A singularity-tolerant inverse kinematics including joint position and velocity limitations

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1 Summary

Humanoid robots have many degrees of freedom which ideally enables them to accomplish different tasks. From a control viewpoint, however, the geometric complexity makes planning and control difficult. Favoring controllability properties, it is popular to operate with crouched knees, since the Center of Mass (CoM) height can be directly manipulated. In addition to a higher energy consumption however, this brings long-term damage to the actuator and series elastic elements. We propose a simple Inverse Kinematics (IK) formulation as a nonlinear optimization that can handle singularities and joint limits with inequality constraints. We also introduce safe regions for joint velocities and propose modifications that help the joint come out of singularities faster. The effectiveness of the proposed method is verified in simulations and on the real hardware for various balancing tasks.

2 Introduction

Operation with crouched knees makes the control easier, but it might have severe consequences for the hardware in a long-term. Besides, it makes the robot less human like. Stretched-knee postures on the other hand have two main difficult aspects to be handled in the controller: one is related to singularity which results in loss of one degree of freedom; the second links to the fact that most of the time, the knee joint reaches the hard limit in stretched postures. Although other joints in the robot might not approach their limits with high speeds in normal conditions, due to the singularity, this can happen easily in the knee joint. Large velocities and accelerations might require large momentary currents because of non-ideal nature of electric actuators, i.e. large rotor inertia. When hitting the joint limits, large velocities can damage the internal shrink fitting mechanisms as well.

The difficulty of stretched legs is not merely limited to the hardware. Implementing traditional inverse kinematics algorithms, we noticed that getting out of singularities is very hard for integration-based algorithms (Goldenberg et al., 1985). Although Jacobians provide a linear relation between task and joint velocities, the underlying pseudo-inversion in damped least-squares methods (Chiaverini et al., 1994; Kryczka et al., 2011; Sugihara, 2011) fails to find enough increment for the knee velocities in singular postures. The integration of velocity therefore gives almost frozen knee angles, meaning that the algorithm can hardly get out of singularity, often delayed or even impossible.

Formally, we consider a set of Cartesian tasks for the end-effectors (hands, feet, CoM) while a subset of them might not be feasible. We look for a flexible inverse kinematics formulation that can accomplish these tasks as much as possible. One such task would be an overshooting squatting motion where at some point, the desired CoM position goes higher than feasible. Besides, we expect the algorithm to give priorities, i.e. keeping balance first and then performing other tasks as precise as possible.

3 Methods

Considering positions directly as decision variables might resolve the freezing problem, since at every iteration, one can start the optimization from a non-singular initial condition. Velocity limitations should be included however (Suleiman, 2016), though optimizing positions and velocities at the same time increases the dimensionality and might violate online computation requirements. Taking advantage of fast nonlinear solvers, we propose an inverse kinematics algorithm that can handle previously-mentioned problems altogether. We only use positions as decision variables like (Wang and Chen, 1991), but consider Taylor series to approximate joint velocities. Positions and approximate velocities are then bounded together in hardware-defined safe regions, where the velocity bounds get tighter as positions reach their limits. A simple example would be a circle, spanning between minimum and maximum positions and velocities. Although we do not explicitly optimize joint velocities, since task velocities are available, we use them in the optimization as well. These velocities help getting out of singular positions faster, demonstrated in a number of tasks discussed in the next section.

4 Results

We discuss balancing tasks that cover important aspects of singular postures and joint limits. Imagine an infeasible squatting (rhythmic up-down) motion where the desired CoM height goes higher than feasible, shown in Figure.1.A. When going up, the knees approach their limit and go into a singular posture. Imagine now that the desired CoM height has passed the highest point and is coming down, but the knees are yet stretched since the task is infeasible. In such a singular posture, the optimization objective is non-zero (due to the task error) and decreasing until the CoM height becomes feasible.

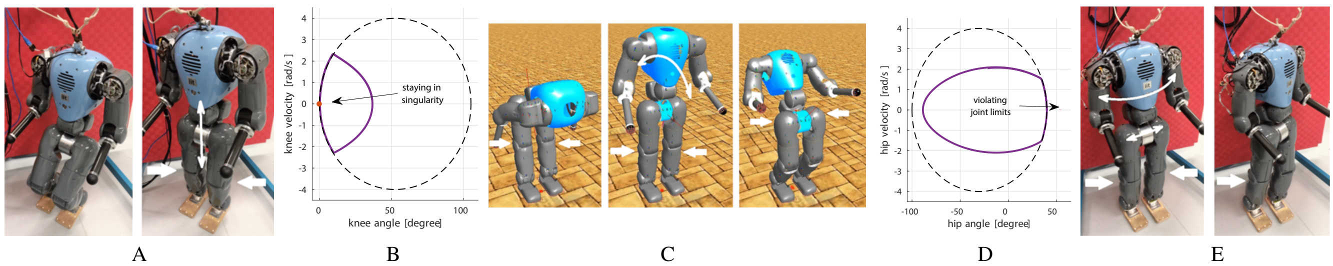

Figure 1: (A) Symmetric squatting task with fully stretched knees. (C) A multi-bound task where singularity and joint limits become active in different joints. (B) Knee and (D) hip trajectories in the multi-bound task. (E) An asymmetric task where singularities in the two legs happen at different times.

Indeed, the knee joint is supposed to get out of singularity only when the desired CoM height becomes feasible. However, the velocity bound limits the movement and causes large delays in tracking. Therefore, it makes sense to start flexing the knee in advance when the task is yet infeasible, but the objective is decreasing. We use task velocities in the objective function to achieve this.

In a second task, imagine a constant unfeasibly high CoM height is commanded, and the torso is performing a rhythmic titling motion, shown in Figure.1.C. At some point, the hip joint reaches the limit (shown in Figure.1.D), where the tilting angle can not be achieved anymore. The flexible formulation of our problem allows for knee bending (refer to Figure.1.B) which helps the torso tilt even further. This is done in compromise with the vertical CoM task, although the balance (horizontal CoM task) is not altered.

Finally, we consider an asymmetric task of rotating around the yaw axis, while again, the CoM height is unfeasibly commanded to be high. The knees become stretched, but due to asymmetry, they have to bend sometimes, shown in Figure.1.E. In this case, the tracking speed becomes important, both in approaching and escaping from singularities. Our proposed method can properly handle the tracking and give a natural motion while integration-based approaches fail, often getting frozen.

5 Discussion

The difficulty of singular postures is mainly viewed as numerical problems in the literature, where damped least-squares or other methods are used to handle this problem. Although joint limits are also considered widely in IK methods, the coincidence of joint limits and singularities is rarely addressed in the literature. In this research, we analyzed these problems and extended our study to dynamic cases as well. In other words, we addressed issues arising in approaching and escaping from the singularity. We proposed a powerful IK method that handles these issues together with a case where singularity and joint limits are triggered in different joints. Our setup is fast enough for online applications, as demonstrated in the real hardware. We believe that operating in singular postures can improve energy efficiency, produce more human-like motions, protect the actuators from long-time damages and yet provide precisions required. In future, we would like to add similar policies to our inverse-dynamics algorithm (Faraji et al., 2015) as well, in order to improve the safety and energy efficiency features.

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