Introduction

My research efforts center on understanding and improving human mobility by developing biomemetic controllers for powered assistive devices and humanoid robots and on developing control augmentation for small manually controlled vehicles. The ability humans have to ambulate and manipulate devices continues to be the envy of engineers who desire to artificially mimic their motion. Understanding and mimicking the intricacies of the mammalian neuromuscular system have the potential to allow us to improve human life through assistive machine and device design. However, contemporary robots and machines are still limited in their ability to emulate the robust capabilities of mammalian sensing and actuation.

The fundamental question that I am interested in is:

> Can dynamically human-similar machines and their controllers be designed to move as a human would move, if provided neurally-limited driving control inputs?

I am interested in identifying practical controllers for devices, robots, and vehicles which encode feedforward and feedback control such that the combined human/machine system has nearly identical motion to an able-bodied human. My current focus is on improving balance while standing and walking with lower limb prostheses and exoskeletons. To do this my research currently has three primary foci:

1. Identifying how humans balance and locomote through data intensive computational estimation, learning, and identification.
2. Applying biomemetic control algorithms and design enhancements derived from identified controllers to assistive devices such as exoskeletons, powered prostheses, small vehicles, and humanoid robots.
3. Developing next generation open and collaborative computational tools to back efforts in the first two items.

Current State of Human Locomotion Simulation & Assistive Control

Deep reinforcement learning has had growing success in creating joint torque driven closed loop controlled simulation of low-fidelity humanoid models in complex virtual environments (e.g. [45, 9]). Parallel to the reinforcement learning are efforts to generate closed and open loop controllers through optimal control methods (shooting and trajectory optimization) that focus on minimizing energy expenditure of high-fidelity neuromuscular models in more basic walking and running tasks. These methods produce simulations of much more realistic gait [2, 47, 48, 8, 39, 46, 6]. Very recently these parallel efforts have merged with signs of promise. For example, in the 2017 NIPS AI challenge contestants used deep reinforcement learning to discover realistic gait control for a muscle activated high-fidelity lower body neuromuscular model [12]. Machine learning and shooting based optimal control using the high-fidelity models are bound by the forward dynamics computation speeds, which are real-time at best. Advancements that reduce forward simulation speeds or circumvent the need to explicitly evaluate the stiff dynamics are needed to make more rapid progress. Successful simulations that incorporate modeled prostheses have just emerging (e.g. [13]) which is an exciting new path in the field.

Powered assistive devices such as powered below- and above-knee prostheses have improved drastically in the last decade and have been shown to reduce the metabolic cost of walking in amputees [3], with some now moving to commercial products (e.g. Rheo Knee). Unpowered [4] and powered [49] exoskeletons can also do the same for able bodied walkers [4]. Powered lower limb exoskeleton for paraplegics are just now being approved by the FDA for the US and European markets (e.g. Rewalk, Indego, Esko). These devices rely primary on non-neural control, offer no balance during gait, and move with a very unnatural gait. Future research will improve all three of these aspects to bring natural self-balanced walking back to the paralyzed.

In the past year, we have started to see merger of the successes in software and the successes in hardware with demonstrations such as in [40] alluding to a bright future for discovery with lower limb systems.

My Past Work in Human Motion and Control

Much of my prior research has focused on the problem of control identification in human balance where I have attempted to answer this question:

> Given the simultaneous measurements of the kinematics of human motion and optionally human/environment interface and internal system forces, what is the casual relationship from sensing to actuation in human motion?

My graduate work focused on understanding the control mechanisms humans use while balancing on a bicycle. Because the bicycle is a dynamically complex vehicle [1, 15, 34, 18] that acts as an intermediary between the human and the environment it is a powerful platform for understanding balance.

I began by applying principal component analysis to a large collection of motion capture data during steady state bicycling on a treadmill, which identified dominant motion patterns and exposed subtle leg motions used for balance at extreme cases [17], [32]. We further confirmed this behavior with video analysis of more natural bicycling behavior around a city and on a treadmill [14]. Following those initial experiments, I developed an instrumented bicycle, capable of accurately measuring the full dynamic state of the rider-vehicle system [20, 30] and collected copious amounts of data during responses to lateral perturbations in path tracking tasks. Using a manual control based theoretic controller [10] and data driven parameter estimation, I identified a set of controllers that explained the dominant rider perturbation linear response behavior [20], which was then used to characterize a general controller able to mimic human behavior for a broader set of control tasks. This was expanded further with other theoretic controller structures for bicycling [41, 43, 42] and also applied to aircraft control identification [11].

The work on bicycle control identification lead into postdoctoral work focused on developing controllers for lower extremity exoskeletons designed to assist paraplegic individuals in walking. We partnered with Parker Hannifin Corp. and targeted their Indego Exoskeleton. My goal was to provide natural gait and unassisted balance for these devices, something that is still lacking today. Utilizing an actuated treadmill coupled with full body kinematic tracking, I collected large quantities of walking data from both normal walking and longitudinally perturbed walking. I published the data as one of the first data papers in the field [29] and demonstrated the effectiveness of the treadmill belt perturbation method. I used this data with a direct gait cycle gain scheduled feedback identification technique to identify possible closed loop controllers [36, 27, 28]. This work led to the development of an indirect identification technique based on parameter estimation with direct collocation to enable simulated validation of the controllers. Direct collocation gave us the computational speed to discretely simulate hours of data. Starting with a simpler problem, I developed methods with data derived from human perturbed standing data. The techniques led to orders of magnitude of improvement in computation speed and control identification strictly from kinematic data [37, 38].

Since moving into a teaching faculty position at UC Davis I have mentored and led a number of sensing, instrumentation, and robotics projects that build on the prior research with various local companies and undergraduate students. We have developed an adaptive mouth-based control for an electric tricycle which is ALS and quadriplegic friendly with Outrider USA and Disability Reports. This past year my students developed a powered cable driven hand prostheses for partial upper body paralysis with Ekso Bionics. With SRE Engineering we developed a wireless boot for measuring ground reaction forces for horse trotting in non-laboratory settings that I would like to apply to human walking. I also mentored a group of students that developed a robot to tie a shoe, one of the more complex tasks human hands perform. Lastly, I have developed a desktop balancing robot that will be used to validate the indirect identification methods for standing balance that I mentioned above. My current projects can be viewed on my lab website: http://mechmotum.github.io.

All of my research relies heavily on open source computational data analysis and simulation tools, much of which I have developed and published. Most notably, I am a core developer of SymPy [44], a computer algebra system, and the maintainer of the classical mechanics package [7]. Our 2017 paper [16] on the 11 year old software has over 100 citations, along with thousands of users and hundreds of contributors making it one of the most popular packages in the Scientific Python ecosystem. Additionally, I have developed a suite of bicycle dynamics related software packages [21, 22, 23, 19] and dynamics/biomechanics packages [5, 24, 25, 26, 33, 31]. Recently I have published a package for general purpose trajectory optimization and parameter estimation [35] and also for ski jump design [31].

My Research Plans at UC Davis

As a professor of prosthetics and assistive robotics I will play an integral role in UC Davis's vision for growth in neuroengineering. I plan to lead a laboratory that will provide computational and experimental biomechanics expertise alongside humanoid robot and assistive device design. This will complement the existing and upcoming efforts that focus on the neural aspects of an interdisciplinary neuroengineering core. I hope to revive the MAE department's past notability in biomechanics with a modernized biomechatronics focus. I also want to help catalyze making the Sacramento region a leader in bio-robotics. The combination of UC Davis Engineering, UC Davis Med Center, CSUS Engineering, our proximity to the Bay Area, and local companies such as Intel and Siemens paired with the burgeoning local startup scene can tie in with the Chancellor's plans for Sacramento and Davis to become a new hub for technical innovation.

With more than a decade in the region, I have a wide network of partners to bring this vision to life that span the UC Davis faculty and centers, UC Davis Med Center, UC Davis Vet Med Center, local orthotics companies, and Bay Area biomechanic and robotics companies. My network also spans beyond the region to the state, national, and international collaborations. I plan to grow my collaborations with regional companies and labs (e.g. Toyota Research Institute, Motion Analysis, Ekso Bionics, Inscitech, Open Robotics, Stanford's Neuromuscular Biomechanics Lab) along with my expanded collaborators (e.g. Cleveland State's Human Motion and Control Laboratory, Cornell's Biorobotics Lab, TU Delft's Biomechanics Department, and Meijo University).

I will continue to participate in a number of academic communities that I am currently involved with. The lab will target conferences such as Dynamic Walking and ROSCon along with the American and International Societies of Biomechanics (including the ISB Technical Simulation group). On the software side, we will continue to present at SciPy, PyData, and PyCon for open source computation.

In the MAE department, I am interested in developing and growing collaborations with Zhaodan Kong for high level robot planning and machine learning, Xinfan Lin for estimation needs in human motion, Karen Moxon for neural sensing and control, Sanjay Joshi for electromyography and control, and Stephen Robinson's human/robotics integration. I have relationships with emeritus Profs. Hess, Hubbard, Hull, Eke, Margolis, and Karnopp for dynamics, biomechanics, and control. I am a faculty affiliate at the new Data Science Initiative and plan leverage that relationship to grow our data centric computational work. I also look forward to developing more cross disciplinary research partners, many which have begun with the 70+ capstone design projects I have mentored.

The lab I am planning will be able to 1) collect motion data from humans and robots in mobility related activities both in the lab and in natural environments, 2) apply cutting edge learning, estimation, and identification methods to characterize human control, 3) build and test controllers in humanoid robots and assistive devices, and 4) contribute to and develop the next generation of open source biomechatronic related software.

My initial project plans are multifold and will build from my prior work. I will start recruiting students for 1) applying parameter identification using direct collocation to perturbed walking data to discover a gain scheduled closed loop control, 2) development of a scaled balancing robot that simulates perturbed human balancing, 3) accelerating lower body neuromuscular forward dynamics simulations through implicit dynamics and optimized code generation and common sub-expression evaluation across CPU/GPU cores, and 4) development of a low-fidelity lower limb exoskeleton for controller testing.

I will use the results from these initial projects to develop grant proposals for the National Science Foundation's CMMI, IIS, CBET, and CNS divisions[1] and the NIH's rehabilitation and data focused initiatives which all have a history of and currently support similar research. Additionally, I will pursue funding with private foundations such as the Gordon and Betty Moore Foundation and the Alfred P. Sloan Foundation for open source computational and data innovation support and partner with prior mentioned companies for small commercially relevant project support.

Given the opportunity, I have the skills, network, and vision to succeed as a professor of prosthetics and assistive robotics at the University of California, Davis.

[1] Division of Civil, Mechanical and Manufacturing Innovation, Division of Information & Intelligent Systems, Division of Chemical, Bioengineering, Environmental, and Transport Systems, and Division of Computer and Network Systems, respectively.

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