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WALKING DESPITE THE PASSIVE COMPLIANCE: TECHNIQUES FOR USING CONVENTIONAL PATTERN GENERATORS TO CONTROL INSTRINSICALLY COMPLIANT HUMANOID ROBOTS

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There are several problems which arise when using a standard ZMP-based pattern generator to control an intrinsically compliant humanoid robot like COMAN. We present two techniques: pelvis forward trajectory smoothing and polynomial admittance gain modulation, which make it possible to use the conventional pattern generator to control such passively compliant robots. The former method modifies the reference of the pelvis trajectory to counteract its overshooting caused by the compliance of the legs. The latter method is meant to decrease the impact during initial contact and decrease the error between the foot position and original reference during the mid-stance caused by the use of admittance control. We explain details of both of the methods and show results from walking experiments with and without the controls, proving their effectiveness.

Keywords: passive compliance, biped locomotion, ZMP, admittance control

1. Introduction

Most of the walking humanoid robots capable of performing practical tasks use high-gain position control.[1,2] They are easier to control in a structured environment, but prone to model discrepancies or external disturbances. In order for humanoid robots to be more practical, they must be able to operate in unstructured environments. One way of improving the robot's robustness to external disturbances and environment model inaccuracies is to develop robots which are intrinsically compliant[3] or torque controlled.[4]

The intrinsic compliance can have numerous advantages, such as: mechanical separation of harmonic-drives from joints, that softens the impacts and thus increases the lifetime of harmonic-drives; overall compliance improving resistance to the ground unevenness or external disturbances; improvement of energy efficiency by storing and releasing the kinetic energy from the springs.[5] The compliance, however, also has disadvantages: the joint level position control is inaccurate; the leg joints deflect under the weight of the robot, thus making the walking control more difficult;[6] the overall system's resonant frequency is much lower than in high-gain position controlled robots and can affect walking stability. Moreover, most of the existing model-based pattern generators developed for humanoid robots assume ideal position control and thus cannot be directly used in compliant robots.

In this work we explain difficulties which arise when using the ZMP-based pattern generator (PG) to control passively-compliant robots. We also present techniques than can be used to control compliant robots with existing PGs. In the second section we introduce our research and discuss the consequences of passive compliance. In the third section we present the PG, developed control techniques and experimental results proving their effectiveness. We conclude the paper with summary of our work.

2. Problem formulation

In this work we focus on the description of the pattern modifications and real-time control necessary to execute the dynamically consistent gait pattern created when assuming a joint level position controllability on the compliant robot COMAN[3] Fig. 1. In this section we describe our research platform and the main consequences of the intrinsic joint-level compliance.

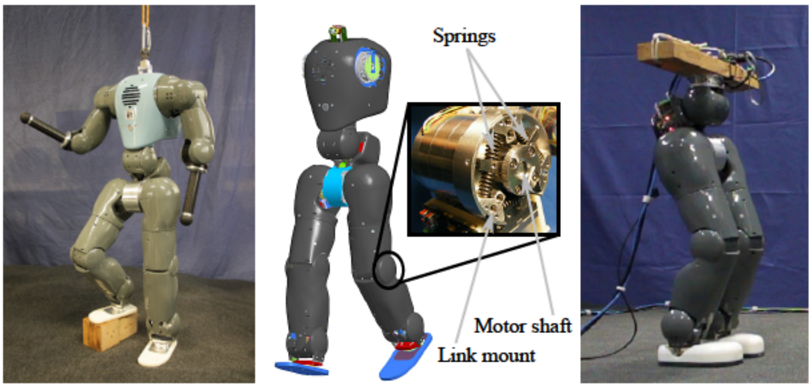


Fig. 1. Full body of our research platform COMAN. The figure in the middle shows knee's passive compliance mechanism. The picture on the right shows the version of the platform used in the experiments.

2.1. *COMAN structure*

The COmpliant huMANoid robot COMAN has an anthropomorphic bipedal structure equipped with series-elastic actuators. Every leg pitch joint (hip, knee, ankle) is actuated by a brushless DC motor connected to the joint by six linear springs as shown on Fig. 1. COMAN uses a distributed control system, that enables control of the motor position or joint torque. The robot with upper body is 0.93m high and weighs 28kg. The platform used in the experimental part of this work was without the upper body (see Fig. 1 right). The pelvis height is 0.5m and total weight of the lower body and waist is 18kg.

2.2. *Effects of the passive compliance on the robot's motion*

The passive compliance embedded in the COMAN's joints; while being advantageous in decreasing effects of sudden impacts on the structure and storing energy, is disadvantageous for joint level position control. When the position control is done on the motor level and the joint is subjected to high torque, the springs deflect and the joint diverges from the desired position. This makes the direct use of the trajectory references obtained from the pattern generator impossible. Whenever there is a sudden acceleration the springs deflect and the link does not reach the desired position. Furthermore, because of the compliance of the support leg the pelvis tends to sink, which causes discrepancies between the desired and real feet position. Using motor-position based control, this results in undesired early ground contact. Since the springs used in the structure have constant and relatively high stiffness, the structure is not able to damp the instantaneous impact occurring during the early ground contact, what causes a big disturbance and destabilizes the robot.

One possible solution to this problem is to detect early indications of instability (such as early ground contact) using automated real-time analysis of force sensor data from the feet.[7] Such information can be used to change the pattern dynamically during walking to improve stability. However, this would require real-time pattern regeneration capabilities, which is out of the scope of this paper and is our future work. In this paper, we investigate techniques for addressing this problem using only off-line pattern generation and feedback control.

3. Gait pattern generation and feedback control

As a source of the dynamically consistent gait patterns we use the ZMP-based preview controller with dynamic filter.[8] Due to the Multibody System (MBS) embedded in the dynamic filter, the resultant trajectories closely follow the reference ZMP that guarantee the system's stability, given the ideal experimental conditions (accurate robot model, joint level high-gain position control, flat ground etc.). Since the COMAN platform is equipped with mechanical compliance, the discrepancy between the real system and the MBS is too big to allow direct execution of the pre-calculated gait patterns on the robot. To cope with the difficulties described above and in 2.2 we implemented two techniques. The first one copes with the deformation of springs during high acceleration and deceleration of the pelvis, the second one copes with the impact caused by the early foot contact with the ground. In the following subsections we describe the techniques and present the experimental results confirming their performance. In all experiments we used the same gait parameters: step size 6cm, cycle time 1.75s, double support time 0.34s, foot clearance 4cm, steps number 21. A video of the conducted experiments can be found in Ref. 9.

3.1. *Pelvis sagittal trajectory smoothing*

Since the platform used in our experiments was not equipped with the upper body, the total Center of Mass (CoM) was located below the pelvis (37cm from the ground in free standing condition). Because of this, for CoM to follow a smooth reference generated by the preview controller the pelvis needs to move back and forth. This further results in high accelerations

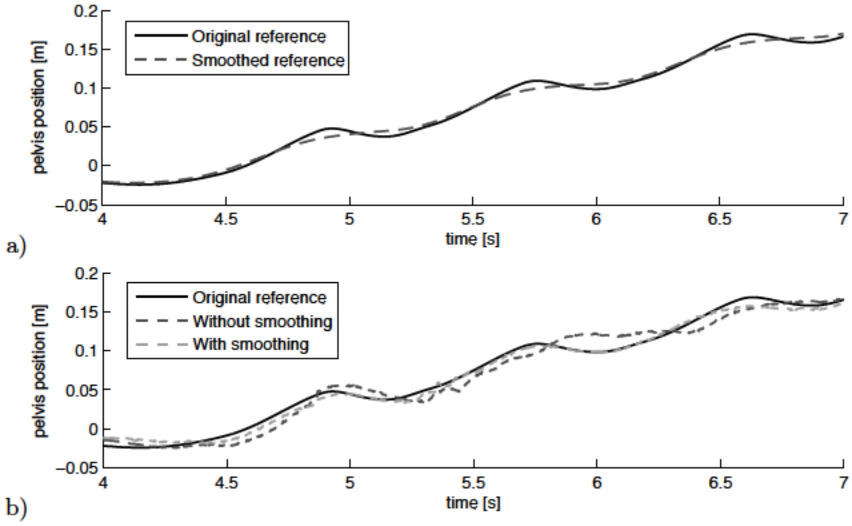
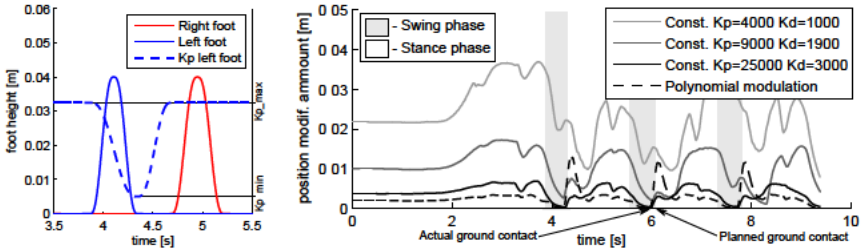


Fig. 2. The pelvis trajectory in the sagittal plane. Graph (a) shows the original trajectory and trajectory after smoothing and (b) shows the original trajectory and experimental results of walking with pelvis reference trajectory with and without smoothing.

and decelerations that cause excessive springs deflection and result in an unstable gait. To cope with the problem we smoothed the pelvis reference trajectory obtained from the preview controller, to reduce the acceleration and deceleration, and as a result follow the real reference closer than before. For smoothing we used the centered moving average filter with the averaging period 0.5s (the value was chosen experimentally). Thanks to use of the centered averaging filter we were avoid introducing lag into the reference. The fragment of trajectory before and after the smoothing is presented on Fig. 2a. The difference between the trajectory of the pelvis in walk with and without smoothing is presented on Fig. 2b. The trajectory was obtained using forward kinematics of joint angles data registered by joint encoders. We can see from the graph that the pelvis follows closer the original reference when executing the smoothed trajectory reference. The graph show only the first four steps. In the experiment without smoothing the robot tipped over after 7^{th} step.

3.2. *Admittance control with polynomial gain modulation*

As described in chapter 2.2, because of the passive compliance, the pelvis sinks down during the single support phase. This results in the swing foot



(a) (b)

Fig. 3. Graphs present (a) modulated admittance gain (Kp) reference for left foot during single gait cycle and (b) results from walking experiments comparing left foot height modification amount for the constant gain and the modulated gain. The modulated gains vary as follows: $Kp =$ 1000-50000 and $Kd =$ 750-2500.

being closer to the ground compared with the reference and thus causes early ground contact. This results in strong impact that disturbs the motion of the robot. To cope with the problem we implemented admittance control which adds active compliance to the leg by rising the foot according to the force feedback from the force-torque sensor located below the ankle joint.[10] The formula for calculation of the amount of the leg reference position modification is derived from the force balance of the parallel spring and damper mechanism and has the following form:

$$\Delta z[i] = \frac{F_z + \frac{K_d \Delta z[i-1]}{\Delta t}}{K_p + \frac{K_d}{\Delta t}}, \tag{1}$$

where, K_p and K_d are the spring and damping constants, respectively; the sampling time Δt is 1ms and F_z is the measured vertical ground reaction force. Initially we tuned the proportional relation between the force and displacement. In order to compensate for the high impact we needed to set the spring constant of the admittance controller to a low value, this however resulted in even bigger sinking of the pelvis and respectively higher impact during the ground contact. To ensure both the soft ground contact and small sinking of the pelvis we developed the polynomial gain modulation. The gain of the admittance control starts from a very high value during the stance phase, then decreases to the minimal value during the swing phase to provide the soft contact and during the double support phase goes back to the high value to reduce the pelvis sinking (see Fig. 3a). We used the polynomial interpolation to extend the duration of the low gain period right before and after the initial contact. The experimental results presented on Fig. 3b show the foot vertical position modification amount resulting from admittance control. One can notice that the lower the Kp gain (spring constant) the higher the sinking of the robot during the stance phase, which not necessarily is followed by the big reaction during the ground contact. The results from experiments with polynomial gain modulation however show that the foot moves up by a significant distance right after the ground contact to decrease the impact and later moves down during the stance phase.

4. Summary

We presented two techniques that make it possible to successfully control the compliant humanoid robot COMAN with conventional pattern generator. We experimentally proved that the smoothing of the sagittal pelvis trajectory reference decreased overshooting of the real pelvis trajectory caused by spring deflection and helped in following the original reference. We also showed that the polynomial modulation of admittance gain helps in increasing the initial reaction to the ground contact and minimizes the amount the whole robot sinks during the stance phase. Application of both techniques results in the long stable gait, while omitting any of them, results in destabilization of the robot and eventual fall. Our future research will focus on the real-time pattern generation techniques, which would allow to regenerate the motion reference in case of big divergence from the original reference.

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References

1. K. Kaneko, F. Kanehiro, S. Kajita, H. Hirukawa, T. Kawasaki, M. Hirata, K. Akachi and T. Isozumi, Humanoid robot HRP-2, in *Proc. IEEE Int. Conf. Robotics and Automation ICRA*, 2004.
2. Y. Sakagami, R. Watanabe, C. Aoyama, S. Matsunaga, N. Higaki and K. Fujimura, The intelligent ASIMO: system overview and integration, in *Proc. IEEE/RSJ Int Intelligent Robots and Systems Conf*, 2002.

3. N. G. Tsagarakis, Z. Li, J. Saglia and D. G. Caldwell, The design of the lower body of the compliant humanoid robot cCub, in *Proc. IEEE Int Robotics and Automation (ICRA) Conf*, 2011.
4. M. Raibert, Dynamic legged robots for rough terrain, in *Proc. 10th IEEE-RAS Int Humanoid Robots (Humanoids) Conf*, 2010.
5. P. Kormushev, B. Ugurlu, S. Calinon, N. Tsagarakis and D. G. Caldwell, Bipedal walking energy minimization by reinforcement learning with evolving policy parameterization, in *Proc. IEEE/RSJ Intl Conf. on Intelligent Robots and Systems (IROS)*, (San Francisco, USA, 2011).
6. L. Colasanto, P. Kormushev, N. Tsagarakis and D. G. Caldwell, Optimization of a compact model for the compliant humanoid robot COMAN using reinforcement learning, *Journal of Cybernetics and Information Technologies* **12** (2012).
7. P. Kormushev, B. Ugurlu, L. Colasanto, N. G. Tsagarakis and D. G. Caldwell, The anatomy of a fall: Automated real-time analysis of raw force sensor data from bipedal walking robots and humans, in *Proc. IEEE/RSJ Intl Conf. on Intelligent Robots and Systems (IROS)*, 2012.
8. S. Kajita, F. Kanehiro, K. Kaneko, K. Fujiwara, K. Harada, K. Yokoi and H. Hirukawa, Biped walking pattern generation by using preview control of zero-moment point, in *Proc. IEEE Int. Conf. Robotics and Automation ICRA*, 2003.
9. Video accompanying the paper, available online: http://kormushev.com/goto/CLAWAR-2013
10. K. Hashimoto, Y. Sugahara, H. Sunazuka, C. Tanaka, A. Ohta, M. Kawase, H.-o. Lim and A. Takanishi, Biped landing pattern modification method with nonlinear compliance control, in *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*, 2006.