Previous Research Experience

Introduction: As described in my Proposed Plan of Research, my current research involves modeling and analyzing a turbocharged engine system in order to design a combined torque and emission controller. My past projects and research have allowed me to develop the skills necessary for such an endeavor.

Formula SAE Team: *(Aug. 2006 – Jun. 2010)* During my undergraduate years, I was an active member on the UC Berkeley FSAE team. Formula SAE is a competition organized by the Society of Automotive Engineers (SAE) which challenges university teams to design, build, test, and race a small formula-style race car. The goal was to build a car which was faster than the competing cars around a track. I first focused on vehicle dynamics, which involved analyzing a model of the race car in order to design and fabricate suspension and brakes systems for the best performance, i.e. most conducive to quick lap times. I also worked with the engine team, learning how to disassemble and reinstall engine components, how to make a reliable wiring harness, and how to tune fuel and ignition maps on an engine dynamometer. The engine tuning was particularly interesting to me, since it was closely related to my interest in controls. However, I found it inconvenient that we continually had to make changes to the engine maps after installing the engine in the car. It seemed that our engine was very sensitive to disturbances from the external environment (e.g. air temperature), and our original control maps had to be adjusted to retain good performance. Although we had general ideas of how changing the parameters would affect the engine's behavior, I felt that this process could be expedited by better knowledge and analysis of a system model.

Bio-inspired Robotic Tail Research: *(Jul. 2009 – May 2010)* In order to explore further aspects of model-based control, I joined Prof. Masayoshi Tomizuka's Mechanical Systems Control Lab in the summer after my junior year. The goal was to use a mechanical tail to regulate the orientation of a mobile terrestrial robot. This would allow the robot to travel more quickly since it would be able to maintain its stability (i.e. proper orientation) even when traveling across rough, uncertain terrain – similar to the way lizards use their tails to stabilize their body orientation. A stabilizing device such as a low-weight tail could be applied to improve the performance of many types of mobile robots which are required to move through uncertain terrain, such as the search-and-rescue robots used in the wake of the recent Japan earthquake.

I began by designing and fabricating the first prototype of a biologically-inspired robotic tail. This was a simplified proof-of-concept that involved two moving links (body and tail) rotating about a common fixed vertical axis. The two links were connected by a shape memory alloy (SMA) wire actuator, which could be contracted to change the relative angle between the two links. After fabricating the prototype, I conducted system identification experiments to characterize the moment of inertia values of the two links, the amount of damping in the system, and the nonlinear characteristics of the SMA wire. Armed with this knowledge, I designed a linear quadratic regulator (LQR) controller to regulate the body position via actuation of the SMA wire, and confirmed its performance in simulation. I then used a LabVIEW-based field-programmable gate array (FPGA) to experimentally validate the controller design.

This research project is ongoing. Although an SMA actuator has the benefit of very high force density, my work demonstrated that its nonlinear behavior adds a lot of complexity to the control design process. This has informed the current research team to pursue linear DC motors as actuators instead. The recently published experimental results show that the robotic tail does indeed regulate the robot's orientation in the face of external disturbances, and additionally provides a faster response compared to other orientation-stabilizing methods [1].

Flywheel Helicopter Project: *(Aug. 2009 – Dec. 2009)* Inspired by the orientation control of the tail project while brainstorming ideas for my senior design project, I came up with an idea to replace the tail rotor of a helicopter with a flywheel on the same axis as the main rotor. The spinning of the main rotor creates lift, but it also causes an undesirable torque on the helicopter chassis. The purpose of the tail rotor is to create a counter-torque via aerodynamics, but I speculated that an equivalent counter-torque could be produced with a spinning flywheel, which would have the benefit of reducing the footprint and potentially the weight of the helicopter.

I began by creating a dynamic model of the flywheel helicopter system and using MATLAB/Simulink to simulate its response to various situations – such as when the main rotor initializes its spin and when the chassis experiences an external disturbance – with a simple state feedback controller applied to the flywheel. My team members and I built a simplified system with three bodies spinning about a common axis: a chassis, a main rotor, and a flywheel. We used a DC motor to actuate the flywheel, and an optical encoder and Hall effect sensor to measure the position and velocity of the chassis. An additional DC motor was used to spin the main rotor. With the model of the system, I used the pole placement method to design a state feedback controller, and then implemented it with an Arduino microcontroller. Through this project, I was further convinced that modeling a dynamic system was extremely beneficial in the process of designing a controller to achieve a performance goal.

Turbocharged Engine Control Research: *(Jan. 2011 – present)* In January 2011, I began working on my current graduate research on turbocharged engine control, under the supervision of Prof. Tomizuka. Through discussions with a senior engine control engineer at Toyota as well as extensive literature review, I learned about the trend of downsizing and turbocharging engines for reducing fuel consumption. I noted that the various control loops (e.g. torque, emissions) are usually run independently, and thus there is the possibility of interference between them. This is a particular issue in a turbocharged system, due to the strong nonlinear coupling between the intake and exhaust systems via the turbocharger.

In order to study this effect, I formulated a control-oriented model of the turbocharged engine system based on thermodynamic energy conservation laws and empirical relationships observed by other researchers ([2], [3], [4]). This model provides significant insight into interactions between the control loops, and preliminary open-loop simulation results show behavior typical of a turbocharged engine. Although the model is admittedly complex (as it must be to accurately reflect the behavior of an engine), it is tractable enough to be used as a basis for controller design. I am currently in the process of analyzing the system in order to develop an effective nonlinear multivariable strategy to control both torque and emissions in an optimal manner. Additionally, I am preparing a 2.3L turbocharged, gasoline direct injection Mazda engine test cell for experimentation, first for system identification and then for control validation.

References: **[1]** Chang-Siu E, Libby T, Tomizuka M, Full R. *A Lizard-Inspired Active Tail Enables Rapid Maneuvers and Dynamic Stabilization in a Terrestrial Robot*. 2011 IEEE/RSJ Int. Conf. on Intelligent Robots and Syst. 2011;1: 1887-1894. **[2]** Guzzella L, Onder C. *Introduction to Modeling and Control of Internal Combustion Engine Systems*. 2nd ed. Berlin: Springer; 2010. **[3]** Cho D, Hedrick J. *Automotive Powertrain Modeling for Control*. ASME J. Dyn. Syst., Meas., Control. 1989;111(4):568-576. **[4]** Fox J, Cheng W, Heywood J. *A Model for Predicting Residual Gas Fraction in Spark-Ignition Engines*. SAE Technical Paper 931025; 1993.