

RESEARCH STATEMENT

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Unconventional locomotion systems have drawn significant interest in recent years because of their ability to tackle terrains that wheeled robots are incapable of traversing and because the novel actuation modes they use present advantages in size, power consumption and weight. Such systems find applications in search and rescue, interplanetary exploration and surveillance. The research effort in this area requires advances in design and integration of actuation, control and sensing to create novel locomotion systems that exploit unique dynamics and actuation techniques.

My primary research interest is in developing and studying unconventional locomotion systems that use novel modes of locomotion. I have extensive experience in my thesis and post-doctoral work in this area. As part of my PhD thesis, I developed a general framework for studying modular locomotion systems composed of multiple locomotion modules like powered wheels, passive wheels (skates) and legs. Figure 1 shows some of the robots I designed and studied in this research. The RoboTrikke is a novel underactuated robot with a single input. The Rollerblader is a rollerblading robot which, with modifications in design, should also be able to skate on surfaces like ice. I was also able to put an interesting twist on the bicycle and show how it could be actuated without pedaling.

Nonholonomic constraints arise when a wheel or knife-edge is in contact with the ground and restricts motion in a direction perpendicular to its rolling direction or knife-edge respectively. The Rollerblader, RoboTrikke and bicycle are all acted upon by multiple *nonholonomic* constraints and thus are restricted to motion along certain directions. The momenta along these directions are referred to as generalized momenta and can be used to reduce and simplify the equations of motion. My main contribution to this geometric analysis was in the analysis of *nonholonomic impacts*, *i.e.* impacts that occur when modules like wheels or legs with nonholonomic constraints acting on them come into contact with the ground. This technique was applied to the analysis of the Rollerblader, the first *true* rollerblading robot capable of human-like rollerblading gaits.

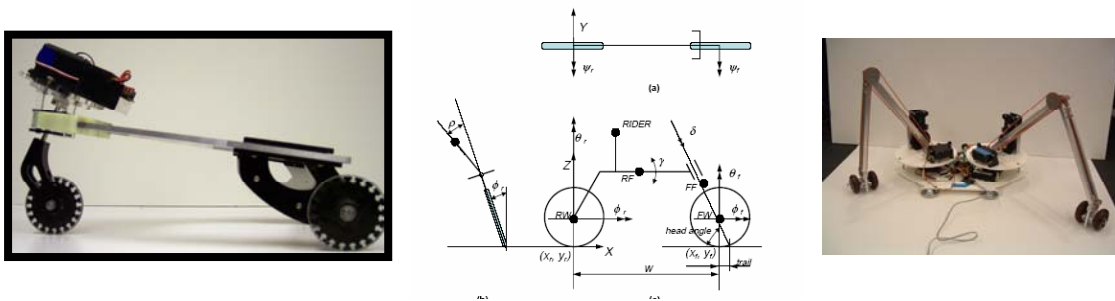


Figure 1: The RoboTrikke, bicycle and Rollerblader

Gait generation for systems with multiple nonholonomic constraints is a difficult problem. The local controllability and small-time local controllability (STLC) properties of the system play a big role in the choice of gait generation methods for such systems. The RoboTrikke is not STLC in the absence of friction while analysis of the Rollerblader

proved inconsequential in determining controllability. However, for the Rollerblader, I was able to derive two novel gaits that result in forward motion along a straight line and rotary motion in place. A kinematic abstraction allowed these gaits to be composed for point to point motion. Taking inspiration from human rollerblading, I also derived and implemented true rollerblading gaits that allow the robot to pick up its feet and use a walking and skating motion for propulsion.

The RoboTrikke is similar to a more interesting and complicated system – a bicycle with no pedals. The RoboTrikke is actuated by using a single rotary input and its motion is necessarily dynamic. Its motion can be further enhanced by an additional input in the form of a rider and I was able to show, both experimentally and through geometric analysis, how the right phasing of inputs can be used to speed up the robot. Further, using external feedback, I was also able to experimentally control it to follow a straight line trajectory. Extending this work to more dynamic systems, the bicycle can be considered to be a dynamic version of the RoboTrikke. I was able to show that a bicycle with no pedals can be actuated in the same manner as the RoboTrikke by periodic motion of the handlebar while a rider actively controls balance of the bicycle. Both these systems display an interesting dynamic interplay of inputs resulting in coupling of the yaw and roll motions of the system and consequent higher maneuverability, a property that I hope to exploit in future work with legged systems.

In my postdoctoral work, I have continued to focus on locomotion systems in two particular areas: manually reconfigurable modular robotic systems and legged locomotion. Modular robots bring the promise of versatility- the ability to use a single robot for multiple tasks either through automatic or manual reconfiguration. I led a team to develop hardware, software and control algorithms for a highly mobile homogeneous modular robot capable of performing both manipulation and locomotion tasks. The ability to multi-task is essential to some of the applications where I believe locomotion systems will be most beneficial: search and rescue and interplanetary exploration.

Locomotion is a multi-disciplinary field requiring skills in areas ranging from design, manufacturing, nonlinear control to graph theory. For example, an important problem in self-reconfiguration and self-repair for modular robots is the issue of automatic recognition of configurations. Using techniques from graph theory and spectral decomposition, we were able to develop algorithms for automatic recognition of new configurations to allow predefined gaits and controllers to be mapped onto them. Using the modular robot system developed in this work, we were able to demonstrate gaits for a variety of robots suitable for different tasks. Figure 2 shows one such configuration: A rolling wheel like



Figure 2: Rolling wheel configuration for a modular robot.

configuration, for which we have designed and demonstrated a dynamic gait, allows the robot to travel large distances more efficiently.

My interest in legged locomotion was sparked by my involvement in the Robocup Legged League at the beginning of graduate study where I developed omni-directional gaits for walking robots playing soccer. I furthered this interest through my postdoctoral work in developing controllers for enabling a quadruped robot to climb over extremely rough terrain. I have developed algorithms for analyzing complex terrain, choosing footholds based on a desirable set of terrain features and generating a statically stable gait that can get the robot over the rough terrain. The primary objective of this research is to *learn* better controllers and we have made significant progress in being able to learn better foothold positions and trajectories using a combination of supervised learning and online detection of slip during trials.

My future research interests, in legged robots in particular and in unconventional locomotion in general, are inspired by biological systems and by insights from previous research in control and design. Current research into legged locomotion, especially quadruped walking, has tended to focus on designing systems optimized for forward motion. Further, quadruped robots tend to consist of a stiff, heavy central platform where most of the mass of the robot is concentrated due to the presence of actuators, batteries and controller hardware. This mass dominates the dynamics of walking leading to the necessity for more powerful actuators, lower robustness to uncertainty in the environment and very low maneuverability.

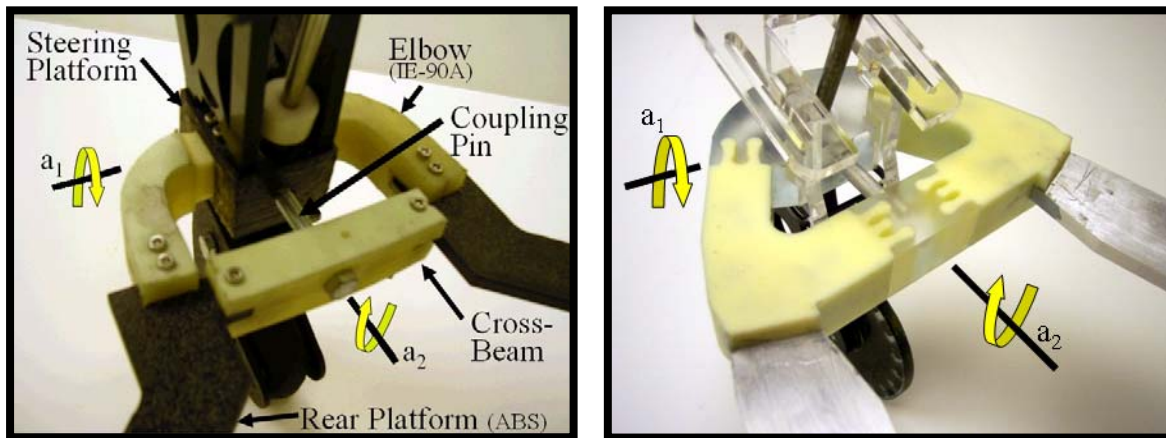


Figure 3: RoboTrikke compliant joint prototypes built using traditional manufacturing techniques (left) and using SDM (right).

I plan to address these problems using a combination of design and control techniques. An essential component of designing better walking robots is more compliance in all parts of the body. Compliance enhances the natural ability of the robot to handle disturbances and reduces the complexity of controllers otherwise required to achieve the fine control needed for robustness to uncertainty. I aim to use a manufacturing technique called SDM (Shape Deposition Manufacturing) that was used to prototype the latest

generation of the RoboTrikke. Figure 3 shows two models of the RoboTrikke built using SDM and traditional manufacturing techniques. The most difficult part to manufacture was a compliant joint attaching the steering column to the body of the robot. As seen from Figure 3, SDM allowed this joint assembly to be manufactured as a single piece with no fasteners thus reducing the complexity of assembly and increasing the robustness of the joint. SDM allows embedding of actuators, design of one-piece models with variable stiffness and the ability to embed sensors and controllers directly into the robot's body and has already been used in designing walking robots. I believe it will play a crucial role in the design of a new generation of biologically inspired robots.

Design of the right controllers will also play a major role in the success of the new robots and I believe I can contribute substantially in this area by building on my experience in designing controllers for several unconventional robots. Walking robots are hard to model and the traditional approach to dealing with this difficulty has been to use simpler reduced models like a hopping pogo-stick model as a basis for deriving controllers. An interesting approach to controller design for walking robots has been the use of virtual models where the robot is controlled to follow the known dynamics of a simpler system. I believe a similar approach can be used to apply some of the controllers used in my earlier work with the RoboTrikke and bicycle to generate appropriate yaw-roll coupling in walking robots resulting in better maneuverability.

The theory behind the analysis and design of gaits for unconventional locomotion systems continues to fascinate me. While several techniques have been explored for such systems, I believe the dynamic behavior of these systems has still not been fully explored or exploited. For example, there is still a lot to explore in gait generation for the Rollerblader, especially for control using human-like gaits. The intermittent contact of the feet for such systems results in the need to model them as hybrid systems. Optimization techniques developed for hybrid systems may be applicable to the generation of gaits in the Rollerblader. In the long term, I would also like to explore the design and control of a humanoid rollerblading robot capable of dynamic gaits. I believe this would serve as an ideal platform for development of cutting-edge controllers for extreme dynamic behavior. The unique underactuated nature of systems like the RoboTrikke may also find applications at the micro-level where having fewer actuators while still being able to cover a planar workspace would reduce weight and power consumption.