Journey of a Dynamic Walker

The journey of studying dynamic walking can take many paths. My own path is perhaps relatively uncommon among those attending Dynamic Walking 2017, but I hope my participation will nonetheless be of interest to others. This abstract describes elements of my personal journey as well as some of the questions that I hope to address as I journey forward. Overall, I am most interested in interacting with those pursuing similar journeys, although perhaps at different speeds, in slightly different directions, and on different numbers of legs.

Since I have long been out of the dynamic walking world, a bit of introduction seems appropriate. My journey as a dynamic walker began as a graduate student of Prof. Thomas Kane at Stanford University in the early 1980's and continued as a post-doc in the Institut für Mechanik at the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland. Since 1987, I have been faculty member in Mechanical Engineering at Bucknell University in Lewisburg, Pennsylvania, but in recent years have deviated from the true path of studying dynamic walking by becoming Dean of Engineering at Bucknell. I was dean from 2009 through 2016 and fortunately am now on sabbatical and have the opportunity to return to my dynamic walking path.

As a longtime member of the Bucknell faculty, my research into legged locomotion began in earnest over ten years ago with initial experiments into developing a passive dynamic walker. This work built directly upon that of Andy Ruina, whom I visited at Cornell with my students at that time. My work was greatly expanded through a sabbatical in the fall of 2007 working with Prof. Roland Siegwart in his Autonomous Systems Laboratory at the ETH. During that time, I worked most directly with one of his Ph.D. students, C. David Remy, who is now an Assistant Professor of Mechanical Engineering at the University of Michigan. My work with David focused on the design, development, and analysis of primarily four legged devices, considering both passive and active locomotion. We were successful in publishing a number of papers on our work [1-6] as well as in securing funding from the Swiss National Science Foundation to study "Dynamic Locomotion with Quadrupeds: Energy Efficient Locomotion by Exploiting Passive Dynamics" [7]. We were able to make significant progress on the design, analysis, and fabrication of four legged walking robots. My sabbatical also provided me with time to visit and work with students in the laboratory of Prof. Ken Waldron at Stanford. My work there was most directly with Alexander Perkins, who completed an Honors Thesis under my supervision at Bucknell and went on to obtain his Ph.D. with Prof. Waldron and now works at Boston Dynamics on the next generation of the Atlas bipedal robot.

Upon my return to Bucknell after my sabbatical, I was able to obtain two sizable grants from the Office of Naval Research to fund work in partnership with Dr. Jerry Pratt and Dr. Peter Neuhaus at the Institute for Human and Machine Cognition (IHMC) in Pensacola, Florida. Jerry and Peter had recently developed a new version of the M2V2 walking robot, and our work together focused on the hardware development of articulated feet, a stereo vision head, and an articulated arm [8]. A video of some of our work together was presented at *IROS* in 2009 [9]. Concurrently, related but separate work was being conducted at Bucknell by one of my master's students, Christian Hubicki, on energy-efficient, heuristic-based control of compass gait walking on stochastically varying terrain [10]. This work explored the inherent tradeoffs between relatively high-speed, robust robotic walking and minimizing energy consumption, and resulted in a novel controller that yielded the same step speed while using less energy than traditional robotic walking controllers.

At this point, after 7 years in a purely administrative role, I am returning to work directly related to dynamic walking, and hope to build on my own previous work as well as the work of others who will be attending Dynamic Walking 2017. Particular questions that I seek to address include:

- Although significant insights have been obtained with relatively simple dynamic models of walking robots, particularly for limit cycle stability analyses, models that are more representative of the structural and actuator complexity of walking robots are needed to refine stability analyses and to bridge the gap to model-based hardware controllers.
- In human-machine interactions, compliant robots with "soft" actuators are necessary to minimize risks to humans and the human environment. To create such robots, a systematic framework for the analysis, synthesis, and control of soft actuators is needed.
- Past work has focused on energy efficient walking on uneven or rough terrain, and more recently researchers have considered walking and jumping on granular surfaces [11], but much work is left to be done with modeling, path planning, and control on irregular terrain.
- Even the Boston Dynamics robot Atlas, The Next Generation https://www.youtube.com/watch?v=rVlhMGQgDkY does not have articulated feet. How best to design and take full advantage of feet with some number of toes is an as yet open question.
- Development of effective force-sensing contact sensors is challenging. How best to design and implement robust yet accurate and reliable force sensing robotic feet is also a question worthy of further consideration.

I hope through interactions with those attending Dynamic Walking and through my continued work with students at Bucknell and colleagues in various institutions around the world to be able to make great strides in addressing these and other questions related to how to build more stable, more versatile, and more energy-effective legged robots.

[1] Remy, C.D., Buffinton, K.W., Petit, F., and Siegwart, R.Y., 2008, "Passive Dynamic Walking with Quadrupeds," *Robotics Science and Systems Conference Workshop on Control of Locomotion: From Animals to Robots*.

[2] Remy, C.D., Buffinton, K.W., and Siegwart, R.Y., 2010, "Energetics of Passivity Based Running with High-Compliance Series Elastic Actuation," *Mechatronics2010: The 12th Mechatronics Forum Biennial International Conference*.

[3] Remy, C.D., Buffinton, K.W., and Siegwart, R.Y., 2010, "Stability Analysis of Passive Dynamic Walking of Quadrupeds," *International Journal of Robotics Research*, Vol. 29, pp. 1173-1185.

[4] Remy, C.D., Buffinton, K.W., and Siegwart, R.Y., 2011, "A MATLAB Framework for Efficient Gait Creation," *Proceedings of the International Conference on Intelligent Robots and Systems*.

[5] Remy, C.D., Buffinton, K.W., and Siegwart, R.Y., 2012, "Comparison of Cost Functions for Electrically Driven Running Robots," *Proceedings of the IEEE International Conference on Robotics and Automation*.

[6] Remy, C.D., Buffinton, K.W., and Siegwart, R.Y., 2012, "Energetics of Passivity Based Running with High-Compliance Series Elastic Actuation," *International Journal of Mechatronics and Manufacturing Systems*, Vol. 5, pp. 120-134.

[7] "Dynamic Locomotion with Quadrupeds: Energy Efficient Locomotion by Exploiting Passive Dynamics," *Swiss National Science Foundation*, 2008-10. (with R.Y. Siegwart and C.D. Remy; award number 200021_119965/1; total project funding: 147,725 CHF)

[8] Rittase, W.R., Kandler, M.F., Shooter, S.B., and Buffinton, K.W., 2011, "Development of an Interoperable and Robust Bipedal Robot Vision Platform with Image Stabilization," *Proceedings of the 17th IASTED International Conference on Robotics and Applications*.

[9] Pratt, J., Krupp, B., Ragusila, V., Rebula, J., Koolen, T., van Nieuwenhausen, N., Shake, C., Craig, T., Taylor, J., Watkins, G., Neuhaus, P., Johnson, M., Shooter, S., Buffinton, K., Canas, F., Carff, J., and Howell, W., 2009, "The Yobotics-IHMC Lower Body Humanoid Robot," *International Conference on Intelligent Robots and Systems*.

[10] Hubicki, C.M., 2011, "Energy-Economical Heuristically Based Control of Compass Gait Walking on Stochastically Varying Terrain," Master's thesis, Bucknell University, Lewisburg, Pennsylvania.

[11] Chang, A., Hubicki, C.M., Aguilar, J.J., Goldman, D.I., Ames, A.D., Vela, P.A., 2017, "Learning to Jump in Granular Media: Unifying Optimal Control Synthesis with Gaussian Process-Based Regression," *IEEE International Conference on Robotics and Automation* (under review).