Ontario Graduate Scholarship: Plan of Study

Adan Moran-MacDonald

Background

When a gymnast is performing a swing-up routine on a bar, they do not kick their feet at specified time intervals. Rather, a more natural human motion is to smoothly swing their legs based on their current speed and position [1]. In doing so, they are able to generate enough momentum to perform backflips on the bar. When controlling mechanical systems, standard practice is to have a robot's actuators track a function of time. Much like the gymnast, it can be more natural to have the robot track a function of speed and position instead. The recent techniques of virtual constraints offer this ability to produce realistic, biologically plausible motion.

Mechanical systems can be constrained in two ways. Holonomic constraints restrict position (for instance, car tires remain a fixed distance apart), while nonholonomic constraints restrict velocities (such as how car tires cannot slide sideways). Previous research has shown that one can enforce holonomic constraints through a robot's actuators, using the method of "virtual holonomic constraints" (VHCs) [2]. VHCs have been used to control walking robots [3], autonomous bicycles [4], gymnastics robots [5], and snake robots [6] among others. These VHCs are a special case of the more general virtual nonholonomic constraints (VNHCs). In my master's thesis [7] I developed a theory for enforcing VNHCs and designed one which injects energy into the gymnastics robot created by Wang [5], thereby enabling it to perform backflips on a bar.

Proposal

Mohammadi *et.al.* [8] showed that a single VHC can result in several motion patterns (known as "orbits"), from which one specific motion pattern can be chosen if the robot is initialized with a configuration that is "close enough" to it. However, their method does not work for all starting configurations of the robot. We propose to extend this work by investigating a method for transitioning between VNHCs.

VNHCs have been studied with applications to human-robot cooperation [9] and walking robots [10]. Horn *et.al.* [11] have also examined properties of VNHCs for general mechanical systems and applied their results to stabilizing a chosen gait on walking robots. Our approach is novel since we assume one can stabilize two distinct VNHCs independently, and will develop techniques to transition between them while maintaining safety constraints. Doing so will allow one to chain together VNHCs which drive a robot's configuration towards a desired orbit, regardless of the initial configuration.

First we will study mathematical conditions under which one can transition between two VNHCs. These conditions will allow us to create a control algorithm to switch between motion patterns. After completing this mathematical formulation, we will test the theory on a gymnastics robot by designing a gymnastics routine which is performed solely by transitioning between several different VNHCS.

The advancements in mathematics from this research will bring improvements to the control of other autonomous systems. The ability to transition between complex constraints will allow for more expressive motion and may become a standard technique for controlling biologically inspired robots.

References

[1] V. Sevrez, E. Berton, G. Rao, and R. J. Bootsma, "Regulation of pendulum length as a control mechanism in performing the backward giant circle in gymnastics," *Human Movement Science*, vol. 28, no. 2, pp. 250–262, Mar. 2009.

[2] M. Maggiore and L. Consolini, "Virtual holonomic constraints for euler-lagrange systems," *IEEE Transactions on Automatic Control*, vol. 58, no. 4, pp. 1001–1008, Apr. 2013, ISSN: 0018-9286. DOI: 10.1109/TAC.2012.2215538.

[3] F. Plestan, J. W. Grizzle, E. R. Westervelt, and G. Abba, "Stable walking of a 7-dof biped robot," *IEEE Transactions on Robotics and Automation*, vol. 19, no. 4, pp. 653–668, Aug. 2003, ISSN: 1042-296X. DOI: 10.1109/TRA.2003.814514.

[4] L. Consolini and M. Maggiore, "Control of a bicycle using virtual holonomic constraints," *Automatica*, vol. 49, no. 9, pp. 2831–2839, Sep. 2013. DOI: 10.1016/j.automatica.2013.05.021.

[5] X. Wang, "Motion control of a gymnastics robot using virtual holonomic constraints," Master's thesis, University of Toronto, 2016.

[6] A. Mohammadi, E. Rezapour, M. Maggiore, and K. Y. Pettersen, "Maneuvering control of planar snake robots using virtual holonomic constraints," *IEEE Transactions on Control Systems Technology*, vol. 24, no. 3, pp. 884–899, May 2016, ISSN: 1063-6536. DOI: 10.1109/TCST.2015.2467208.

[7] A. Moran-MacDonald, "Energy injection for mechanical systems using virtual nonholonomic constraints," Expected completion August 2020, Master's thesis, University of Toronto.

[8] A. Mohammadi, M. Maggiore, and L. Consolini, "Dynamic virtual holonomic constraints for stabilization of closed orbits in underactuated mechanical systems," *Automatica*, vol. 94, pp. 112–124, Mar. 2018. DOI: 10.1016/j.automatica.2018.04.023.

[9] T. Takubo, H. Arai, and K. Tanie, "Virtual nonholonomic constraint for human-robot cooperation in 3-d space," in *Proceedings. 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2000) (Cat. No.00CH37113)*, IEEE, 2000. DOI: 10.1109/IROS.2000.894621.

[10] B. Griffin and J. Grizzle, "Nonholonomic virtual constraints for dynamic walking," in *2015 54th Conference on Decision and Control (CDC)*, IEEE, 2015. DOI: 10.1109/CDC.2015.7402850.

[11] J. Horn, A. Mohammadi, K. Hamed, and R. Gregg, "Hybrid zero dynamics of bipedal robots under nonholonomic virtual constraints," *IEEE Control Systems Letters*, vol. 3, no. 2, pp. 386–391, Apr. 2019. DOI: 10.1109/lcsys.2018.2888571.