Research Statement

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Introduction

My primary research efforts have centered on understanding and improving human mobility by developing biomemetic controllers derived from data collected on human motion during unassisted activities (e.g. standing, walking) and activities in which the human is operating a vehicle (e.g. bicycling, skateboarding) or interacting with a machine or implement (e.g. leg prostheses, sporting equipment). I am most interested in developing human control compatible machine designs and human-in-the-loop control systems that augment a person's experience for improved control, safe operation, and performance enhancement. The fundamental question that I am currently focused on is:

> Can dynamically human-similar or human-coupled machines and their controllers be designed to move as well as or better than a human controller would move, if provided neurally-limited control inputs?

To answer this question, my current research 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 bicycles, exoskeletons, powered prostheses, personal mobility vehicles, and humanoid robots.
3. Developing next generation open and collaborative computational tools to back efforts in the first two items.

My prior research combines knowledge and methods derived from multibody dynamics, sports biomechanics, human motion and control, transportation, and computational engineering. I consider myself an applied computational and experimental dynamics and control engineer; equally comfortable at the whiteboard, on the computer, and in the lab. Much of my work utilizes single track vehicles as a platform for studying multibody dynamics and manual control.

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, 36, 18] that acts as an intermediary between the human and the environment, it is an ideal vehicle platform for understanding balance and manual control.

My early graduate work focused on 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 low speeds [17, 35]. We further confirmed this low speed behavior with video analysis of more natural bicycling behavior around a city and on a treadmill [13]. This work has since been widely cited in the motion studies literature.

Following those initial experiments, I designed and fabricated a uniquely instrumented bicycle, capable of accurately measuring the full dynamic state of the rider-vehicle system [21, 32], including the most accurate steer torque measurements to date. With this instrument, I collected copious amounts of data during responses to lateral perturbations in path tracking tasks. Then, starting with our theorectic manual control model [11], I applied data driven parameter estimation techniques to arrive at a set of controllers that explained the rider's dominant linear response behavior to the perturbations [21]. I showed that this control model was able to mimic human behavior for a broader set of control tasks and could be used to estimate the handling qualities of different bicycle designs. This work also supported other theoretic controller structures for bicycling [45, 47, 46] and was also applied to aircraft control identification [12].

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 research was led by the goal 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 [30] and demonstrated the effectiveness of the treadmill belt perturbation method. The data has been used in a variety of other control studies (e.g. [42, 49, 51]), as well as inspiring more data papers [43, 8, 7, 44].

I used the perturbed walking data with a direct gait cycle gain scheduled feedback identification technique to identify possible closed loop controllers [38, 28, 29]. The technique proved to be very computationally efficient and the identified controllers exhibited repeatable feedback patterns in the gait cycle across the walkers.

Difficulties in utility of the prior work led to the development of an indirect identification technique based on parameter estimation with direct collocation to enable simulated validation of the controllers [40, 41]. We demonstrated the computational efficiency and ability to accurately identify control from kinematic data in simulated perturbed human standing. I further codified this technique in a general purpose software library that efficiently constructs the optimization or identification problem from a high level problem description [39, 37].

My Current Work in Human Motion and Control

Since moving into a teaching focused position at UC Davis, I have mentored and led a number of sensing, instrumentation, software, and robotics projects with various local companies and undergraduate students that build on my prior research. We have developed an adaptive mouth-based control for an electric tricycle which is quadriplegic friendly with Outrider USA and Disability Reports and 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 develop for human walking. I also mentored a group that developed a robot to tie a shoe [3], one of the more complex tasks human hands perform.

I have further developed our single track vehicle handling quality metric proposed in [11] and utilized it in discovering a variety of bicycle designs with theoretically optimal handling [19, 34]. To validate this theory, we have developed experimental methods with preliminary results indicating a likely relationship in the handling quality metric and rider subjective ratings [14]. And most recently, we have begun constructing the optimal bicycles [10] and evaluating them in terms of their handling.

I have also led two projects in sports engineering in the past couple of years: 1) development of a web application for designing and analyzing ski jumps for improving jumper safety [33, 5] and 2) the implementation of real-time algorithms that improve estimation of competitive rowing performance metrics from smartphone inertial measurement unit data [4].

All of my research relies heavily on open source computational data analysis and simulation tools, many of which I have developed and published. Most notably, I am a core developer of the computer aided algebra system, SymPy [48], and the lead maintainer of the associated classical mechanics package [9]. Our 2017 paper [16] on the now 13 year old software has over 250 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 and control software packages [22, 23, 24, 20], general purpose dynamics and control packages [39, 25], and biomechanics packages [6, 25, 26, 27].

More about my research projects can be viewed on my lab website: `http://mechmotum.github.io`.

My Bicycle Research Plans

Over the last two decades, the use of bicycles has increased in many countries where its use as a mode of transportation has been historically low. This positive change is the result of many factors, including advances in bicycle related technologies such as electrification and public use designs. In the near future, I foresee bicycles connected into the smart city, far greater use of electric bicycles, growing use of cargo bicycles in urban centers, and growth in both older and younger riders. Yet, despite the increase in ridership, bicyclists will still remain vulnerable road users. More political and technological solutions will be needed to increase safety for bicyclists. As a mechanical engineer, I plan to play an integral role in increasing bicycle safety and use around the world through technological advances.

The lab I envision will support all types of bicycle technologies. Collaborations with other TU Delft researchers will help us make advances in tire material properties, evaluation of electric bicycle transmissions, power augmentation control in pedal assist bicycles, ergonomics, and performance improvements.

As a professor focusing on bicycle dynamics and control, I will have several parallel and intertwined avenues of research that will support this broader social vision:

- Data driven vehicle and biomechanical modeling of the bicycle-rider system
- Data driven manual control characterization and identification in bicycle balance and navigation
- Design and augmented/autonomous control for improvements in bicycling safety and handling
- Development of the next generation of bicycle designs for improvements to transportation
- Application of vehicle dynamics to influence transportation infrastructure design
- Performance and safety improvements in the sport of cycling

I will initiate these research avenues by focusing on several low hanging fruit among the current state of the art, my prior work, and the TU Delft Bicycle and Control Laboratory's prior work. The following paragraphs detail the initial projects I have in mind.

The most popular open loop bicycle vehicle dynamics model fails to make accurate predictions of the vehicle's motion resulting from prescribed input forces acting on the handlebars [31]. Using data collected during closed-loop riding (via robotic and/or human control) I want to identify the missing first principles. I also plan to develop a simple rider biomechanical model that captures the most important degrees of freedom and actuation methods based on [25]. These two aspects will advance the state of the art vehicle-rider system models.

Identification of the controller in a closed-loop feedback and feed-forward system is not a simple task [50]. I want to expand on the robustness of my earlier efforts by collecting data during a broad set of events more rich in frequency content while also collecting additional physiological measures to capture signals related to the human's internal sensing system. This identification will use optimal control, parameter identification, and physics-informed machine learning methods. This will result in general validated human control models for single track vehicles.

To succeed at the above initiatives, I want to design and construct a new force sensing treadmill for single track vehicle experimentation. Measuring the ground reaction forces and moments at each individual tire while performing maneuvers on a treadmill in a simulated environment will provide the next level of fidelity in understanding the vehicle and rider dynamics. This treadmill will be unique to the world and combined with simulation environments developed at TU Delft will offer a capable experimental platform that will be attractive for many industry interests.

Using both a robotic bicycle (currently on loan to TU Delft from UC Davis) and TU Delft's steer-by-wire bicycle, I plan to explore how vehicle and controller design can effectively assist the rider's control, i.e. to take over when the human's deficiencies are present and to maximize the performance in safety critical maneuvering. These efforts will provide essential elements to having autonomous single track vehicles in the future and safety enhancements that go far beyond simple traction control.

I want my research to have direct impact on transportation mode share and safety for bicycling. I have preliminary work on using bicycle simulations for evaluating bicycle transportation infrastructure and creating standards for infrastructure [2]. There is also an opportunity to apply bicycle balance and control theory to the design of cargo bicycles and other non-traditional bicycles. Both of which will connect my work to practice.

Finally, I have long had a dream of being part of a team that could attain the world human powered speed record. TU Delft has done so in the past and I intend to help them do so again. I would like to apply both my work in trajectory optimization for speed improvements and lateral control to to relieve the rider so they can focus fully on power generation.

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