Wandering Through the Desert: How Kod*lab Launched My Career

Aaron M. Johnson, Carnegie Mellon University

Kod*lab PhD student, 2008–2014, Postdoc 2014

I feel incredibly fortunate to have had the opportunity to complete my PhD under Dan – it was, with no exaggeration, life changing. My time with Dan has set me up for a lifetime of exciting research and a career that I love. It is impossible to capture in a short document all the ways that Dan has influenced my work and my life, but I will attempt to capture some relevant anecdotes and reflections along with a summary of the research I did in Kod*lab and since.

1 My start in Kod*lab

I feel especially luck to have ended up in Dan's lab since I wrote my graduate school application essay about multi-robot systems and computer vision (which is not at all what Dan works on or what I ended up doing, with small exceptions [22]). Dan was wise enough to ignore what I wrote and extend me an offer. Dan often talks about having a "nose for talent," and this ability to look past the surface (in my case, an undergrad claiming to be interested in unrelated topics) and find good talent is one that I hope to develop further over time.

I think many of us remember our first meeting with Dan. For both the initial phone call and when I came to visit in person, I remember discussing deep philosophical ideas about robotics and coming out of the meeting with a long list of things to look up. Once I was in the lab, we would always try to catch perspective students right after their meeting with Dan. They often came out dazed and overwhelmed, but with an excitement about the grand ideas that they covered, and needed some time to debrief and recover.

2 Mix of theoretical and empirical

One thing that is incredible about Kod*lab is that it has always been strong in both theoretical and empirical engineering. Dan is, clearly, the driving force on the theoretical side. What is surprising once you get to know Dan is that the lab has also been so strong in the design and experimental side of robotics, most notably with the RHex, RiSE, and Minitaur robots as well as alumni (and designs) going on to key roles in Boston Dynamics, Ghost Robotics, and other companies. I don't know how conscious a effort this has been, but my suspicion is that Dan intentionally recruits students who are strong empirically to maintain the success in that area.

A good example of this mix from my thesis work is my ICRA 2013 paper [17], which both introduced a way to describe the different contact conditions that a legged robot will experience as an abstract simplicial complex, and also demonstrated that different paths through this complex led to different leaping behaviors that could jump onto ledges and across gaps.

Continuing on this theme, the main focus of my research then as now has been contact. Changing contact conditions is a fundamental challenge to both legged locomotion and object manipulation. On the more theoretical side, in addition to [17], another major part of my thesis was a new formulation of hybrid dynamical systems where we were able to prove several consistency properties [11]. On the more empirical side, my first paper in Kod*lab was a proprioceptive contact detection and reactive controller [13], which we then used for stair climbing [12, 39, 9] and terrain identification [27].

In my lab this focus on contact and hybrid systems has continued, with both theoretical and empirical results. A lot of work has focused on the saltation matrix, which captures first order variations through impacts, which we can use to analyze stability [40], perform Kalman filtering [21, 31], and generate new trajectories with iLQR [20]. We have also developed new methods of contact localization [36], improved the accuracy of contact-implicit optimization [28, 34], and built robot hands that can more transparently react to contact [2, 3].

3 Students need to wander in the desert

Dan would often say that a young graduate student needed to "wander in the desert" for a while to figure out what the most important thesis topic is. I found this phrase incredibly confusing, seeing as how I went on a total of four trips to actual deserts (Mojave, Jornada, and White Sands) [12, 32]. In truth, that time literally wandering in the desert was incredibly valuable to my development.

The initial trips to the Mojave desert with Clark Haynes and an original RHex (plus some small robustness upgrades) exposed many limitations with the design and required a lot of in-field repairs. This motivated the need to build the next generation X-RHex and XRL robots [6, 7], exposed to me the importance of thermal modeling for motors [6, 5], and led me to derive the self-manipulation modeling framework (capturing the kinematics of legged locomotion in the same way as an object manipulation) [14, 16], which was required in order to prove the validity of a controller that reactively stands on rocky terrain without burning up the motors. These trips also provided a test case for hill climbing autonomy [12, 8, 15, 19] and motivated need for jumping [17] and tails [18, 23, 4, 26] to traverse extremely rocky terrain. Pictures and videos from these trips would be a mainstay of every talk I gave for about a decade after the first trip.

I have tried to apply this philosophy in my own lab as well, giving students the space to explore different ideas and change topics along the way. As for the literal wandering in the desert, I have managed to get one student to a desert, the Atacama, where we tested an approach for digging trenches in sand using the wheels of a rover [29, 30]. (My lab has also taken environmental monitoring robots out to west Texas, though not technically in the desert.)

4 The legacy of RHex as a "model organism" for robotics

It is incredible how deep and wide an impact RHex has had. Over a span of about two decades (I believe starting in 1999, with first papers in 2001 [33]), RHex has provided generations of researchers with a dynamically-interesting but relatively stable platform to conduct research. It has been used for graduate research, undergraduate classes, and K12 outreach. At times it held records for efficiency, speed, leaping ability [17], autonomous stair climbing [12, 39, 9], and more on legged robots. In some ways its simplicity as a legged robot gives it an advantage in terms of longevity – if a new idea can be demonstrated on a simple, well understood robot like RHex, isn't that more valuable then showing it on a more complicated robot with multiple confounding factors?

I think that RHex should be considered a "model organism" for robotics. Some criteria for this designation: Versions of RHex have been used in more than a dozen labs at McGill, Michigan, Berkeley, CMU, Boston Dynamics, Georgia Tech, NTU, ARL, RVC, FSU, JHU, OSU, and more. I estimate that in total there have been at least 30 copies made and at least 50 papers featuring RHex, though the real numbers could be twice this. Its dynamics and control are incredibly well understood. Any new results produced on RHex are more valuable than a random new robot because there is a rich history and context that the new work falls into. (Some other robots that should probably be considered "model organisms" include: PR2, Turtlebot, quadrotors, and, increasingly, the class of quadrupeds that include Spot, Vision 60, Cheetah, A1, and ANYmal).

When we were building the X-RHex and XRL robots about 10 years after the original RHex [6, 7], Dan would ask us "are we just building YARR – Yet Another RHex Robot". But there were a number of important innovations that came with that generation of robot. They were the first to feature BLDC motors with low gear ratios (quasi-direct drive) that enable transparency and proprioception – an architecture that is now standard in legged robots. They were the first legged robots with a GPU, and were capable of greatly improved perception and autonomy. They had improved peak power output. Though designing X-RHex and XRL was a major undertaking, they enabled a new generation of students to work on RHex during its second decade of relevance.

I am sad to say that while I have an XRL in my lab now, it has not been used in a few years and we recently disposed of the aging batteries. I don't know if it will walk again. However, my lab has produced two new robots on the RHex family: MiniRHex [1] is a small, open-source, $200 RHex robot that we developed for outreach events (though it has also been used for research in my lab and elsewhere). T-RHex [24] is a slightly bigger version that includes microspine toes that is capable of hanging from vertical surfaces and climbing slopes up to 60°. Interestingly, my lab has also recently developed a new legged robot design featuring just "one actuator per leg," one of the defining features of RHex, but in this case as a passive dynamic walking-inspired bipedal robot [10].

5 Misc thoughts on Dan

Dan did not like to use the word "planning" (or "learning"), instead in the lab we would call everything "control" (or at most "planning and control"). I think Omur Arslan and Vasileios Vasilopoulos have cured Dan's aversion to the word. This is one area that I have worked to expand beyond the scope of Kod*lab's research, working on both planning [35, 15, 25] and learning [37, 38], though bringing in many ideas from control into these domains.

Dan would always treat his postdocs like faculty, his grad students like postdocs, and his undergrads like grad students. As a grad student, I spent a lot of time managing the RCTA project, even working out the budget for the DMUM section with Al Rizzi on the phone and calling in as Penn's rep to the PI meetings at times. I think this was incredibly valuable in preparing me for a faculty position, and has also led to at least 16 other PhD/Postdocs and at least 5 BS/MS students from Kod*lab that went on to faculty positions.

Dan taught me a greater degree of restraint and patience – sometimes it is better to hold back and get a better paper/video/job/etc a few months later. As a student I found this frustrating as I was too eager to get things moving, but I have come to appreciate the value of patience.

Dan also taught me how to write and, by negative examples, now not to write. Dan once told me that what he liked about the English language was that it had "infinite depth" – you can always add another comma, parenthetical phrase, etc. What results is that text from Dan would involve incredibly long sentences that I would then go back through and break up into multiple sentences. One example that made it into a paper [17] are these two sentences that have between them five commas, four parenthetical phrases, two dashes, and span 15 lines in the original document:

> Next, in Section II, we review some preliminary formal ideas concerning the central object of study, a two legged sagittal plane hopper, and exhibit the topological space – the "ground reaction complex" (in this case a simplicial tetrathedron) – over whose variously dimensioned cells the Hamiltonian flows of its holonomically constrained body evolve as directed by the ground reaction forces. This cellular construction indexes in a computationally effective ("grammatical") manner the realizable sequences of continuous dynamics that are physically available, providing crucial intuition for hand-designed behaviors (as suggested by the new capabilities we document) as well as parameterizing the various sequences of constraints that would be required for any automated method of behavior generation (i.e. a learning or optimization based approach).

While Dan's sentences are always formally correct, they taught me to appreciate the importance of readability in technical communication.

References

[1] M. Barragan, N. Flowers, and A. M. Johnson. MiniRHex: A small, open-source, fully programmable walking hexapod. In *Robotics: Science and Systems Workshop on "Design and Control of Small Legged Robots"*, Pittsburgh, PA, June 2018.

[2] A. Bhatia, A. M. Johnson, and M. T. Mason. Direct drive hands: Force-motion transparency in gripper design. In *Robotics: Science and Systems*, Messe Freiburg, Germany, June 2019.

[3] A. Bhatia, M. T. Mason, and A. M. Johnson. Reacting to contact: Transparency and collision reflex in actuation. *In prep*, 2022.

[4] A. L. Brill, A. De, A. M. Johnson, and D. E. Koditschek. Tail-assisted rigid and compliant legged leaping. In *IEEE/RSJ Intl. Conference on Intelligent Robots and Systems*, pages 6304–6311, Hamburg, Germany, 2015.

[5] A. De, G. Lynch, A. M. Johnson, and D. E. Koditschek. Motor sizing for legged robots using dynamic task specification. In *IEEE Intl. Conference on Technologies for Practical Robot Applications*, pages 64–69, Boston, MA, April 2011.

[6] K. C. Galloway, G. C. Haynes, B. D. Ilhan, A. M. Johnson, R. Knopf, G. Lynch, B. Plotnick, M. White, and D. E. Koditschek. X-RHex: A highly mobile hexapedal robot for sensorimotor tasks. Technical report, University of Pennsylvania, Philadelphia, PA, 2010.

[7] G. C. Haynes, J. Pusey, R. Knopf, A. M. Johnson, and D. E. Koditschek. Laboratory on legs: An architecture for adjustable morphology with legged robots. In *Unmanned Systems Technology XIV*, volume 8387, page 83870W. SPIE, 2012.

[8] B. D. Ilhan, A. M. Johnson, and D. E. Koditschek. Autonomous legged hill ascent. *Journal of Field Robotics*, 35(5):802–832, August 2018.

[9] B. D. Ilhan, A. M. Johnson, and D. E. Koditschek. Autonomous stairwell ascent. *Robotica*, 38(1):159–170, 2020.

[10] S. Islam, K. Carter, J. Yim, J. Kyle, S. Bergbreiter, and A. M. Johnson. Scalable minimally actuated leg extension bipedal walker based on 3D passive dynamics. In *IEEE Intl. Conference on Robotics and Automation*, Philadelphia, PA, May 2022.

[11] A. M. Johnson, S. E. Burden, and D. E. Koditschek. A hybrid systems model for simple manipulation and self-manipulation systems. *International Journal of Robotics Research*, 35(11):1354–1392, September 2016.

[12] A. M. Johnson, M. T. Hale, G. C. Haynes, and D. E. Koditschek. Autonomous legged hill and stairwell ascent. In *IEEE Intl. Workshop on Safety, Security, & Rescue Robotics*, pages 134–142, Kyoto, Japan, November 2011.

[13] A. M. Johnson, G. C. Haynes, and D. E. Koditschek. Disturbance detection, identification, and recovery by gait transition in legged robots. In *IEEE/RSJ Intl. Conference on Intelligent Robots and Systems*, pages 5347–5353, Taipei, Taiwan, October 2010.

[14] A. M. Johnson, G. C. Haynes, and D. E. Koditschek. Standing self-manipulation for a legged robot. In *IEEE/RSJ Intl. Conference on Intelligent Robots and Systems*, pages 272–279, Algarve, Portugal, Oct. 2012.

[15] A. M. Johnson, J. E. King, and S. Srinivasa. Convergent planning. *IEEE Robotics and Automation Letters*, 1(2):1044–1051, July 2016.

[16] A. M. Johnson and D. E. Koditschek. Legged self-manipulation. *IEEE Access*, 1:310–334, May 2013.

[17] A. M. Johnson and D. E. Koditschek. Toward a vocabulary of legged leaping. In *IEEE Intl. Conference on Robotics and Automation*, pages 2553–2560, Karlsruhe, Germany, May 2013.

[18] A. M. Johnson, T. Libby, E. Chang-Siu, M. Tomizuka, R. J. Full, and D. E. Koditschek. Tail assisted dynamic self righting. In *Intl. Conference on Climbing and Walking Robots*, pages 611–620, Baltimore, MD, July 2012.

[19] N. Kong and A. M. Johnson. Optimally convergent trajectories for navigation. In *International Symposium on Robotics Research*, October 2019.

[20] N. J. Kong, G. Council, and A. M. Johnson. iLQR for piecewise-smooth hybrid dynamical systems. In *IEEE Conference on Decision and Control*, December 2021.

[21] N. J. Kong, J. J. Payne, G. Council, and A. M. Johnson. The Salted Kalman Filter: Kalman filtering on hybrid dynamical systems. *Automatica*, 131:109752, 2021.

[22] H. Kumar, J. J. Payne, M. Travers, A. M. Johnson, and H. Choset. Periodic SLAM: Using cyclic constraints to improve the performance of visual-inertial SLAM on legged robots. In *IEEE Intl. Conference on Robotics and Automation*, Philadelphia, PA, May 2022.

[23] T. Libby, A. M. Johnson, E. Chang-Siu, R. J. Full, and D. E. Koditschek. Comparative design, scaling, and control of appendages for inertial reorientation. *IEEE Transactions on Robotics*, 32(6):1380–1398, 2016.

[24] M. Martone, C. Pavlov, A. Zeloof, V. Bahl, and A. M. Johnson. Enhancing the vertical mobility of a robot hexapod using microspines. Technical Report arXiv:1906.04811 [cs.RO], arXiv, 2019.

[25] J. Norby and A. M. Johnson. Fast global motion planning for dynamic legged robots. In *IEEE/RSJ Intl. Conference on Intelligent Robots and Systems*, pages 3829–3836, Las Vegas, NV, Oct. 2020.

[26] J. C. Norby, J. Y. Li, C. C. Selby, A. Patel, and A. M. Johnson. Enabling dynamic behaviors with aerodynamic drag in lightweight tails. *IEEE Transactions on Robotics*, 37(4):1144–1153, 2021.

[27] C. Ordonez, J. Shill, A. M. Johnson, J. Clark, and E. Collins. Terrain identification for RHex-type robots. In *Unmanned Systems Technology XV*, volume 8741, page 87410Q, Baltimore, MD, 2013. SPIE.

[28] A. Patel, S. Shield, S. Kazi, A. M. Johnson, and L. T. Biegler. Contact-implicit trajectory optimization using orthogonal collocation. *IEEE Robotics and Automation Letters*, 4(2):2242–2249, 2019.

[29] C. Pavlov and A. M. Johnson. Soil displacement terramechanics for wheel-based trenching with a planetary rover. In *IEEE Intl. Conference on Robotics and Automation*, pages 4760–4766, Montreal, Canada, May 2019.

[30] C. Pavlov and A. M. Johnson. Field experiments in nonprehensile terrain manipulation with planetary exploration rovers. In *International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS)*, October 2020.

[31] J. J. Payne, N. J. Kong, and A. M. Johnson. The uncertainty aware salted kalman filter: State estimation for hybrid systems with uncertain guards. *arXiv*, (arXiv:2202.12729 [cs.RO]), 2022.

[32] S. Roberts, J. Duperret, A. M. Johnson, S. v. Pelt, T. Zobeck, N. Lancaster, and D. E. Koditschek. Desert RHex technical report: Jornada and White Sands trip. Technical report, University of Pennsylvania, Philadelphia, PA, 2014.

[33] U. Saranli, M. Buehler, and D. E. Koditschek. Rhex: A simple and highly mobile hexapod robot. *Int J Rob Res*, 20(7):616–631, 2001.

[34] S. L. Shield, A. M. Johnson, and A. Patel. Contact-implicit direct collocation with a discontinuous velocity state. *IEEE Robotics and Automation Letters*, 7(2):5779–5786, 2022.

[35] S. S. Srinivasa, A. M. Johnson, G. Lee, M. C. Koval, S. Choudhury, J. E. King, C. M. Dellin, M. Harding, D. T. Butterworth, P. Velagapudi, and A. Thackston. A system for multi-step mobile manipulation: Architecture, algorithms, and experiments. In D. Kulić, Y. Nakamura, O. Khatib, and G. Venture, editors, *International Symposium on Experimental Robotics*, volume 1, pages 254–265, Tokyo, Japan, October 2016. Springer Proceedings in Advanced Robotics.

[36] S. J. Wang, A. Bhatia, M. T. Mason, and A. M. Johnson. Contact localization using velocity constraints. In *IEEE/RSJ Intl. Conference on Intelligent Robots and Systems*, pages 7351–7358, Las Vegas, NV, Oct. 2020.

[37] S. J. Wang and A. M. Johnson. Domain adaptation using system invariant dynamics models. In *Learning for Dynamics and Control Conference*, volume 144 of *Proceedings of Machine Learning Research*, pages 1130–1141, May 2021.

[38] S. J. Wang, S. Triest, W. Wang, S. Scherer, and A. M. Johnson. Rough terrain navigation using divergence constrained model-based reinforcement learning. In *Conference on Robot Learning*, Proceedings of Machine Learning Research, November 2021.

[39] G. J. Wenger, A. M. Johnson, C. J. Taylor, and D. E. Koditschek. Semi-autonomous exploration of multi-floor buildings with a legged robot. In *Unmanned Systems Technology XVII*, volume 9468, pages 94680B–8, Baltimore, MD, April 2015. SPIE.

[40] J. Zhu, N. J. Kong, G. Council, and A. M. Johnson. Hybrid event shaping to stabilize periodic hybrid orbits. In *IEEE Intl. Conference on Robotics and Automation*, Philadelphia, PA, May 2022.