Compliant Whole-Body Robot Control with Kinematic and Dynamic Constraints

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I. INTRODUCTION

We previously released a high-performance multi-goal inverse kinematics solver (BioIK 2) [1] [2], which can be used for full-body motion control. The IK problem can be specified through user-defined cost functions or by choosing from a comprehensive set of pre-defined goal types. Since the first release, we have added several dynamic goal types, allowing BioIK 2 to solve kinematic and dynamic constraints simultaneously.

In this work, we will focus on compliant interaction with the environment using sensor feedback, discuss different applications and feedback strategies, provide a generalized cross-dimensional compliance model, and test the presented methods on simulated humanoid robots as well as on a physical robot arm.

II. COMPLIANT END-EFFECTOR CONTROL

Compliant control of an end effector can be achieved using PD control and limited end effector displacement. The PD controller is configured to produce a linear relationship between end effector displacement and contact force. By limiting the distance between measured end effector position and goal position, a constant contact force can be obtained. If the estimated end effector position is calculated from joint angles, incorrect joint calibration will affect end effector position estimates and inverse kinematics solutions equally, allowing estimation errors to be canceled out.

BioIK 2 can thus be used as a force controller, while simultaneously respecting additional kinematic and dynamic constraints.

Compliant end effector control can be used to solve a typical whiteboard wiping task. Execution of the compliant end effector control task may be combined with other goals, such as dynamic balancing. (Figure 1)

III. FULL-BODY COMPLIANCE

Compliance along redundant dimensions can be increased using direct joint feedback, eg. keeping an end effector at a specific position while allowing compliant ellbow movements. Joint compliance can be implemented using an additional goal which favors solutions close to the current joint values.

IV. SELECTIVE COMPLIANCE

If used directly, compliant control could result in compliance towards all external forces, which may not always be desired. E.g. on a humanoid robot, full-body compliance towards gravitational forces can result in loss of balance, which can be corrected using gravity compensation. To do so, we estimate gravitational and/or accelerational forces through inverse dynamics, subtract the expected forces from the measured forces, and use the computed differences to control compliance.

V. CROSS-DIMENSIONAL COMPLIANCE

While compliance is traditionally implemented as displacement in the same direction as the measured error, compliant control can be extended to include compliance along different directions. If touching a surface perpendicular to the direction of movement, backward compliance would stop the motion, and it may be desireable to instead move along the surface and perpendicular to the measured error.

Furthermore, for some applications, it may also be desirable to respond to translational errors with rotational compliance or to rotational errors with translational compliance. If walking on uneven terrain, a humanoid robot may respond to errors in foot orientation by also adjusting foot heights, eg. to prevent the flying foot from hitting the ground when encountering a sudden slope. (Figure 2)

Cross-dimensional compliance may be defined using a compliance transfer function $C : \vec{e} \mapsto \vec{d}$, which maps an error vector to a displacement vector. Parameters and results can be defined in joint space or in cartesian space.

VI. TASK SPECIFICATION

BioIK 2 provides several kinematic and dynamic goal types, which can be combined to specify complex manipulation tasks. Each goal type computes a partial cost function from joint values and/or cartesian poses. The final cost function is computed as a weighted average over a user-supplied goal set. New goal types can be added by deriving from an existing base class and implementing a custom cost function.

Although BioIK was originally developed as a fast multi-goal inverse kinematics solver with support for user-defined cost functions, it proved to be flexible and efficient enough to handle dynamic constraints as well. After first implementing simple smoothness constraints, we added goal types for

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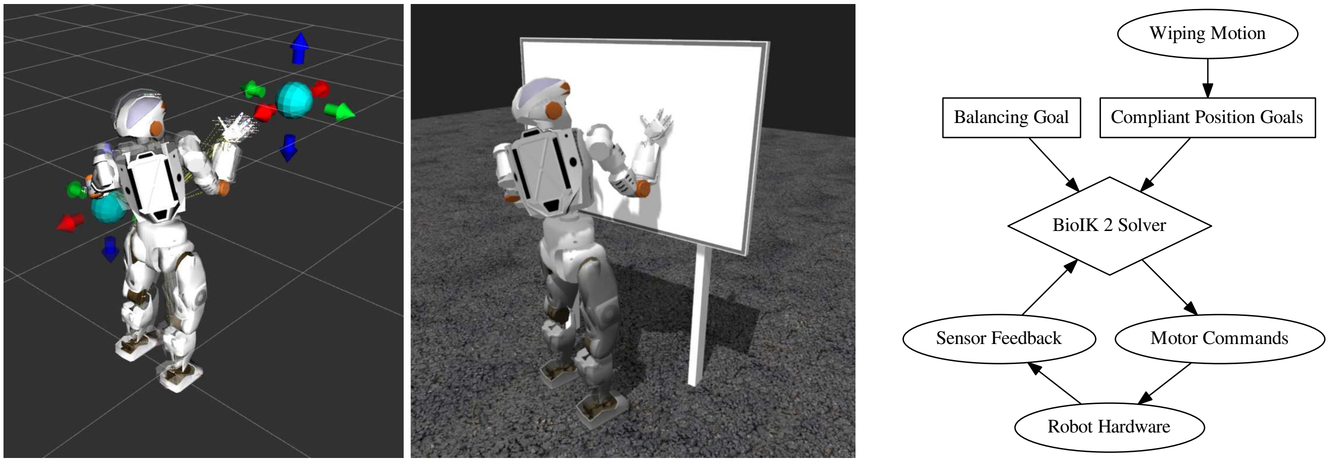

Fig. 1. Executing a whiteboard wiping task using compliant inverse kinematics with balancing: Robot model and IK goals (left), physics simulation in Gazebo [7] using Simbody [10] (middle), goal and controller configuration (right). Without compliance, the robot would either fail to reach the whiteboard or throw itself over.

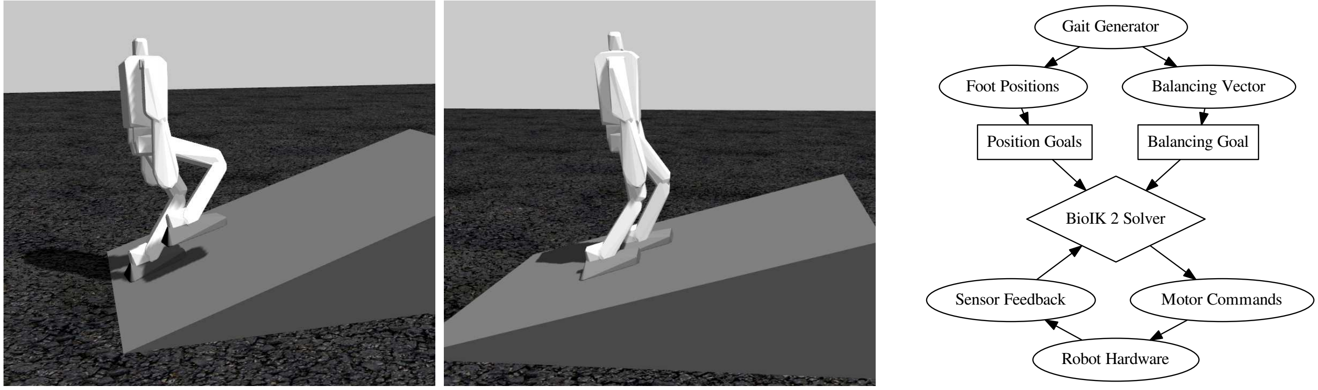

Fig. 2. Adaptive walking with cross-dimensional compliance, responding to foot orientation errors with translational compliance to prevent the flying foot from hitting the ground. Physics simulation in Gazebo [7] using ODE [9] (left, middle), goal and controller configuration (right).

Fig. 3. Compliant drawing (left) and whiteboard wiping (right) using a KUKA LWR arm. The exact pose of the whiteboard is unknown and the robot has to adjust it's motions using joint feedback. During drawing (left), an additional low-priority goal is attached to the arm, which can be used to prevent the arm from blocking the view; however, if necessary for fulfilling the high-priority end effector goal, the low priority goal can be violated. Disabling compliance during wiping either directly leads to loss of contact or causes the robot to push the whiteboard away and to then lose contact. Disabling compliance during drawing leads to excessive force on the pen as well as frequent loss of contact and large gaps in the drawing. If compliance is disabled from the beginning, the robot is unable to find the correct distance at all. If compliance is enabled, the whiteboard can also be moved during execution and the robot adjusts it's motions accordingly.

physically correct inverse dynamics (eg. for stable robot walking, also taking into account velocites and accelerations), and are currently developing new goal types for compliant manipulation.

Compliance can be controled in joint space or in cartesian space. Force measurements can be acquired directly using force sensors, or indirectly from position displacements and known stiffness parameters. For cartesian-space compliant position control, a compliant position goal can be used, which implements cartesian PD control. Compliant behavior can be arbitrarily combined with non-compliant IK or dynamics goals.

VII. CONCLUSION AND FUTURE WORK

Our BioIK 2 solver appears to be well suited for compliant robot control and can simuntaneously handle kinematic constraints, dynamic constraints, and compliant force control. In addition, we provide a cross-dimensional compliance model to simplify the implementation of non-trivial compliant behaviors such as compliant walking. The general principles presented in this work were tested in simulation as well as on a real robot arm. Some tasks could only be tested in simulation since we are currently not in possession of a sufficiently actuated life-sized humanoid robot. During the tests that we were able to do, the robots moved as intended in simulation as well as on real hardware.

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