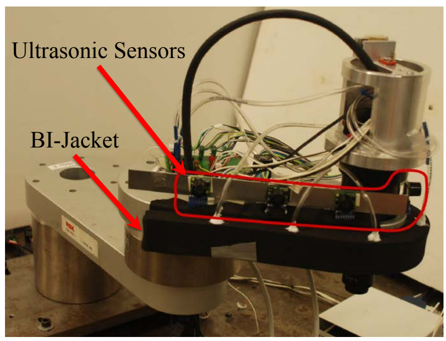
Motivation and Approach

In human-robot collaboration, the safety of the human worker has higher priority than achieving the task in the robot system. Hence the robot safety system should be able to:

1. Detect the human worker and the potential collisions via non-contact sensor.
2. Avoid the potential collision and detour to the goal if possible.
3. Provide the last shield of protection as the fail-safe mechanism if the detection algorithm fails.

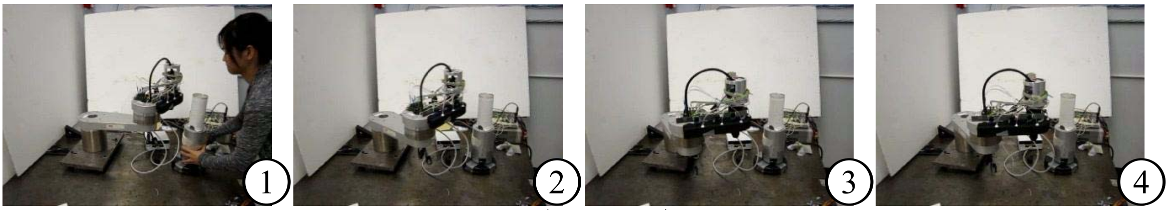
Main Results

The ultrasonic sensors mounted on the robot are used to build the local map, in which the approximate positions of objects in the vicinity of the robot can be extracted. With the position information, the potential field method is implemented to control the robot and achieve collision avoidance in real-time.



Two-link robot with the BI-Jacket and an array of ultrasonic sensors

The BI-Jacket, consisting of a soft deformable substance and air pressure sensors, is mounted on the critical part of the link on the robot. The BI (Berkeley-ITRI)-Jacket not only provides a buffer between the human worker and the robot when a collision actually happens, but also detects the occurrence of the collision by monitoring the air pressure change inside the BI-Jacket.



Two-link robot to achieve obstacle (white tube) avoidance in motion pictures

Dynamic Trajectory Generation via Safety Index

Motivation and Approach

In order for the robot to react to the complex environment and unexpected objects properly, an effective quantitative measure about the safety in the vicinity of the robot is necessary. For this, the safety index is defined, which consists of distance safety index (DSI) and momentum safety index (MSI). DSI is self-explanatory, i.e., a shorter distance between the robot and an object indicating a higher DSI value. MSI, on the other hand, accounts for the linear momentum of every link on the robot towards an object in the workspace of the robot.

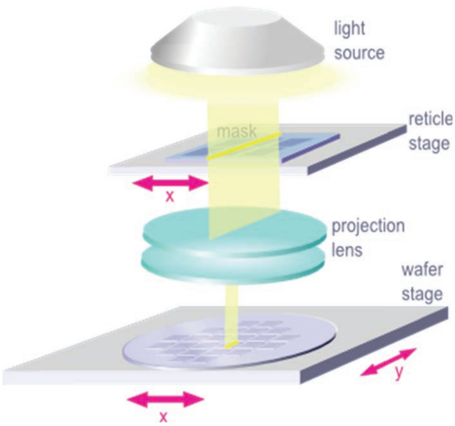
The robot reacts to those objects, either a human worker or another robot, by generating a new trajectory on-line. The trajectory generation is based on solving an optimization problem which penalizes the safety index and the time to accomplish the original task.

Researcher: Xu Chen (Lecturer and postdoctoral researcher)
Liting Sun (Visiting student researcher)

Recent Graduate: Hoday Stearns (Panasonic, Japan),
Shuwen Yu (Areva Solar),
Sandipan Mishra (Rensselaer Polytechnic Institute),
Benjamin Fine (Sandia National Labs)

Sponsor: Nikon Research Corporation of America, Agilent Technologies

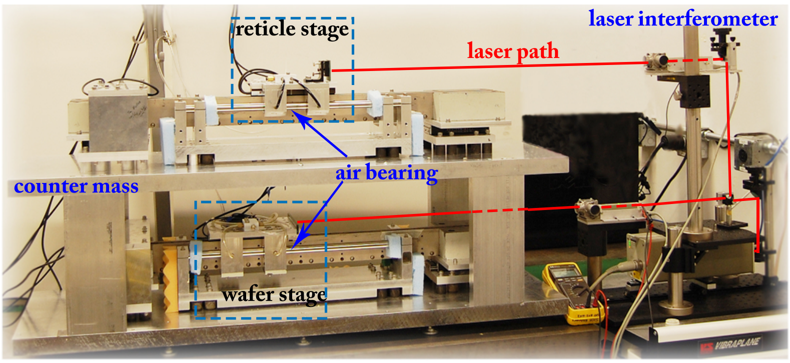
Introduction



Photolithography is a critical step in the manufacturing of integrated circuits (ICs). In this process, ICs are built similar to the erection of a building, in a device called a wafer scanner (stepper). At each layer, a pattern is transferred from a photomask (reticle) to a chemical photoresist coating on a silicon wafer, by shining a light source through the pattern. The pattern is later engraved into the resist through chemical etching. This process is repeated to create the circuit layer by layer.

It is of great importance to maintain high precision control of the wafer scanner. This research focuses on improving the mechanical performance of the wafer scanner by the devlopement of innovative control strategies, modeling methods, and metrology solutions.

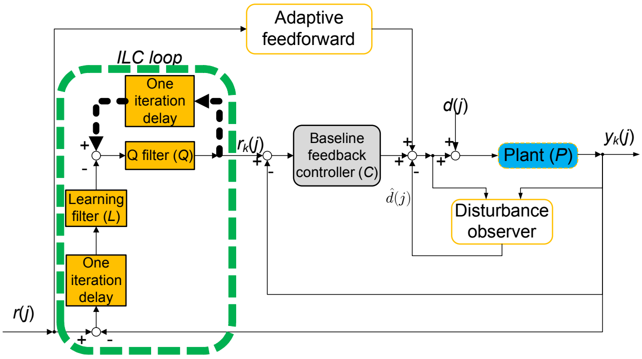
Experimental Setup



Not shown: linear permanent magnetic motors; FPGA; and LabVIEW Real Time

FPGA: interfaces with the stage actuators and measurement systems for accurate timing for real-time (RT) control;
LabVIEW RT: runs the stage control algorithms and data logging operations.

Overview of Controller Structure



Functions of Each Module

Adaptive feedforward	Compensates the force ripples due to imperfect electromagnetic field interaction
Baseline feedback controller (C)	Stabilizes the closed loop and provides the baseline servo performance
Disturbance observer	Offers enhanced disturbance rejection and robustness for model - based feedforward algorithms
ILC loop	Learns the repeatable errors iteratively for improved tracking and regulation

Iterative Learning Control (ILC)

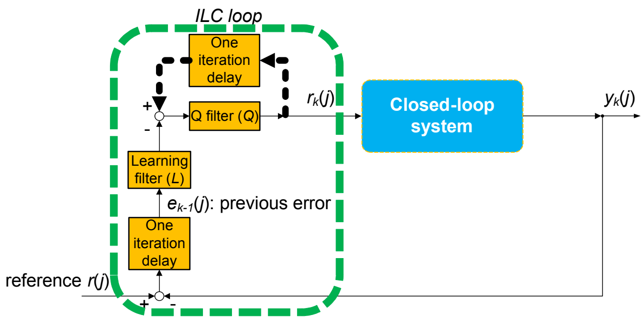
Motivation and Approach

In wafer scanning, both the tracking trajectory and the external disturbance contain large amounts of repeatable information. Similar to human learning, the previously made errors in a servo process can be learned to improve the current and future tasks.

In the main ILC algorithm, the reference signal r_k is updated iteratively to improve the tracking performance:

$$r_k(j) = Q(q^{-1})[r_{k-1}(j)+L(q^{-1})e_{k-1}(j)]$$

At each iteration, the errors from the last operation are learned via the learning filter $L(q^{-1})$ and added to the previous reference command r_{k-1}. The low-pass Q-filter $Q(q^{-1})$ is applied to avoid excessive learning and to maintain stability. With simple configuration, the ILC algorithm can significantly improve the servo performance, as shown in the figure on the top of the next page.



The key research items include design of $Q(q^{-1})$ and $L(q^{-1})$ for high-performance learning, allocation of learning signals, robust ILC under imperfect initial conditions, and generalized learning.

Recent Key Publications

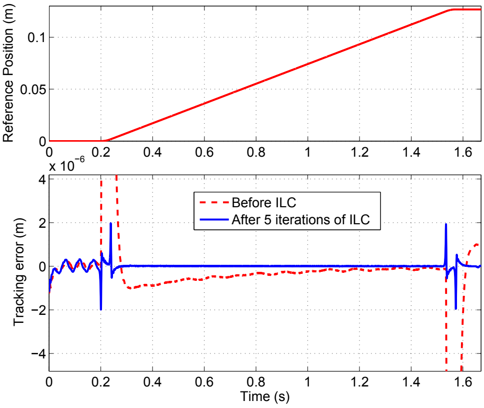
[1] S. Mishra and M. Tomizuka, "Projection-Based Iterative Learning Control for Wafer Scanner Systems," *IEEE/ASME Transactions on Mechatronics*, Vol. 14, No. 3, June 2009, pp. 388-393.

[2] S. Mishra, J. Coaplen and M. Tomizuka, "Precision Positioning of Wafer Scanners: Segmented Iterative Learning Control for Nonrepetitive Disturbances," *IEEE Control Systems Magazine*, Vol 27, No. 4, August 2007, pp. 20-25.

[3] X. Chen and M. Tomizuka, "Spiral Servo Writing in Hard Disk Drives Using Iterative Learning Based Tracking Control," in *Proceedings of the 18th World Congress of the International Federation of Automatic Control (IFAC)*, Aug. 28-Sept. 2, 2011, Milano, Italy, Vol. 18(1), pp. 5279-5285. *cross-linked with Hard Disk Drive Research

[4] H. Stearns, B. Fine and M. Tomizuka, "Iterative Identification of Feedforward Controllers for Iterative Learning Control," in *Preprints of the 9th International Symposium on Robot Control (SYROCO)*, IFAC, Gifu, Japan, Sept. 2009, pp. 313-318.

[5] H. Stearns, S-W. Yu, B. Fine, S. Mishra and M. Tomizuka, "A Comparative Study of Feedforward Tuning Methods for Wafer Scanning Systems," in *Proceedings of 2008 ASME Dynamic Systems and Control Conference*, Ann Arbor, MI, October 20-22, 2008, DSCC2008-2195-1/8.



Example ILC performance

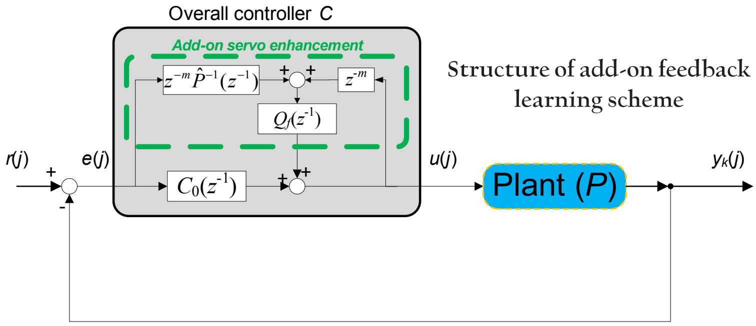
Enhanced Repetitive Control

Motivation

One key assumption for successful feedforward ILC design is to have identical initial condition in the repetitive process. In feedback learning control, this requirement is greatly relaxed. In this research, we investigate high-performance repetitive control for feedback learning in noisy environments.

Main Approach and Results

For a general linear closed-loop control system in the figure on the right, the transfer function from the reference $r(j)$ to the feedback error $e(j)$, namely, the sensitivity function S (a.k.a. output error-rejection function), is $S = G_{er} = \frac{1}{1+PC}$

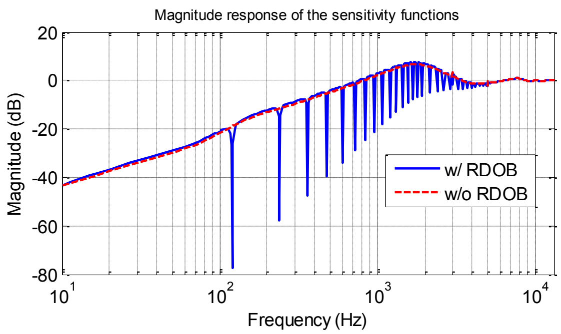


Structure of add-on feedback learning scheme

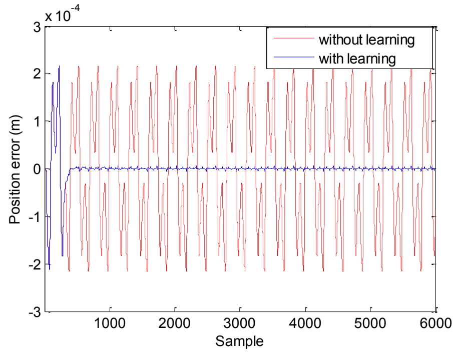
To make the error $e(j)$ small, the magnitude of S has to be small in the desired frequency region, hence the requirement of *|C|* being large in the formulation of S. A plug-in repetitive disturbance observer (RDOB) is proposed to reduce the magnitude of S at frequencies of the repetitive components. It uses an add-on module inside the grey box in the figure shown above, to selectively increase *|C|* without damaging the already achieved good performance at the non-repetitive frequencies.

An example of S is shown on the next page, where the add-on servo enhancement module has greatly reduced the magnitude of S in the solid blue line, which in turn provides great attenuation of the periodic errors shown on the next page .

Wafer Scanner Control



An example sensitivity function in enhanced repetitive control



Comparison of the tracking errors

Recent Key Publications

[1] X. Chen and M. Tomizuka, "Control Methodologies for Precision Positioning Systems," in *Proceedings of 2013 American Control Conference*, Washington, DC, Jun. 17-19, 2013, pp. 3710-3717. **(Tutorial Paper)**

[2] X. Chen and M. Tomizuka, "New Repetitive Control with Improved Steady-state Performance and Accelerated Transient," *IEEE Transactions on Control Systems Technology*, 2013, doi:10.1109/TCST.2013.2253102

[3] X. Chen and M. Tomizuka, "An Enhanced Repetitive Control Algorithm using the Structure of a Disturbance Observer," in *Proceedings of 2012 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Taiwan, Jul. 11-14, 2012, pp. 490-495.

[4] X. Chen and M. Tomizuka, "Add-on Loop Shaping via Youla Parameterization for Precision Motion Control," in *Proceedings of American Society for Precision Engineering 2013 Spring Topical Meeting and the MIT Laboratory for Manufacturing and Productivity Annual Summit*, Cambridge, MA, Apr. 21-23, 2013, pp. 80-83.

Additional Accomplishments to Date

1) Force Ripple Compensation

Linear permanent magnet motors (LPMMs) have widespread applications in precision positioning. However, the performance of LPMMs is significantly constrained by the force ripples during motion. This type of non-repetitive disturbances is caused by irregular magnetic fields and variance of the winding self-inductance between the permanent magnets and the translator. It is a great limiting factor for precision servo control. In [A1], a dynamic model is constructed to parameterize the force ripples. The model parameters are then identified by on-line adaptive estimation, and then used to construct feedforward algorithms to compensate the force ripples.

2) Two-axis Synchronization

Modern wafer scanners contain two moving stages: a reticle stage and a wafer stage. The two motion control problems must be synchronized to minimize the alignment errors. This multi-input-multi-output control problem is challenging in both theory and practice. Areas of investigation in our lab include, modeling of the cross-coupling between the stages, analysis and innovation of synchronization control algorithms.

Recent Key Publications

[A1] S-W. Yu, S. Mishra and M. Tomizuka, "On-line Force Ripple Identification and Compensation in Precision Positioning of Wafer Stages," in *Proceedings of the 2007 ASME International Mechanical Engineering Congress and Exposition*, Seattle, Washington, November 2007, IMECE2007-42563

[A2] S. Mishra, M. Tomizuka and W. Yeh, "Iterative Learning Control Design for Synchronization of wafer and Reticle Stages," in *Proceeding of the 2008 American Control Conference*, Seattle, Washington, June 2008, pp. 3908-3913.

Hard Disk Drive Control

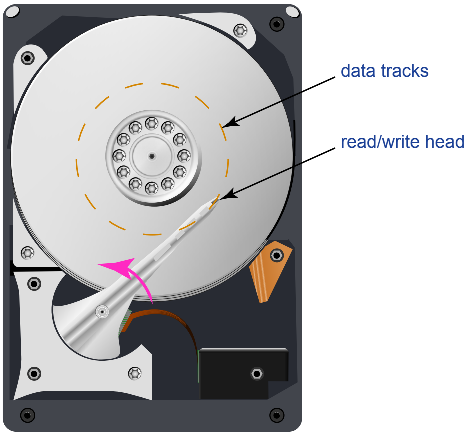
Researcher: Xu Chen (Lecturer and postdoctoral researcher), Minghui Zheng (Graduate student), Liting Sun (Visiting student researcher)

Recent graduate: Qixing Zheng (Western Digital Co.) Nancy Dong (Covidien Ltd.),

Sponsor: Western Digital Co., Computer Mechanics Laboratory at UC Berkeley

Introduction

In a hard disk drive (HDD) system, the user data/information is stored on and retrieved from concentric data tracks using a magnetic read/write head. The positioning of the head over specific tracks is a control problem that is central to the performance of HDDs.



Two sub problems exist for general HDD motion control. First, the actuator needs to provide fast and precise (nm-level accuracy) positioning of the read/write head when switching over different tracks. This transition between data tracks is called "track seeking". The second problem is called "track following," which maintains the read/write head over a particular track in the presence of various disturbance signals.

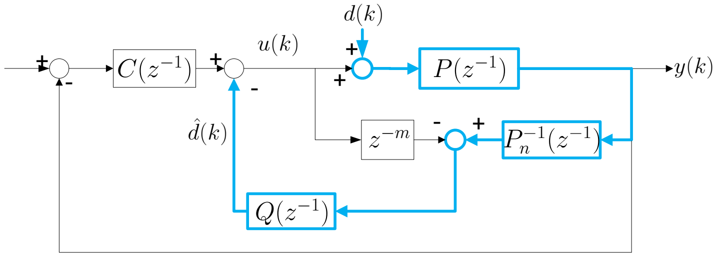
Work in our lab deals with analysis and design of feedback and feedforward controllers for both the track-seeking and track-following problems in modern HDDs.

Adaptive Narrow- and Wide-band Vibration Rejection

Motivation and Approach

With the ever increasing demand of HDD applications in multimedia environments, internal and external vibrations are becoming a dominating source of the position error signal (PES) in HDDs. For instance, audio vibrations from the computer/TV speakers contaminate the HDD performance by introducing strong and wide peaks to the PES spectrum. Such disturbances differ in each product and can additionally be time dependent. This requires intelligent/adaptive controller configurations. In addition, control design faces the challenge that the disturbances frequently occur at frequencies above the servo bandwidth and hence not compensated or even amplified due to the waterbed effect, a fundamental limitation of the feedback design.

A series of direct and indirect adaptive control schemes have been developed to address the aforementioned practical and theoretical challenges. These algorithms all provide flexible design as well as strong tuning intuitions. For instance, in the disturbance observer structure in the figure on the next page, using a model of the inverse dynamics of the plant, we construct a cancellation path for the equivalent input disturbance $d(k)$. The design and tuning are then directly reflected in the frequency-selection filter $Q(z^{-1})$.



Generalized disturbance-observer scheme for vibration rejection

Advantages of the proposed scheme include:

* it requires the minimum number of adaptation parameters;

* it is a flexible loop-shaping tool that maintains the achieved baseline servo performance while rejecting vibrations at frequencies much higher than the bandwidth of the servo loop

Main Results

1) High-performance adaptive compensation for multiple narrow-band disturbances [1, 4, 5, 7];
2) Adaptive audio-vibration rejection with control of the "waterbed effect" [9, 11];
3) Flexible extension to dual-stage HDDs [8, 9];
4) Generalization to other mechanical systems [2, 6, 7, 12];
5) Solution of the robust strictly positive real (SPR) problem via convex optimization [10].

Recent Key Publications

[1] X. Chen and M. Tomizuka, "A Minimum Parameter Adaptive Approach for Rejecting Multiple Narrow-Band Disturbances with Application to Hard Disk Drives," *IEEE Transactions on Control Systems Technology*, vol. 20, no. 2, pp. 408-415, Mar. 2012.

[2] X. Chen and M. Tomizuka, "Selective Model Inversion and Adaptive Disturbance Observer for Time-varying Vibration Rejection on an Active-Suspension Benchmark," *European Journal of Control*, vol. 19, no. 4, pp. 300-312, Jul. 2013.

[3] X. Chen and M. Tomizuka, "Optimal Plant Shaping for High Bandwidth Disturbance Rejection in Discrete Disturbance Observers," in *Proceedings of the 2010 American Control Conference*, Baltimore, MD, Jun. 30-Jul. 02, 2010, pp. 2641-2646.

[4] X. Chen and M. Tomizuka, "An Indirect Adaptive Approach to Reject Multiple Narrow-Band Disturbances in Hard Disk Drives," in *Proceedings of the 2010 IFAC Symposium on Mechatronic Systems*, Cambridge, MA, Sept. 13-Sept. 15, pp. 44-49, 2010.

[5] X. Chen and M. Tomizuka, "Unknown Multiple Narrow-Band Disturbance Rejection in Hard Disk Drives–an Adaptive Notch Filter and Perfect Disturbance Observer Approach," in *Proceedings of the 2010 ASME Dynamic Systems and Control Conference*, Cambridge, MA, Sept. 13-Sept. 15, Vol.1, pp. 963-970, 2010.

[6] X. Chen and M. Tomizuka, "Handling Narrow-Band Disturbances in Precision Motion Control Systems," in *2nd Workshop on Dynamics and Control of Micro Nanoscale Systems*, Newcastle, Australia, Feb. 23 and 24, 2012. **(Keynote Speech)**

[7] X. Chen and M. Tomizuka, "Adaptive Model Inversion For Rejection of Time-varying Vibrations On A Benchmark Problem," in *Proceedings of The European Control Conference 2013*, Zurich, Switzerland, Jul. 17-19, 2013, pp. 2897-2903.

[8] X. Chen and M. Tomizuka, "Reduced-Complexity and Robust Youla Parameterization for Discrete-time Dual-input-single-output Systems," in *Proceedings of 2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Wollongong, Australia, Jul. 9-12, 2013, pp. .1707-1712

[9] X. Chen and M. Tomizuka, "Decoupled Disturbance Observers for Dual-input-single-output Systems with Applica-

tion to Vibration Rejection in Dual-stage Hard Disk Drives," in *Proceedings of 2012 ASME Dynamic Systems and Control Conference, and 2012 Motion & Vibration Conference*, Ft. Lauderdale, FL, Oct. 17-19, pp. 1544-1554, 2012.

[10] X. Chen and M. Tomizuka, "A Convex Optimization Approach for Solving the Robust Strictly Positive Real (SPR) Problem" in *Proceedings of 2012 ASME Dynamic Systems and Control Conference, and 2012 Motion & Vibration Conference*, Ft. Lauderdale, FL, Oct. 17-19, 2012, pp. 48-56.

[11] X. Chen, A. Oshima, and M. Tomizuka, "Inverse Based Local Loop Shaping For Vibration Rejection In Precision Motion Control," in *Proceedings of The 6th IFAC Symposium on Mechatronic Systems*, Hangzhou, China, Apr. 10-12, 2013, pp. 490-497.

[12] A. Oshima, X. Chen, and M. Tomizuka, "Control Design for Cancellation of Unnatural Reaction Torque and Vibrations in Variable-gear-ratio Steering System," to appear in *2013 ASME Dynamic Systems and Control Conference*, Standord University, Munger Center, Palo Alto, CA, Oct. 21-23, 2013.

Nonlinear Feedback for Rejection of Large External Disturbances

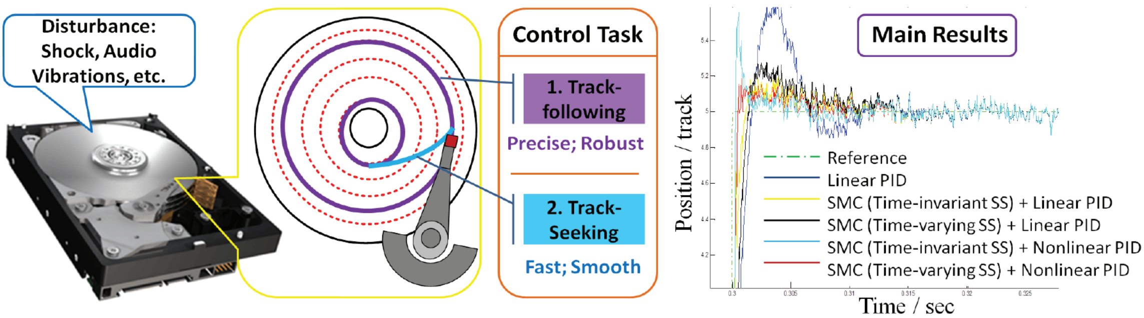
Motivation and Approach

Large external disturbances (shock, audio vibrations, etc.) seriously affect the servo performance of HDDs. The long settling time, large overshoot, and oscillations caused by such disturbances greatly limit the application of HDDs in modern multimedia devices.

A nonlinear control scheme, consisting of a time-varying sliding mode controller and a nonlinear PID controller, has been proposed to break the potential limitations of linear control and to enhance the servo performance of HDDs, in both the transient and the steady-state performances.

Main Results

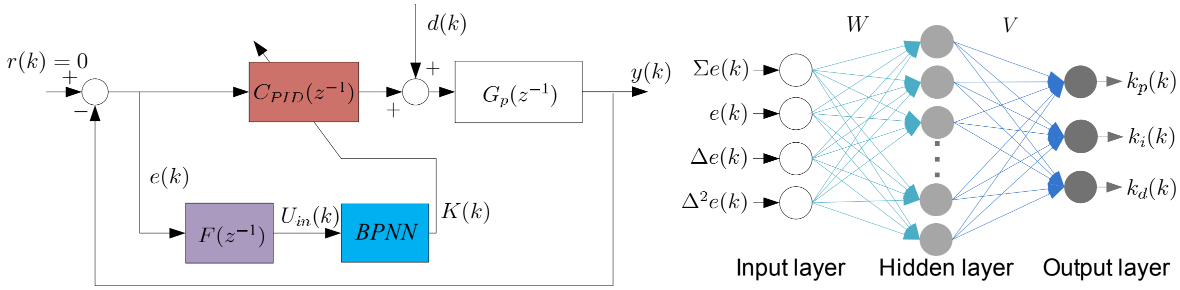
1) Unified track-seeking and track-following schemes;
2) Faster and smoother transient performance during the settling process;
3) Enhanced rejection of high-frequency disturbances during the track-following process.



Automatic PID Gain Tuning Based on Neural Networks

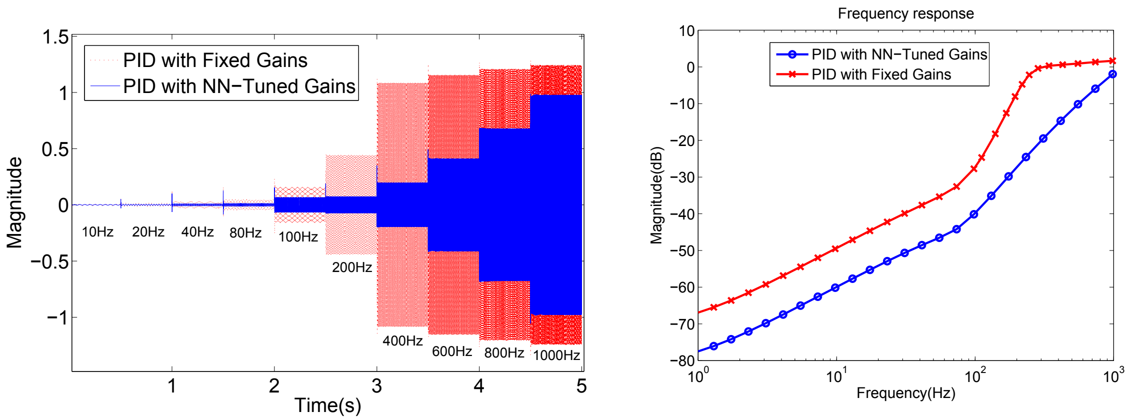
Motivation and Approach

In HDD systems, disturbances commonly contain time-varying frequency components for different products or under different operating environments. It is difficult for a fixed-gain PID controller to maintain a good overall performance. The neural-network-based PID controller, as an adaptive nonlinear control scheme, can automatically learn from the error signal, and adjust the PID gains online when the characteristics of the disturbances change. The neural network adopted here is a two-layer backpropagation neural network (BPNN), and steepest descent method is used to update the PID gains to minimize the cost function $E = e^2(k)/2$.



Main Results

1) Better overall rejection performance for disturbances with time-varying frequency components;
2) Reduction of "waterbed" effect at all test frequencies (10Hz-1000Hz).



Simulation results of disturbance reduction
(piecewise sinusoidal disturbance) and the equivalent sensitivity functions

Recent Key Publication

[1] L. Sun, X. Chen, and M. Tomizuka, "Neural-Network Based Automatic PID Gain Tuning in the Presence of Time-varying Disturbances in Hard Disk Drivers," in *Proceedings of 2013 ASME Information Storage and Processing Systems Conference*, SE-A4, Jun. 24-25, 2013, Santa Clara, CA, USA.

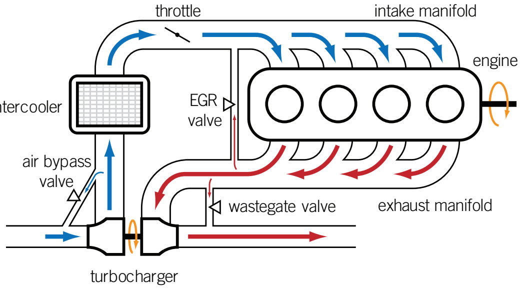
Turbocharged Engine Control

Researcher: Raechel Tan (Graduate student)

Sponsor: Toyota, Ltd.

Motivation

Improving the fuel economy of commercial vehicles is a critical area of development in the automotive industry. Turbocharging a downsized (smaller) engine has emerged as an effective method of reducing fuel consumption compared to a naturally aspirated engine delivering the same power output. The goal of this research project is to find an optimal tradeoff between good fuel efficiency and fast torque response, and to devise a control scheme to obtain the desired performance.



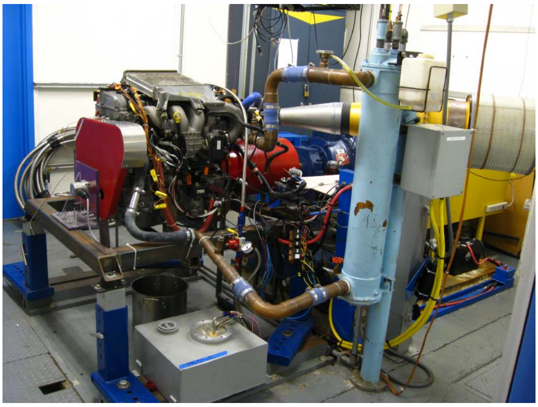
Engine model schematic

Approach

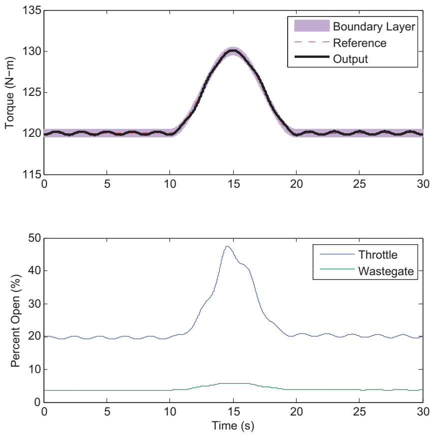
A mathematical model of a turbocharged engine has been implemented in MATLAB/Simulink for simulation. A sliding control scheme has been formulated for low-level torque control via the throttle and wastegate actuators, and an investigation into a high-level strategy to optimize the tradeoff between fuel efficiency and torque response has begun. Additionally, a turbocharged engine has been set up on an engine dynamometer for experimental validation.

Results

The sliding control scheme is able to obtain good torque trajectory tracking, even in the presence of disturbances. In order to reduce actuator chatter, a smoothed control scheme permits tracking error within a specified boundary layer.



Turbocharged engine test bench



Torque control via throttle and wastegate.

Desired torque trajectory is matched within a boundary layer in the presence of disturbances.

Intelligent Power Assist Steering

Researcher: Hironori Ogawa (Visiting industrial fellow),
Xu Chen (Lecturer and postdoctoral researcher),
Wonhee Kim (Visiting researcher)

Recent Graduate: Evan Chang-Siu (PhaseSpace Inc)
Ahmed Hamdy El-Shaer (LineStream Technologies)

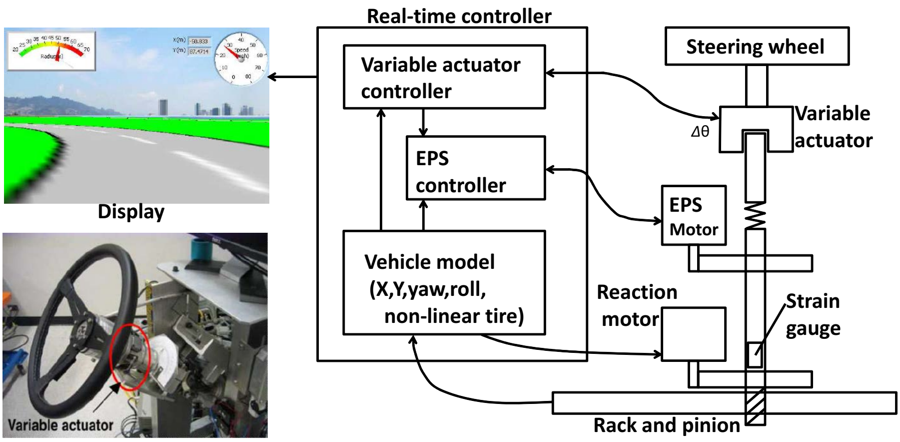
Sponsor: NSK Ltd.

Introduction

Variable-gear-ratio steering (VGRS) is a speed-dependent steering system. The ability to vary the steering gear ratio brings various advantages. For example, the steering gear ratio is set to be high when the vehicle speed is low. This allows a small steering-wheel motion to provide a large steering angle, which is desirable in situations such as parking. On the other hand, the steering gear ratio is switched to be low value at high speeds, therefore enhancing vehicle stability in situations such as driving on the freeway.

A serious problem of VGRS system is that unexpected torque is relayed to the driver whenever the variable-gear-ratio control is activated. More specifically, when the variable actuator moves to change the steering gear ratio, a reaction torque from the motor is transmitted up along the steering column, which is felt by the driver as an unnatural torque. This research focuses on reducing this unnatural torque.

Experimental Setup



NSK VGRS hardware-in-the-loop simulator system
(NSK Rack and pinion EPS system, Variable actuator, EPS motor, Reaction motor, LabVIEW Real-Time ETS targets, Strain gauge)

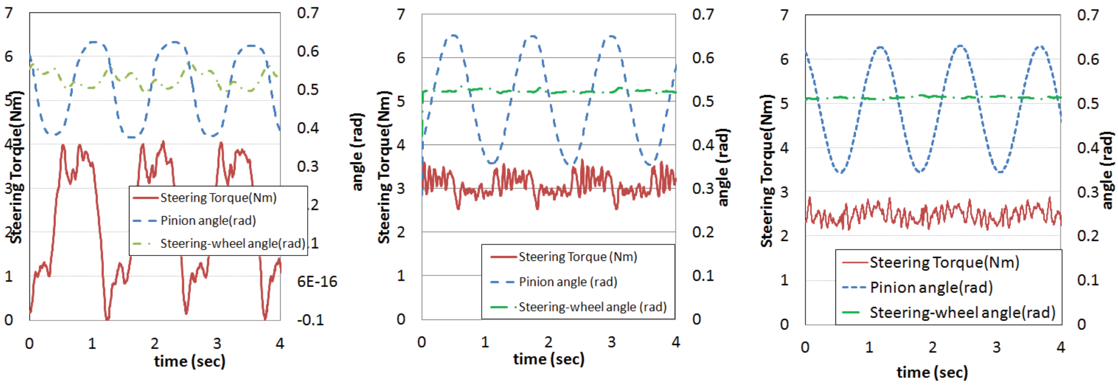
Approach and Results

To reduce this unnatural torque and vibrations in the VGRS system, we designed loop-shaping controllers with friction compensation and narrow-band disturbance observer (DOB) to fullfill the following performance objectives:

1) The velocity of the variable actuator does not affect the steering torque.

2) The original operability of the steering wheel is preserved.
3) The road condition is normally transmitted to the driver.

As shown in the figures below, the controller with friction compensation and narrow-band DOB provides significant compensation of the unnatural torque during steering tests. The system is also robustly stable under 10% model uncertainty.



(a) Normal EPS system (b) Controller w/o friction compensation and narrow-band DOB (c) Controller with friction compensation and narrow-band DOB

Recent Key Publications

[1] A. Oshima, X. Chen, S. Sugita, and M. Tomizuka, "Control Design for Cancellation of Unnatural Reaction Torque and Vibrations in Variable-Gear-Ratio Steering System," in *Proceedings of the 2013 ASME Dynamic Systems and Control Conference (DSCC)*, October 21-23, 2013

[2] S. Sugita and M. Tomizuka, "Cancellation of Unnatural Reaction Torque in Variable-Gear-Ratio," *ASME Journal of Dynamic Systems, Measurement, and Control*, Vol. 134, March 2012.

[3] X. Chen, A. Oshima, and M. Tomizuka, "Inverse Based Local Loop Shaping For Vibration Rejection In Precision Motion Control," in *Proceedings of The 6th IFAC Symposium on Mechatronic Systems*, Hangzhou, China, Apr. 10-12, 2013, pp. 490-497.

Mechanical Systems Control Laboratory Office (2103 Etcheverry Hall)

Guide Dog Robot

Researcher: Hironori Ogawa (Visiting industrial fellow)

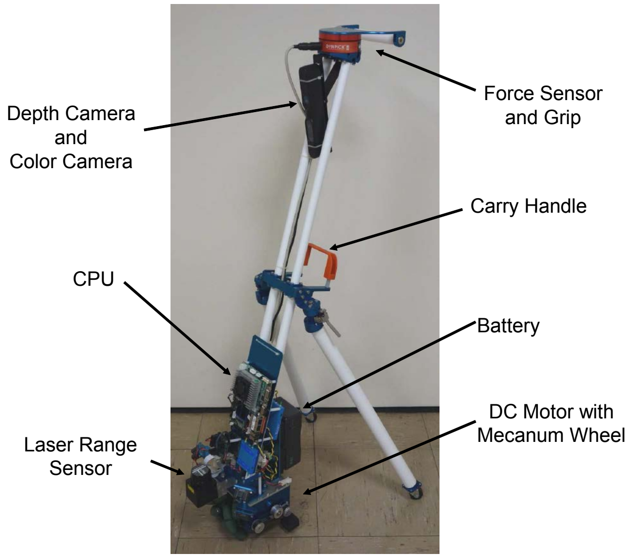
Sponsors: NSK Ltd.

Introduction

There are about 8,000 active guide dogs in the United States, while the estimated market demand is over 55,000. In addition, there is a community of people who are physically not suited (due to allergy or personal preference) for guide dogs. Typically starting at the age of 22 to 26 months, guide dogs need to be trained for four to six months before actual service, with a total cost of approximately $42,000. Moreover, animals are too unhygienic for hospitals and restaurants. In this research, we design a guide dog robot to address the aforementioned practical difficulties.

Experimental Setup

See figure on the right.



Main Approach

Users and guide dogs communicate through a harness. This is mimicked by a mechanical guidance grip in guide dog robots. Sensor fusion algorithms that combine the information of cameras and laser range sensors are constructed for obstacle avoidance and environmental feedback during motion of the guide dog robot. Finally, speed and position control of the DC motors are designed to actuate the motion in each local control loop.

Research Topics

1) Comfortable Speed Control with Environmental Learning
2) Obstacle Avoidance
3) Landmark Recognition

Attitude Estimation and Control

Researcher: Yizhou Wang (Graduate student)

Recent Graduate: Hoday Stearns (Panasonic, Japan)

Sponsor: King Abdulaziz City for Science and Technology (KACST), Quanser

Introduction

Three degrees of freedom (DOF) orientation estimation is useful and necessary for a broad area of applications such as satellites, mobile robots, phones, motion tracking for video games and the film industry, sports and medicine.

Arduino Mini Pro

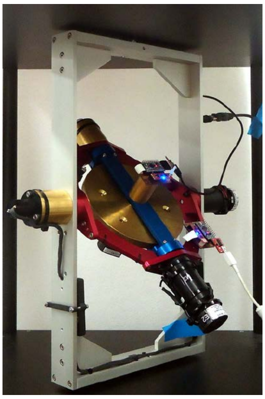
9-DOF Sensor Stick

Computationally Efficient Sensor Fusion

We developed an innovative methodology of attitude estimation in 3D combining the TRIAD algorithm and a time-varying nonlinear complementary filter [1]. It has been implemented on a small-scale microprocessor to accurately estimate attitude from inertial sensors in an IMU package in the figure shown above. Its attitude is calculated in real-time and can be transmitted to a computer for real-time display and record.

Spacecraft Large Angle Maneuvers

A spacecraft must point in the right direction. For example, communication satellites must have their antenna point toward Earth, or have solar panels facing the sun. Spacecrafts are always subject to various environmental disturbances, such as gravitational torque and aerodynamic torque, causing difficulties in precisely stabilizing or controlling the attitude.



Study has been conducted on the rigid body dynamics of a spacecraft, mathematical parameterizations of attitude, and various control methodologies including simple quaternion feedback control, sliding mode control for disturbance rejection and parametric uncertainties, and adaptive tracking control for good tracking performance and inertial matrix identification at the same time.

Robotic Applications

Service robots are becoming more popular nowadays. Low-cost MEMS inertial sensors with developed extended Kalman filter (EKF) can be used for revolute joint angle estimations replacing traditional expensive optical encoders [2]. We developed IMUs that are attached to a gyroscope for the purpose of joint angle estimation, as shown in the picture above.

Recent Key Publications

[1] Y. Wang, E. Chang-Siu, M. Brown, M. Tomizuka, M. Almajed, B. Alsuwaidan, "Three Dimensional Attitude Estimation Via The TRIAD Algorithm and A Time-Varying Complementary Filter", in *Proceedings of the 2012 ASME Dynamic Systems and Control Conference (DSCC)*, DSCC2012-MOVIC2012-8512, pp. 1-9, 2012.

[2] Y. Wang, W. Chen, M. Tomizuka, "Extended Kalman Filtering for Robot Joint Angle Estimation Using MEMS Inertial Sensors", in *Proceedings of the 6th IFAC Symposium on Mechatronic Systems (Mechatronics '13)*, pp. 406-413, 2013

Connected Corridor Management

Researcher: Yaoqiong Du (Graduate student)

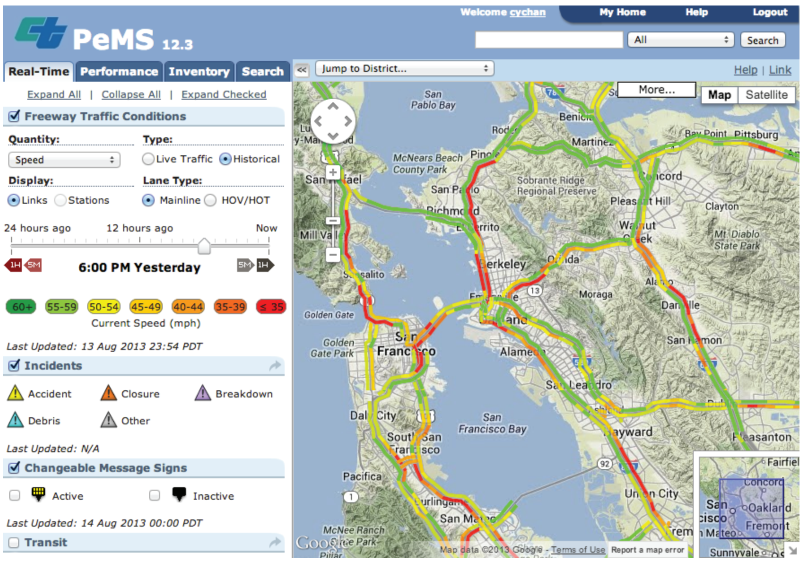
Sponsor: California Department of Transportation (Caltrans)

Introduction

In order to help Caltrans make real-time whole-system traffic management recommendations, the Connected Corridor Management project gathers real-time traffic data and creates a modeling program that quickly evaluates traffic conditions and then recommends the best possible mitigating actions for the agencies to control both the freeway itself and the smaller arterials surrounding it.

Approach

- Assemble data and information about the corridor (the freeway and arterials) and its partners, event and trip generators, accident data, trucks, traffic control devices and software, etc. Use machine-learning algorithms (Adaptive Boosting, Support Vector Machine) to build real-time crash risk evaluation models.
- Use data mining methodologies to estimate and compare corridor performance measures, which include system reliability, congestion, safety, freight movement and economic vitality, based on state-wide Loop Detector Station traffic data (see the right figure).
- Collect video data from the corridor-side cameras and helicopters. Develop driver behavior models by using image-processing technologies.
- Develop a traffic-decision-support system based on control and estimation theories that recommend optimal metering light operation on entrance ramp to relieve congestion on the freeway.



Bay area real-time traffic in the PeMS (Performance Measurement System)

Recent Key Publications

[1] Y. Du, C. Chan, "Empirical Study on Lane-Changing Behaviors Along Different Types of High-Occupancy-Vehicle Lanes in California," *Transportation Research Board 88th Annual Meeting*, Paper 13-3979, January 2009.

[2] Y. Du, C. Chan, "Demand Shifts and Observed Effects on Traffic Operation as a Result of Congestion Pricing Implementation on San Francisco Bay Bridge," *Transportation Research Board 92nd Annual Meeting*, Paper 13-4672, January 2013.

[3] C. Chan, Y. Du, "Operational Performance of High-Occupancy-Vehicle Facilities: Comparison of Contiguous and Limited Access HOV Lanes in California," *Transportation Research Board 92nd Annual Meeting*, Paper 13-4039, January 2013.

Vehicle Attitude Motion Control

Researcher: Iljoong Youn (Visiting scholar)

Sponsor: Gyeongsang National University, Korea

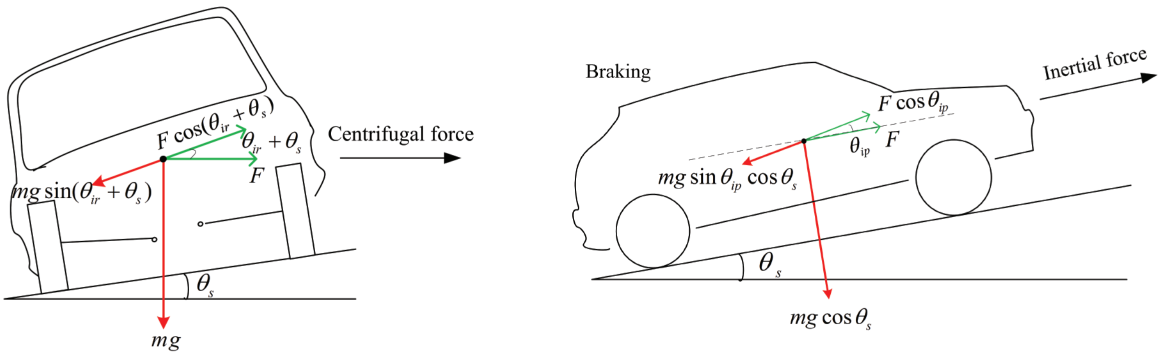
Motivation and Approach

Ride comfort and handling capability are normally considered as conflicting goals in vehicle controller design. Vertical vibrations of the vehicle body, caused by road elevation, worsen ride comfort, and handling capability is related to ground gripping force of the tire. However, the two design goals can be improved together in the case of controlling the attitude motion of a vehicle.

When the vehicle is accelerating, braking, cornering, or traveling on tilted roads, the vehicle body leans and this motion varies depending on the forces experienced: back, forth, centrifugal and gravitational forces. If the attitude motion controller reduces the unpleasant feeling that occurs with attitude motion, it may also improve the handling capability of the vehicle because of the balanced weight distribution achieved by the proper combination of lateral and longitudinal forces and the position change of the mass center. The attitude tracking controller is designed to let the actual motion of the car body follow the ideally guided value, which is computed by the methods developed to eliminate lateral and longitudinal forces acting on passengers. Roughly, the car body leans outside around sharp turns because of centrifugal force and it pitches forward when braking and pitches back when accelerating. However, the attitude tracking controller makes the car body skew inside at cornering, squat at braking, and dive at accelerating.

Main Results

The optimal controller which includes the integral action for the suspension deflection considerably improves the attitude control of a vehicle because the roll and pitch motions in cornering and braking maneuvers are reduced, respectively.



Ideal attitude motion of a vehicle turning on banked circular road and travelling on the slope

Recent Key Publications

[1] I. Youn, J. Im, and M. Tomizuka "Level and Attitude Control of Active Suspension System with Integral and Derivative Action", *Vehicle System Dynamics*, Vol. 44, No. 9, 2006, pp. 659-674.

[2] I. Youn, S. Lee, and M. Tomizuka "Optimal Preview Control of Tracked Vehicle Suspension Systems", *International Journal of Automotive Technology*, Vol. 7, No. 4, 2006, pp. 469-475.

Lab Members

Post-Doctoral Scholars:

Wenjie Chen Ph.D.

Robotics
Human Mechatronics
Graduated: 2012

Ph.D. Xu Chen

Precision Control, Manufacturing
Graduated: 2013
Lecturer at UC Berkeley

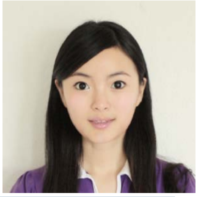
Graduate Students:

Chen-Yu Chan

Human Mechatronics
Expected Graduation: 2016

Michael Chan

Robotics
Expected Graduation: 2013



Yaoqiong Du

Traffic Control
Expected Graduation: 2017

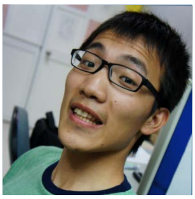
Kevin Haninger

Human Mechatronics
Expected Graduation: 2017

Kan Kanjanpas

Human Mechatronics
Expected Graduation: 2014

Chung-Yen Lin

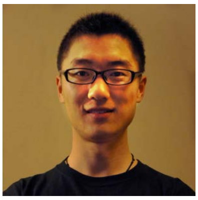


Robotics
Expected Graduation: 2016

Changliu Liu

Human Mechatronics
Expected Graduation: 2017

Junkai Lu



Human Mechatronics
Expected Graduation: 2016

Lab Members

Graduate Students:

Pedro Reynoso-Mora

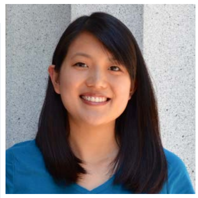
Robotics
Expected Graduation: 2013

Robert Matthew

Human Mechatronics
Expected Graduation: 2016

Chi-Shen Tsai

Human Robot Collaboration
Expected Graduation: 2014



Raechel Tan

Vehicle Control
Expected Graduation: 2015

Yizhou Wang

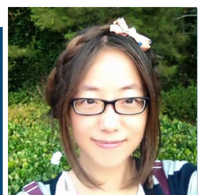
Precision Motion Control
Expected Graduation: 2015

Cong Wang

Robotics
Expected Graduation: 2015

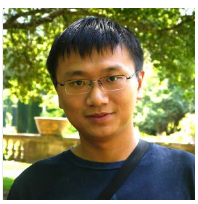
Xiaowen Yu

Robotics
Expected Graduation: 2017



Minghui Zheng

Hard Disk Drive Control
Expected Graduation: 2016



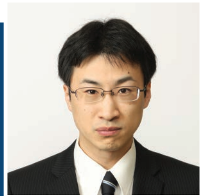
Wenlong Zhang

Human Mechatronics
Expected Graduation: 2015

Visiting Scholars:

Wonhee Kim

Hanyang University, Korea
2013/05-2014/04

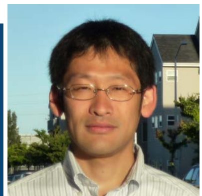


Shigeyuki Mori

Mitsubishi Heavy Industries, Japan
2013/06-2014/07

Hironori Ogawa

NSK Ltd, Japan
2013/01-2015/01



Shuro Nakajima

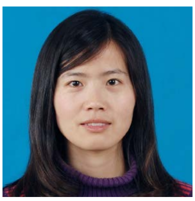
Chiba Institute of Technology, Japan
2013/06-2014/03

Shunta Saito

Keio University, Japan
2013/06-2014/05

Ernesto Solanes

Institute of Design & Manufacturing
Polytechnic University of Valencia, Spain
2013/07-2013/12



Liting Sun

University of Science and Technology of China
2012/08-2014/08

Changfu Zong

Jilin University, China
2013/04-2014/10

Zhenwei Wang

University of Electronic
Science and Technology of China
2013/05-2014/04

Selected Publications

The following publications are selected for being highly cited (more than 50 citations by August 2013). For recent publications, please refer to the research project highlights for more details. For complete publication list and citation statistics, please refer to Professor Tomizuka's google scholar page at
http://scholar.google.com/citations?user=8m8taGEAAAAJ&hl=en

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Dissertations

1977-1978
- D. R. Gunewardana, "Preview Control Applied to Cooling Systems of Power Plant"

1980-1981
- Saad A. Zaghlool, "Time-Domain Vibration-Testing Techniques in Stochastic Environment Model Reference Adaptive Approach"

1982-1983
- C. S. Lin, "Adaptive Digital Control of Multi-Input, Multi-Output Industrial Processes"

1983-1984
- Roberto Horowitz, "Model Reference Adaptive Control of Mechanical Manipulators"

1984-1985
- Jun-Ho. Oh, "Model Reference Adaptive Control of the Milling Process"

1985-1986
- Chen-Foo. Chen, "Modern Digital Motion Control for a Two Dimensional Welding Table"
- Q-S. Zhang, "Multivariable Adaptive Control with Multi-rate Sampling"

1986-1987
- Tse-Liang. A. Yeh, "A Unified Approach to Recursive Identification of Physical System Dynamics"

1987-1988
- Han-Shue Tan, "Adaptive and Robust Controls with Application to Vehicle Traction Control"
- Chee-Leong Teo, "Frequency Reshaped Linear Quadratic Regulator with Application to the Controls of a Flexible Arm"
- Tsu-Chin Tsao, "Digital Tracking Control and Its Application to Noncircular Machining"
- S-S. Yang, "Pulse Control Positioning of Mechanical Systems"

1988-1989
- Min-Shin Chen, "On the Design of Nonlinear Robust Controllers for Linear Systems"
- Kok-Kia Chew, "Digital Repetitive and External Model Controllers"
- Gun Bok Lee, "Digital Control for Burr Minimization in Drilling"
- Alfredo Ong Chingcuanco, "Modelling and Control of a Balloon Borne Stabilized Platform"

1989-1990
- Ming-Chang Tsai, "Theory and Implementation of Adaptive and Repetitive Control for Robot Manipulators"
- Jack Butler, "Minimum Time Trajectory Planning for Torque Limited Multiple Axis Contouring Systems"
- Jiun-Haur Tarn, "Frequency Domain Linear Quadratic Optimal Control Problem"
- Wei-Chi Yang, "On the Design of Discrete Time Robust Control Systems"

1990-1991
- Jwu-Sheng Hu, "Adaptive Regulation and Tracking Under Periodic Disturbances"
- George Anwar, "Repetitive Control and Its Application to Direct Drive Robot Manipulators"
- Gholmareza Langari, "A Framework for Analysis and Synthesis of Fuzzy Linguistic Control Systems"
- Doyoung Jeon, "Force and Position Control of Robot Manipulators: Learning and Repetitive Control Approach"

1991-1992
- Alireza Jabbari, "Robust Discrete Time Control of Uncertain Continuous Time Plants"
- Huei Peng, "Vehicle Steering Control for Highway Automation"

1992-1993

- Pin-Yuang Jacob Pien, "Adaptive Force Control for Two-Dimensional Milling"
- Kurt Hallamasek, "Optimized Repetitive Control for Track Curvature Correction in Helical-Scan Tape Recording"

1993-1994

- Yean-Ren Hwang, "Analysis and Controller Design for Semi-Active Suspension Systems: From the Viewpoint of Variable Structure Systems"
- Eugene David Tung, "Identification and Control of High-Speed Machine Tools"
- Eric M. Gross, "A Feedforward Stable Approximation to Uncancellable Inverse Dynamics in Discrete Time Systems"
- Pushkin Kachroo, "Nonlinear Control Strategies and Vehicle Traction Control"
- Tsu-Chih Chiu, "Coordination Control of Multiple Axes Mechanical Systems: Theory and Applications to Machining and Computer Disk File Systems"
- Liang-Jong Huang, "On the Use of Fuzzy Logic in Self-Paced Tracking Controller Design"
- Satyajit N. Patwardhan, "Fault Detection and Tolerant Control for Lateral Guidance of Vehicles in Automated Highways"
- Addisu Tesfaye, "Theory and Implementation of Robust Performance Digital Servo Controllers"
- Wei-Hsin Yao, "Robust Servo Controller Designs for Positioning Systems based on H-infinity Controller Synthesis"

1994-1995

- Carl Kempf, "Design of Servo Systems for Disturbance Rejection and Applications to Disk File Storage Systems"
- Ho-Seong Lee, "Robust Digital Tracking Controllers for High-Speed/High-Accuracy Positioning Systems"
- Thomas M. Hessburg, "Fuzzy Logic Control with Adaptive Methods for Vehicle Lateral Guidance"
- Ping-Wei Chang, "The Parameterization of a Fuzzy Inference System and its Application to Control"
- Richard S. Paden, "Robust Discrete Time State Feedback Control of Nonlinear Systems with Parametric Uncertainties"

1995-1996

- Tony Phillips, "Multirate and Variable-Rate Estimation and Control of Systems with Limited Measurement with Applications to Information Storage Devices"
- Bin Yao, "Adaptive Robust Control of Nonlinear Systems with Application to Control of Mechanical Systems"
- Prabhakar Pagilla, "Control of Constrained Nonlinear Mechanical Systems: Applications to Robot Manipulators"
- Lin Guo,"Improved Parameterization for System Identification and Digital Control: Theory and Applications to Motion Control Systems"
- Robert Bickel, "Disturbance Observer Based Robot Control with Applications to Force Control"

1996-1997

- John Tenny, "Repetitive Position and Force Tracking Servomechanisms"
- Victor Chu, "Sliding Mode Control with Nonlinear Sliding Surfaces: A B-Spline Fuzzy Logic Approach"
- Chieh Chen, "Backstepping Design of Nonlinear Control Systems and Its Applications to Vehicle Lateral Control in Automated Highway Systems"
- Wonshik Chee, "Unified Approach to Vehicle Lateral Guidance"
- Sujit Saraf, "Advanced Steering Control of Road Vehicles"
- Matthew White, "Control Techniques for Increased Disturbance Rejection and Tracking Accuracy in Magnetic Disk Drives"
- Hyeongcheol Lee, "Adaptive Robust Control Using a Universal Approximator to Vehicle Motion Control for IVHS"

1997-1998

- Mohammed I. Al-Majed, "High Performance Machine Tool Controllers – A Control Theoretic Study and a PC-Based Realization"
- Pushkar Hingwe, "Robustness and Performance Issues in the Lateral Control of Vehicles in Automated Highway Systems"
- Weiguang Niu, "Coordinated Motion Control Subjected to Actuator Saturation"

Dissertations

1999-2000
- Kai-Ten Feng, "Vehicle Lateral Control for Driver Assistance and Automated Driving"
- Motoyoshi Ozaki, "Supervisory Control of Drilling of Composite Materials"
- S. Craig Smith, "Cost Effective Repetitive Control and Its Application to Magnetic Disk Drives"

2000-2001
- Yuping Gu, "Multi-rate Digital Control and Signal Processing: Theory and Applications to Motion Control Systems"
- Soichi Ibaraki, "Nonconvex Optimization Problems in H-infinity Optimization and Their Applications"
- Jeng-Yu Wang, "Robust Lateral Control of Heavy Vehicles on Automated Highways"
- Li Yi, "Two Degree of Freedom Control for Disk Drive Servo Systems"
- Carlo Cloet, "A Mechatronics Approach to Copier Paperpath Design," (Co-supervisor: Roberto Horowitz)

2001-2002
- Meihua Tai, "Advanced Vehicle Control of Heavy Vehicles for Automated Highway Systems"
- Bo Zhu, "Robust Tuning of Fixed Structure Controllers for Hard Disk Drive"
- Erwin S. Budiman, "Toque Feedback and Saturation Compensation for Motion Control of an Indirect-Drive Unit using a Harmonic Drive"

2002-2003
- Shashikanth Suryanarayanan, "Fault Tolerant Control and its Application to Lane-Keeping Control of Automated Vehicles"
- Dong-Jun Lee, "Use of an Accelerometer in Precision Motion Control Systems Design and Its Applicatoins to Linear Motors"

2003-2004
- Jiagen Ding, "Digital Control of Dual Actuator Hard Disk Drives"
- Ye Sheng, "Modeling and Control of Thrust Force in the Drilling of Composite Materials"
- Guang Lu, "Intelligent Sensing and Control for Autonomous Vehicle Following"

2004-2005
- Jihua Huang, "Vehicle Lateral Control Under Sensor Faults"
- Kun Zhou, "Technology Development to Improve Safety and Efficiency of Transit Bus Operations"

2005-2006
- Te-Sheng Hsiao, "Sensor Fault Detection and Fault Tolerant Control with Application to Vehicle Lateral Control Systems"

2007-2008
- Shiang-Lung Koo, "Vehicle Control Usingan Improved Model of Tire Contact Patch Kinematics"
- Soo Jeon, "State Estimation Based on Kinematic Model and Relay Feedback Stability Arising in Controlled Mechanical Systems"
- Li Yang, "Short Seeking and Settling Control for Single-Actuator and Dual-stage Actuator Hard Disk Drive Servo Systems"

2008-2009
- Sandipan Mishra, "Fundamental Issues in Iterative Learning Controller Design: Convergence, Robustness and Steady State Performance"
- Chun-Chih Wang, "Motion Control of Indirect-Drive Robots: Model Based Controller Design and Performance Enhancement Based on End Effecxtor Sensors"
- Shang-Chen Wu, "Precision Control for High-Density and Cost-Effective Hard Disk Drives"
- Mingyu Shi, "Real Time Human Driver Identification for Improved Safety"

- Ahmed Hamdy El-Shaer, "Robust Control Design of Electric Power Steering Systems"
- Kiyonori Inaba, "Iterative Learning Control for Industrial Robots with End Effector Sensing"
- Edgar Ignacio Ergueta, "Full Sheet Control Through the Use of a Steerable Nips Mechanism" (Co-supervisor: Roberto Horowitz)

2009-2010

- Benjamin Thomas Fine, "Practical Iterative Learning Control: Intuitive Methods for Precision Motion Control"
- Takashi Nagata, "Application and Enhancement of Model-Based Design for Automotive Engine and Powertrain Control"
- Kyoungchul Kong, "Mechatronic Consideration for Human Assistive and Rehabilitation Systems"
- Qixing Zheng, "Adaptive Rejection of Narrow Band Disturbance in Hard Disk Drives"
- Cheng-Huei Han, "High Precision Control of Indirect Drive Systems Based on End-effector Sensor Information"

2010-2011

- Haifei Cheng, "Vision and Inertial Sensors Based Drive Train Control"
- Guoyuan Wu, "Development of Adaptive Signal Control (ASC) based on Automatic Vehicle Location (AVL) System and Its Applications"
- Xuan Fan, "Intelligent Power Assist Algorithms for Electric Bicycles"
- Joonbum Bae, "Mechatronic Considerations of Assistive Systems for Gait Rehabilitation"
- Hoday Stearns, "Iterative Methods for High Precision Motion Control with Application to a Wafer Scanner System"
- Shuwen Yu, "Enhanced Iterative Learning Control with Application to a Wafer Scanner System"
- Feng Dan Dong, "Advanced Control Algorithms for Discrete Linear Repetitive Processes in Self-servowriting of Hard Disk Drive"

2011-2012

- Sanggyum Kim, "Design of the Adaptive Cruise Control Systems: An Optimal Control Approach"

2012-2013

- Wenjie Chen, "Intelligent Control of Robots with Mismatched Dynamics and Mismatched Sensing"
- Evan Chang-Siu, "A Tale of a Tail"

2013-2014

- Xu Chen, "Adaptive Local Loop Shaping and Inverse-based Youla-Kucera Parameterization with Application to Precision Control"

Spring 2013

Spring 2010

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