Course Syllabus

Description This course investigates recent work in the areas of nonlinear dynamics and control of robots that walk, run, fly and swim.

Instructor Prof. Katie Byl (katiebyl@ece.ucsb.edu)
Room 5115, Harold Frank Hall

Time/Location Monday, Wednesday 4:00-5:50pm, in 1437 Phelps

Prerequisites An undergraduate-level background in both *System Dynamics* and *Controls*.

Office Hours Tuesday 10am-noon (and/or by appointment), in 5115 HFH.

Required Text/Readings There is no text for this course. Instead, we will read, analyze and discuss a variety of recent publications relating to robot locomotion. Please be respectful that such publications are *protected by copyright law; any links to publications are for educational use by students within this course, only.*

Grading

Class participation	30%	*(Includes leading at least one class discussion.)*
Homework	35%	*(Lowest HW grade will not be included in average.)*
Final Project	35%	*(With conference-length research paper and talk.)*

Participation Each student will be assigned a particular reading for which (s)he will lead a class discussion. Students are strongly encouraged to meet with me beforehand (either in regular office hours or by appointment) to review their assigned readings. Your grade for class participation will *also* depend on your regular contributions to other class discussions throughout the class.

Homework Homework is due at the start of class. While some collaboration is allowed, direct copying is not (and will be dealt with severely). The lowest homework grade a student receives will *not* be included in calculating the total homework grade contribution.

Projects Details on potential topics for the term project will be discussed in class. Deliverables for the term project include both a conference-length paper (e.g., 6-8 pp.) and a short, in-class presentation (about 15 minutes).

Tentative Schedule

Date	**Topics** (numbering matches HWs)	**Required Readings**†	**Optional Readings**†	Homework **Out**	**Due**
1/4	1: Locomotion overview 1.1 Underactuation and controllability.	[14] [47]	· [44]	·	·
1/6	2: Passive dynamics in walking 2.1 Impedance; robot examples.	[35] [40]	[37] [41]; [12]	1	·
1/11	2.2 Stability analyses and modeling.	[10, 25]	[23, 46, 26]	2	·
1/13	3: Control methods for walking 3.1 Partial Feedback Linearization (PFL).	[11] [48]	· ·	·	1
(1/18)	** *No class. (MLK's Birthday.)* **	–	–	–	–
1/20	3.2 Hybrid Zero Dynamics (HZD). 3.3 Manifold control.	[52] ·	· [20]	3	2
1/25	3.3 Stability margins. 3.4 Preview control for ZMP.	· [31]	[22] ·	·	·
1/27	4: Running gaits 4.1 Raibert hoppers; BigDog.	[36] [42]	[27] [43]	4	3
2/1	4.2 Spring-loaded inverted pendulum (SLIP). 4.3 RHex; CPGs.	[24] [2];[29]	[21] [1];[18]	·	·
2/3	5: Dynamics of (flapping) flight 5.1 Blade element method.	[15] [16]	[3, 13] [50, 19, 38]	5	4
2/8	5.2 Passive dynamics. 5.3 Controllability.	[54] [45]	[4, 39] [28]	·	·
2/10	6: Machine learning 6.1 Dynamic Programming.	· [34]	[30] ·	6	5
(2/15)	** *No class. (Presidents' Day.)* **	–	–	–	–
2/17	6.2 Gradient-based methods.	[53]	[49]	7	·
2/22	6.3 Genetic algorithms.	[7]	·	·	6
2/24	7: Kinodynamic planning 7.1 Motion planning for fully-actuated robots.	[6] [17]	[5] [9]	·	·
3/1	7.2 Rapidly-exploring Randomized Trees (RRTs).	[32]	[51, 8, 33]	·	7
3/3	Review; Future directions	*TBA*	*TBA*	·	·
3/8	*Final project presentations.*	·	·	·	·
3/10	*Final project presentations.*	·	·	·	·

† Use "References" (on pages ahead) as a key to the Readings.

References

[1] R. Altendorfer, N. Moore, H. Komsuoglu, M. Buehler, H.B. Brown Jr., D. McMordie, U. Saranli, R. Full, and D.E. Koditschek. RHex: A biologically inspired hexapod runner. *Autonomous Robots*, 11(3):207–213, Nov 2001.

[2] R. Altendorfer, U. Saranli, H Komsoglu, D. Koditschek, H. B. Brown, M. Buehler, N. Moore, D. McMordie, and R. Full. Evidence for spring loaded inverted pendulum running in a hexapod robot. In *Proceedings of the 7th International Symposium on Experimental Robotics (ISER)*, 2000.

[3] Douglas L. Altshuler, William B. Dickson, Jason T. Vance, Stephen P. Roberts, and Michael H. Dickinson. Short-amplitude high-frequency wing strokes determine the aerodynamics of honeybee flight. *Proceedings of the National Academy of Sciences*, 102(50):1821318218, December 2005.

[4] D.N. Beal, F.S. Hover, M.S. Triantafyllou, J.C. Liao, and G. V. Lauder. Passive propulsion in vortex wakes. *Journal of Fluid Mechanics*, 549:385402, 2006.

[5] J.E. Bobrow, S. Dubowsky, and J.S. Gibson. Time-optimal control of robotic manipulators along specified paths. *Int. J of Robotics Research*, 4(3):3–17, 1985.

[6] J.E. Bobrow, B. Martin, G. Sohl, E.C. Wang, F.C. Park, and Junggon Kim. Optimal robot motions for physical criteria. *J of Robotic Sys.*, 18(12):785–795, 2001.

[7] J. Bongard, V. Zykov, and H. Lipson. Resilient machines through continuous self-modeling. *Science*, 314(5802):1118–1121, Nov 2006.

[8] R.R. Burridge, A.A. Rizzi, and D.E. Koditschek. Sequential composition of dynamically dexterous robot behaviors. *International Journal of Robotics Research*, 18(6):534–555, June 1999.

[9] John F. Canny, Bruce Randall Donald, John H. Reif, and Patrick G. Xavier. On the complexity of kinodynamic planning. In *29th Annual Symposium on Foundations of Computer Science*, pages 306–316. IEEE, 1988.

[10] Michael J. Coleman and Andy Ruina. Motions of a rimless spoked wheel: a simple 2D systems with impacts. August 2002.

[11] Steven H. Collins, Andy Ruina, Russ Tedrake, and Martijn Wisse. Efficient bipedal robots based on passive-dynamic walkers. *Science*, 307:1082–1085, February 18 2005.

[12] Steven H. Collins, Martijn Wisse, and Andy Ruina. A three-dimensional passive-dynamic walking robot with two legs and knees. *International Journal of Robotics Research*, 20(7):607–615, July 2001.

[13] Michael H. Dickinson. Unsteady mechanisms of force generation in aquatic and aerial locomotion. *Amer. Zool.*, 36:537–554, 1996.

[14] Michael H. Dickinson, Claire T. Farley, Robert J. Full, M. A. R. Koehl, Rodger Kram, and Steven Lehman. How animals move: An integrative view. *Science*, 288:100–106, 2000.

[15] Michael H. Dickinson, Fritz-Olaf Lehmann, and Sanjay P. Sane. Wing rotation and the aerodynamic basis of insect flight. *Science*, 284(5422):1954–60, June 1999.

[16] William B. Dickson and Michael H. Dickinson. The effect of advance ratio on the aerodynamics of revolving wings. *Journal of Experimental Biology*, 207:4269–4281, Aug 2004.

[17] Bruce Donald, Patrick Xavier, John Canny, and John Reif. Kinodynamic motion planning. *J. of the ACM*, 40(5):1048–1066, 1993.

[18] J. Duysens and H.W. Van de Crommert. Neural control of locomotion; the central pattern generator from cats to humans. *Gait Posture*, 7(2):131–141, Mar 1 1998.

[19] C. P. Ellington. The aerodynamics of hovering insect flight I. The quasi-steady analysis. *Philosophical Transactions of the Royal Society of London.*, 305(1122):1–15, 1984.

[20] Tom Erez and William D. Smart. Bipedal walking on rough terrain using manifold control. *Proc. International Conference on Intelligent Robots and Systems (IROS)*, pages 1539–1544, 2007.

[21] R.J. Full and D.E. Koditschek. Templates and anchors: neuromechanical hypotheses of legged locomotion on land. *Journal of Experimental Biology*, 202(23):3325–3332, 1999.

[22] Elena Garcia, Joaquin Estremera, and Pablo Gonzalez de santos. A classification of stability margins for walking robots. In *Proceedings of the International Conference on Climbing and Walking Robots (CLAWAR)*, 2002.

[23] M Garcia, A Chatterjee, A Ruina, and M Coleman. The simplest walking model: Stability, complexity, and scaling. *Journal of Biomechanical Engineering – Transactions of the ASME*, 120(2):281–288, Apr 1998.

[24] H. Geyer, A. Seyfarth, and R. Blickhan. Spring-mass running: simple approximate solution and application to gait stability. *Journal of Theoretical Biology*, 232(3):315–328, 2005.

[25] A. Goswami, B. Espiau, and A. Keramane. Limit cycles and their stability in a passive bipedal gait. pages 246–251. IEEE International Conference on Robotics and Automation (ICRA), 1996.

[26] Ambarish Goswami, Benoit Thuilot, and Bernard Espiau. A study of the passive gait of a compass-like biped robot: symmetry and chaos. *International Journal of Robotics Research*, 17(12), 1998.

[27] Jessica Hodgins and Marc Raibert. Adjusting step length for rough terrain locomotion. *IEEE Transactions on Robotics and Automation*, 7(3):289–298, June 1991.

[28] M. Hu, R. Wei, Z. Shi, and L. Zou. Controllability issues for insect like flapping wing micro-air vehicle. In *: Intelligent Control and Automation, 2008. WCICA 2008. 7th World Congress on*, pages 6365–6368, Chongqing, China, June 2008.

[29] A. J. Ijspeert, A. Crespi, and D. Ryczko andJ. M. Cabelguen. From swimming to walking with a salamander robot driven by a spinal cord model. *Science*, 315(5817):1416–1420, Mar 2007.

[30] Leslie Pack Kaelbling, Michael L. Littman, and Andrew W. Moore. Reinforcement learning: A survey. *Journal of Artificial Intelligence Research*, 4, 1996.

[31] S. Kajita, F. Kanehiro, K. Kaneko, K. Fujiware, K. Harada, K. Yokoi, and H. Hirukawa. Biped walking pattern generation by using preview control of zero-moment point. In *ICRA IEEE International Conference on Robotics and Automation*, pages 1620–1626. IEEE, Sep 2003.

[32] J.J. Kuffner and S.M. Lavalle. RRT-connect: An efficient approach to single-query path planning. In *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*, pages 995–1001, 2000.

[33] Steven M. Lavalle. From dynamic programming to rrts: Algorithmic design of feasible trajectories. In *Control Problems in Robotics*. Springer-Verlag, 2002.

[34] Steven M. LaValle. *Planning Algorithms*. (Section 2.3, only.) Cambridge University Press, 2006.

[35] Tad McGeer. Passive dynamic walking. *International Journal of Robotics Research*, 9(2):62–82, April 1990.

[36] Thomas A. McMahon and George C. Cheng. The mechanics of running: How does stiffness couple w/ speed. *Journal of Biomechanics*, 23(Supplement 1):65–78, 1990.

[37] Simon Mochon and Thomas A. McMahon. Ballistic walking. *Journal of Biomechanics*, 13:49–57, 1980.

[38] M.F.M. Osborne. Aerodynamics of Flapping Flight with Application to Insects. *J Exp Biol*, 28(2):221–245, 1951.

[39] Umberto Pesavento and Z. JaneWang. Falling paper: Navier-stokes solutions, model of fluid forces, and center of mass elevation. *Physical Review Letters*, 93(14), October 2004.

[40] Gill A. Pratt. Low impedance walking robots. *Integ. and Comp. Biol.*, 42:174–181, 2002.

[41] Jerry Pratt. Virtual model control of a biped walking robot. Master's thesis, 1995.

[42] Raibert, M. H., Chepponis, M., Brown, and H. B. Running on four legs as though they were one. *IEEE Journal of Robotics and Automation*, 2(2):70–82, 1986.

[43] Marc Raibert, Kevin Blankespoor, Gabriel Nelson, Rob Playter, and the BigDog Team. Bigdog, the rough-terrain quadruped robot. *Proceedings of the 17th World Congress, The International Federation of Automatic Control*, 2008.

[44] M. Reyhanoglu, A. van der Schaft, N.H. Mcclamroch, and I. Kolmanovsky. Dynamics and control of a class of underactuated mechanical systems. *Automatic Control, IEEE Transactions on*, 44(9):1663–1671, Sep 1999.

[45] Luca Schenato, Domenico Campolo, and Shankar Sastry. Controllability issues in flapping flight for biomimetic micro aerial vehicles (mavs). *IEEE International Conference on Decision and Control*, December 2003.

[46] A. L. Schwab and M. Wisse. Basin of attraction of the simplest walking model. *Proceedings of the ASME Design Engineering Technical Conference*, 6:531–539, Sep 2001.

[47] M. W. Spong. Underactuated mechanical systems. In B. Siciliano and K. P. Valavanis, editors, *Control Problems in Robotics and Automation*, Lecture notes in control and information sciences 230. Springer-Verlag, 1997.

[48] Mark W. Spong. Partial feedback linearization of underactuated mechanical systems. In *Proceedings of the IEEE International Conference on Intelligent Robots and Systems*, volume 1, pages 314–321, September 1994.

[49] Richard S. Sutton and Andrew G. Barto. *Reinforcement Learning: An Introduction*. (Chapter 1, only.) MIT Press, 1998.

[50] G.K. Taylor and A.L.R. Thomas. Animal flight dynamics II. Longitudinal stability in flapping flight. *Journal of Theoretical Biolgogy*, 214:351–370, 2002.

[51] Russ Tedrake. LQR-Trees: Feedback motion planning on sparse randomized trees. In *Proceedings of Robotics: Science and Systems (RSS)*, page 8, 2009.

[52] E. R. Westervelt, J. W. Grizzle, and D. E. Koditschek. Hybrid zero dynamics of planar biped walkers. *IEEE Transactions on Automatic Control*, 48(1):42–56, Jan 2003.

[53] R.J. Williams. Simple statistical gradient-following algorithms for connectionist reinforcement learning. *Machine Learning*, 8:229–256, 1992.

[54] R.J. Wood. The first takeoff of a biologically inspired at-scale robotic insect. *IEEE Transactions on Robotics*, 24(2):341–347, Apr 2008.