Summary of My Research

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1 My Research and Objectives

My research interests span control theory, nonlinear and robust control, robotics, hybrid systems, dynamical systems, optimization, and power systems. I develop nonlinear feedback control solutions for dynamical models ranging from robotic systems to power systems. The models of these systems are typically characterized by high dimensional state spaces, with nonlinear and hybrid dynamics. My research has a clear path from theory to practice. While the bulk of my experience has been on the theoretical side of these subjects, recently, in my postdoctoral studies, I have been pursuing experimental implementation of my work on a challenging 3D bipedal robot, ATRIAS [2], [8], [6] (see Fig. 1).

We are on the verge of a new revolution in robotic legged locomotion. During the past three decades enormous advances have occurred in control and motion planning of dynamic locomotion of legged robots. In particular, hundreds of walking mechanisms have been built in research laboratories and companies throughout the world. The study of legged locomotion has been motivated by the desire to allow people with disabilities to walk and to replace humans in hazardous environments with capable machines. Over the coming years and decades, the development of an agile and stable bipedal robot with a desired level of control will impact the developing world in even greater ways than may now be imaginable. However, there is still a long way to go to make this a reality. In particular, while the technology involved in robot construction is advancing rapidly, the science of stabilization of trajectories for these robots based on feedback control algorithms to achieve standing, walking, stepping over obstacles, etc. is lagging.

The technology we currently have for walking robots is about where the automotive industry was 150 years ago - full of promise, with a number of new inventions and about ready to take off. In the next 20 years we are going to see legged robots all over the place, doing all kinds of jobs. Walking or bipedal robots will help people with physical disabilities, take on dangerous missions or aid in disaster response. For example, robots will act as an exoskeleton to help disabled people get around in ways they could not before. They will rush over rough terrain to respond to an emergency.

For researchers within the control systems community, underlying the study of energy-efficient, dynamic, robust and stable legged locomotion, is the challenging mathematical problem of determining the existence and robust stability of periodic solutions (e.g., walking and running gaits) to hybrid systems describing the locomotion by robots. Furthermore, modern complex engineering systems necessitate the application of multiple modes of operation which places stringent demands on controller design. Such systems typically possess a multi-echelon hierarchical hybrid control architecture.

My research is interdisciplinary and well positioned to develop systematic methods, based on robust nonlinear control, hybrid control theory and optimization, for controlling a class of dynamical systems arising from mechanical systems and power electronics [2], [10]. The results of this research can be used for achieving stable, agile, efficient and robust locomotion.

Figure 1: Nonlinear and robust control of ATRIAS, a humanscale 3D bipedal robot designed for energy efficient 3D walking.
in legged robots, especially bipedal robots. They can also be used to improve the control of existing robots, machines, mechanical systems interrupted by collision, electronic power systems interrupted by switches, and also to provide guidelines for improving the mechanical design of future robots, controlled prosthetic legs and wearable robots (biomedical applications), and power electronics devices.

2 Research during the Ph.D.

During my doctoral research under the supervision of Prof. William A. Gruver, Prof. Nasser Sadati, and Prof. Guy A. Dumont, I worked on novel methods for allowing machines to walk and run with the agility and stability of a human being. I used advanced mathematical techniques based on nonlinear control, differential geometry, hybrid and discrete event systems, nonholonomic motion planning, and Lagrangian mechanics to design model-based feedback controllers for hybrid systems of robot legged locomotion. My Ph.D. research proposed novel methods for the improved control and stabilization of periodic orbits for hybrid systems with an application to legged robots (see Fig. 2). I developed a new method of control of bipedal locomotion during the double support phase \[3\]. This is an extremely difficult engineering problem which has wide application and is of great interest within the international robotics community. My research also presented novel hybrid control schemes for 2D and 3D monopedal robots \[4\], \[9\], online and offline motion planning algorithms \[9\], and two-level control schemes to restore the walking gaits in disabled people \[5\].

3 Research during Postdoctoral Studies

During my postdoctoral research fellowship at the University of Michigan, under the supervision of Prof. Jessy W. Grizzle, I worked on designing energetically efficient gaits and developing robust hybrid controllers for hybrid systems describing 3D walking and running locomotion. The motivation is a novel, very advanced 3D bipedal robot in Prof. Grizzle’s laboratory, ATRIAS \[2\], \[8\], \[6\]. This research is a collaborative effort, involving the University of Michigan, Carnegie Mellon University and Oregon State University. ATRIAS is a human-scale 3D bipedal robot designed for energy efficient and robust 3D walking (see Fig. 1). I was developing its dynamic model, motion planning algorithms, and a robust feedback design for the lateral stabilization of ATRIAS.

My postdoctoral and Ph.D. research has resulted in several practical advancements and novel methods for allowing machines to walk and run. In particular, the results have been reported in one book entitled “Hybrid Control and Motion Planning of Dynamical Legged Locomotion” published by Wiley-IEEE Press and ten published peer-reviewed journal papers (IEEE, IEE and ASME). Furthermore, the videos of our recent experiments with ATRIAS have been presented on the websites of IEEE Spectrum, The Atlantic, The Business of Robotics, and Michigan Engineering.

4 Current Research

Robotics and more generally Lagrangian mechanical systems with unilateral constraints have provided the motivation and inspiration for many innovations in path planning and control of hybrid dynamical systems. Furthermore, modern complex engineering systems necessitate the application of hierarchical hybrid controllers acting with both continuous-time and discrete-time modes. I investigate several key points in the area of nonlinear and robust control, hybrid dynamical systems,
Increasing robustness based on nonlinear control and internal stability: I continue to seek out ways to increase the robustness of closed-loop hybrid systems. Important cases where robustness arises are walking on uneven ground, walking with unknown load and push recovery problems. In our design approach, to stabilize periodic orbits for hybrid systems, a set of output functions is defined for the continuous part of the hybrid model and the outputs are zeroed by a feedback law to create an attractive invariant manifold. This approach simplifies the stabilization problem of the full-order system to the analysis of a reduced-order system. At the lower levels of the hybrid controller, the output zeroing problem is asymptotically done through the action of a feedback controller within each phase of the hybrid models. Next, to asymptotically stabilize the orbits, the parameters of the output functions are updated at higher levels of the controller in a discrete-time manner. To date, there is no systematic approach to choose the output functions to guarantee the internal stability of the reduced-order hybrid system. In the case of internal stability, the stabilization is achieved at the lower levels and the higher levels can be used to increase the robustness as well as the domain of attraction for stable orbits. Recently, we could present a systematic method based on sensitivity analysis and bilinear matrix inequalities (BMIs) to design output functions that provide robust exponential stability of a given periodic orbit without relying on higher level event-based controllers. A BMI optimization problem is then setup to tune the parameters of the output functions. The proposed BMI optimization problem can be solved efficiently with existing software packages. The approach has been illustrated to design continuous-time controllers for two underactuated 3D bipedal robots with 13 and 8 degrees of freedom and 6 actuators [1], [7]. The method is practical for real legged systems and can be extended to handle additional optimization goals.

Other mathematical tools for stabilization of hybrid systems: Lyapunov stability, invariance and dissipativity have recently been extended to impulsive and hybrid systems. Most of these results pertain to the study of equilibrium points, not periodic orbits. The most basic tool for analyzing the stability of periodic orbits of time-invariant dynamical systems described by ordinary differential equations as well as hybrid systems is the Poincaré return map. This method unfortunately has some serious limitations. In almost all practical cases, the Poincaré map must be estimated numerically, and when the underlying dynamics is high dimensional and presents a wide range of time scales and uncertainties, the numerical approximations are sufficiently inaccurate that controller design is very difficult. During my postdoctoral research, the way we handled this inaccuracy is to make sure that our hybrid control strategy is insensitive to the numerical approximations. To achieve this insensitivity, we formally apply robust control theory techniques such as linear matrix inequalities, convex optimization and model predictive control. In future work, I plan to consider other analytical approaches and tools for stabilization of orbits for hybrid dynamical systems.

Hybrid and robust control design for robot-assisted walking: Important medical applications of bipedal locomotion research include lower-limb prostheses, exoskeletons, and devices for the rehabilitation of walking and balance after injury. During my postdoctoral research and Ph.D., I have developed motion planning and robust control strategies for autonomous robotic locomotion. High-performance prostheses and orthoses (i.e., exoskeletons) could significantly improve the quality of life for millions of lower-limb amputees. I would like to translate and employ robust and nonlinear hybrid control theoretical approaches from robot walking into control strategies for clinically viable wearable robots. The results of this research can aim to develop high-performance wearable control systems to enable mobility and improve quality of life for persons with disabilities.

Bio-inspired robotics: One of the key characteristics of animals is their ability to efficiently move in different environments. This impressive capability is the result of millions of years of evolution, and its flexibility and energy efficiency are still far from being approached by robots. Understanding animal locomotion as well as developing robots capable of good locomotion are hard problems because of the complex nonlinear interactions between the control, the body, and the environment. Neural control of vertebrates locomotion is not yet fully understood, but there is much evidence suggesting that the main control of vertebrates is done by neural circuits called central pattern generators (CPG) in the spinal cord. These CPGs form a network of coupled nonlinear neural oscillators which together with reflexes can produce rhythmic movements such as walking, running and swimming. During my Ph.D., I developed different topologies of these networks, whose parameters are tuned based on nonlinear optimization problems, for inducing stable walking motion in legged robots. In this regard, I work on the computational aspects of movement control, sensorimotor coordination, and learning in animals and in robots. This research aims to understand the neural mechanisms underlying movement control and learning in animals, and in return to take inspiration from animals to design new bio-inspired control methods for robots as well as novel robots capable of agile locomotion in complex environments.

Dynamic optimization and model predictive control approaches for higher levels of a hybrid controller: Practical demands necessitate that actuator saturation be addressed in all levels of a control hierarchy, while still guaranteeing the stability of orbits. I would like to employ dynamic optimization, model predictive control, and robust optimal control approaches to consider input and state constraints.
**Development and applications of nonlinear, robust and adaptive control strategies to robotic and power systems:** Finally, other areas that I plan to continue to research on stem from nonlinear, robust to adaptive control and their applications in challenging robotic, mechanical, and power systems. For instance, one of the studies that I have recently started is the development of adaptive control methodologies, based on nonlinear control for DC output voltage regulation and power factor correction of three-phase rectifiers in the presence of parametric and non-parametric load uncertainties. Industrial demands require the application of converters that provide (i) fixed output voltage, (ii) high input power factor and (iii) low line current distortion. The three-phase/switch/level (Vienna) rectifier has unique ability in the category of power factor correction switch-mode topology to satisfy the aforementioned features. In this research, I would like to present different nonlinear control approaches based on zeroing output functions such that solving the input-output linearization problems results in internal stability of the closed-loop system. Next, I propose indirect adaptive algorithms to improve the ability of these nonlinear approaches to asymptotically transfer the state vector of the closed-loop system to the desired equilibrium point despite uncertainties in the rectifier and load parameters.

**References**


