Title

Stable and versatile bipedal locomotion using Real Time Model Predictive Control

Motivation

Bipedal robots are more versatile than wheeled mobile robots in various applications, such as moving on rugged terrain, stepping over obstacles and climbing stairs. However, the complex structure, high nonlinearity and non-smooth dynamics of bipedal robots make it a large challenge to develop stable control of bipedal locomotion. As a first step, basic controllers need to be designed to enable stable bipedal locomotion on flat surfaces. Then more advanced control strategies can be developed to take the complex dynamics and situations into account.

State of the Art

Position control has been widely used in the bipedal walking research since an early stage. Reference trajectories resembling bipedal gait are pre-defined in a joint space. Linear controllers are applied to track the these reference trajectories [1], [2]. Due to the pre-definition of the reference, robots cannot adapt themselves to a changing situation, such as external perturbations which causes stability problems.

Recent years, impedance control came into stage. A typical impedance control method is the Virtual Model Control (VMC) [3]. Virtual springs and dampers are added to robot segments to generate desired torques to the joints. The reference to be tracked is in the terms of spring set-points instead of joint position trajectories in position control. This results the benefit of the tolerance of disturbances compared with position control. However, various set-point references still need to be pre-defined for an entire gait cycle.

Meanwhile, central pattern generators (CPGs) based method are increasingly used in controlling bipedal walking of legged robots [4], [5]. The CPGs exhibits a limited cycle behavior to produce stable gait pattern in joint levels in a tunable rhythm. The pre-defined reference in positions and spring set-points are no longer necessary which results reduced control parameters. However, it is difficult to develop particular CPGs to solve a particular locomotor problem and training process is always required.

Our Approach

We use Model Predictive Control (MPC) method in combination with a state machine to synthesize the bipedal locomotion of a legged robot. In each phase of gait, the MPC predicts the future motion of the robot and calculates the desired joint torques by minimizing the difference between the future motion and the motion defined in the control objectives. Additionally, such minimization is subject to certain constraints, e.g. the range of desired torques and joint rotations are limited.

Like CPGs, only high level control parameters are necessary, such as step length and walking speed, to control the entire gait. Meanwhile, the MPC can be easily coupled with Capture Point [6], and other stability concepts like the eXtrapolated Center of Mass (XCoM) [7] to ensure the posture balance and perturbation recovery. Therefore, the MPC can handle sudden change in the environment while no training process is required. Compared with the VMC based methods, the MPC takes the multi-body dynamics into account while the VMC only considers local dynamics. Furthermore, the MPC allows an easy implementation of energy minimization and input-output constraints which benefits from the feature of optimal control.

The MPC algorithm on robot locomotion control in 2D was first published in [8]. Then the control algorithm in 3D was developed and presented in Dynamic Walking 2011. The main obstacle of the MPC approach towards real implementation was the large computation times [9] due to large dimension optimization at each sampling time. Work has been done in [10] to show the real time ability of the MPC in robot control in reduced degrees of freedom. Recent research is focused on optimizing the structure of MPC and integrator to achieve real time control of full degrees of freedom. We also extended the MPC to a nonlinear MPC based method especially to deal with automatic obstacle avoidance and stability improvement by the foot placement strategy.

We would like to give a demo to show that we are able to stabilize an virtual paraplegic walking in a virtual exoskeleton MINDWALKER [11] exposed to external perturbations. The virtual trunk is controlled by users via motion capture sensors and the virtual lower body is controlled by the MPC. The MPC is able to handle the injected trunk motion from users and maintain a stable virtual walking with balance strategies.

Discussion outline

- How does MPC deal with disturbance/perturbation? Real time trajectory generation according to perturbation
- How does MPC treat non-smooth system? Gait phase separation, hybrid control
- How does MPC realize real time ability? Fast integrator, trade-offs between speed and performance

Format

Talk (with interactive demo/ Virtual simulation (MINDWALKER))

Keywords

Bipedal locomotion, model predictive control, balance control

1. Jalics, L., H. Hemami, and B. Clymer, *A control strategy for terrain adaptive bipedal locomotion.* Autonomous Robots, 1997. **4**(3): p. 243-257.
2. Garcia, E., J. Estremera, and P.G. De Santos, *A comparative study of stability margins for walking machines.* Robotica, 2002. **20**(6): p. 595-606.
3. Pratt, J., et al., *Virtual model control: An intuitive approach for bipedal locomotion.* The International Journal of Robotics Research, 2001. **20**(2): p. 129-143.
4. Aoi, S. and K. Tsuchiya, *Locomotion control of a biped robot using nonlinear oscillators.* Autonomous Robots, 2005. **19**(3): p. 219-232.
5. Aoi, S. and K. Tsuchiya, *Stability analysis of a simple walking model driven by an oscillator with a phase reset using sensory feedback.* Robotics, IEEE Transactions on, 2006. **22**(2): p. 391-397.
6. Pratt, J., et al. *Capture point: A step toward humanoid push recovery*. in *Humanoid Robots, 2006 6th IEEE-RAS*. 2006.
7. Hof, A., *The 'extrapolated center of mass' concept suggests a simple control of balance in walking.* Human movement science, 2008. **27**(1): p. 112-125.
8. Van der Kooij, H., et al., *An alternative approach to synthesizing bipedal walking.* Biological Cybernetics, 2003. **88**(1): p. 46-59.
9. Hurmuzlu, Y., F. Genot, and B. Brogliato, *Modeling, stability and control of biped robots - A general framework.* Automatica, 2004. **40**(10): p. 1647-1664.
10. Wang, L., E.H.F. Van Asseldonk, and H. Van Der Kooij. *Model predictive control-based gait pattern generation for wearable exoskeletons*. in *IEEE Int Conf Rehabil Robot:1-6*. 2011.
11. *https://mindwalker-project.eu/.*