A Gravity Compensation Controller for the NAO Robot

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CS 393R: Autonomous Robots
Fall 2015 | Austin, TX
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Abstract— **In this paper, an environmental compliance controller is proposed incorporating positional data from the NAO's major joint sets to compensate against the effects of gravity. This allows the robot to respond to external input forces on its joints and to hold its position against gravity once the user releases its supporting force. In doing so, the compliance controller makes it much easier to manipulate the NAO and provide precise demonstrations, making the teaching process much more feasible for a single user, as they are no longer required to have external assistance in holding the robot's position at any given time during the teaching sequence. An interactive behavior is implemented utilizing the compliance controller to teach the NAO robot new keyframes. The most immediate application of this feature is to more easily design advanced soccer kicking motions, but the applications of this controller can be extended to a wide variety of technical demonstrations.**

I. Introduction

Gravity compensation is a very common issue that needs to be accounted for in serial manipulation. For a serial manipulator to maintain a constant pose, external disturbances such as gravity must be counteracted by the actuators. In standard NAO robot operation, the stiffness parameter is used to counteract the gravitational gradient. However, when manipulating the robot for demonstration training purposes, the stiffness must be lowered significantly for the robot's joints to be easily moved and positioned. When using the keyframe utility tool provided by the UT NAO Villa team, it is difficult to position the robot's multiple joints in exactly the right positions due to a combination of low stiffness and high gravitational force. In addition, it is difficult to know exactly which poses to strive for, and determining even statically-stable poses is a high feat that requires constant tuning and re-tuning.

Gravity compensation has often been used in combination with PD control to allow position-based goal-oriented movement from a starting position to an ending position to be achieved. This requires precise measurements and joint control, along with online, closed-loop correctional movements and torque control. However, in the case of NAO pose training, it is much simpler to achieve gravitational compensation at a static position.

The use of gravity compensation can streamline the process of exploring and holding poses with certain characteristics, such as static stability. By counteracting the force of gravity with the bare minimum amount of force, usability by both expert and novice demonstrators increases dramatically.

II. Related Work

In simulated environments, multilink manipulators are often regulated using linear feedback laws that exploit the physical properties of the mechanical system. In the absence of gravitational forces, simple proportionalderivative feedback control at the joint error level is sufficient to stabilize any arm configuration, as formally proved for rigid arms [1], elastic joints [2], and with distributed link flexibility [3].

When gravitational effects are applied to rigid manipulators, a simple constant gravity compensation can be performed at the desired joint configuration [4] to counteract the physical force. For a robot with elastic joints, simple gravity compensation can be applied under the assumption that joint stiffness overcomes the gradient of the gravitational term [2], utilizing feedback from the elastic coordinates. A. De Luca and B. Siciliano proved in [5] that global asymptotic stability of a joint PD controller, utilizing feedback only from joint errors, can be achieved under constant gravity compensation, evaluated at the desired configuration, for a nonlinear, multilink flexiblejoint robot. However, the position error of the endeffector depends heavily on the link stiffness of the joints.

De Luca builds on the previous result in [6], noting that an exact knowledge of the gravity vector is required to evaluate constant gravity compensation. This is difficult to realize and introduces a steadystate error that is nevertheless present for PD control. In traditional mechanics, an integral term is applied to offset this effect, but due to the nonlinear nature of gravitational control, the design of a PID controller introduces several problems, one of which is that asymptotic stability of robot PID control is proven only locally around the desired configuration. Instead, the paper proposes a fast iterative method that builds the required gravity compensation forces at the final configuration using a PD controller that applies an integral term at discrete, fixed time instants. In this way, PD control can approach the destination and utilize an integral action closer to the goal, avoiding windup effects and providing finetuned gravitational compensation and stateerror minimization around the desired endpoint.

In [7], the previous results are applied to flexiblejoint multilink manipulators, with the assumption that the arm stiffness should dominate gravitational effects.

In [8], De Luca details an overall mechanism for gravity compensation in flexible and nonflexible joint and link configurations. PD+ control is applied for motor torques, with torque u chosen as:

$$u = KP(d)KD + g(d, d), KP > 0, KD > 0 \quad (1)$$

with the associated d defined as the solution of

$$g(d,) + K = 0. \quad (2)$$

These equations cover the cases of both fullyrigid arms, where $d = 0$, and that of elastic joints.

On top of PD+ control, an iterative compensation scheme achieves setpoint regulation for a general flexible robot without knowledge of gravity. In particular, they drive the robot motor variables to specified angle values, satisfying unknown gravity term constraints that is determined through a control reading at the steady state position.

$$g(i, i) = 1/KP(di) + ui1 \quad (3)$$

$$g(i, i) = Ki. \quad (4)$$

In [9], the effects of gravitational force are similarly compensated using a simple PD setpoint controller scheme that estimates gravitational force at a nonsingular position. However, unknown frictions were observed during the implementation of this controller and had a strong impact on the performance of the compensation controller on a real robotic system. To counter this, the methods are expanded upon in [10] to estimate and compensate the forces of both gravity and friction.

Friction forces can be modeled as a combination of static, viscous, and Coulomb friction forces. Viscous friction has a linear damping effect, while stiction and Coulomb friction contain strong nonlinearities near the zerovelocity level, resulting in finitetime trapping effects and positioning errors. As a result, stiction and Coulomb frictions have hindered conventional PD and PID controllers with positioning errors at setpoint and low velocities. To improve performance, a number of control strategies have been proposed. In [10], the focus is on the estimation and compensation of unknown static friction in the same vein as gravitational compensation.

In [11], the effects of elasticity in mechanical transmissions is taken under consideration due to static deformations under gravity, which induces position errors at the robot end effector. Previous applications of gravity compensation have assumed a strong level of joint stiffness that overcomes the gradient of gravitational forces. In the presence of high joint elasticity, gravity torque depends on the robot link positions, whereas motor positions are often the only measurable effects.

The main contribution of [11] is the addition of a new variable, gravitybiased motor position, to evaluate the gravity torque at each configuration, allowing for more flexibility in proportional gain tuning. Under this controller, PD control is introduced as

$$u = KP(d)KDd + g( ), KP > 0, KD > 0 \quad (5)$$

where is the aforementioned gravitybiased modification of the measured motor position, , and is defined as follows:

$$= K1(g(qd)). \quad (6)$$

It is important to note that white g( ) is only an approximate cancellation of gravity at any robot configuration during motion, it evaluates as the correct gravity compensation at steady state.

In [12], an inner torque feedback loop is incorporated into a passivitybased analysis, interpreting torque feedback in terms of how it shapes the motors inertia. A linear state feedback controller with gravity compensation is introduced utilizing this concept.

For position control, the interpretation of joint torque feedback as shaping motor inertia allows torque feedback to be used directly within the passivity framework and divides the controller design into two steps, one related to torque feedback and the other to position feedback. Unlike previous singular perturbation approaches, however, their system does not require the two feedback loops to have different time scales.

Torque feedback is considered in the form:

$$\tau_m = BB_\theta^- 1u + (I - BB_\theta^- 1)(\tau + DK^-1\dot{\tau}) \quad (7)$$

where u is an intermediate control input and B_θ is a diagonal, positive definite matrix. However, to effectively damp the torque dynamics, a more general torque controller can be considered:

$$\tau_m = BB_\theta^- 1u + \tau + DK^-1\dot{\tau} - BB_\theta^- 1(\tau + D_sK^-1\dot{\tau}) \quad (8)$$

Along with the joint model, this provides new motor dynamics given by:

$$B_\theta\ddot{\theta} + \tau + D_sK^-1\dot{\tau} = u \quad (9)$$

In [13], we have the most direct, applicable resource for implementing gravity compensation on a bipedal humanoid robot like the NAO. By using the manipulator Jacobian to calculate joint torques on the robot from external forces, we can quickly and efficiently find the joint torques that must be applied to counteract the external force, and use a simple stabilizing PDcontroller to hold the desired position. In the paper, the feedforward controller is adapted to a stable walking gait, first in the doublesupport phase, then the singlesupport phase.

Finally, in [14], a modified gravity compensation controller utilizes force vector projections to calculate a general gravitational model for the multiDOF robot arm and counteract it while allowing dexterous easiness in arm manipulation by uncommon external human forces through haptic control, which is similar to the goal that we are attempting to accomplish on the NAO. A parabolic function models the velocity of the arm over time, allowing more torque to be applied over time, and allowing the arm to gradually slow towards a more stable state. The monitoring of angular momentum and impulses signifies the start of a haptic command, allowing the arm to reduce antigravitational torque and release its position when desired.

III. Implementation

The first goal of the project was to implement a satisfactory gravity compensator, allowing joints to maintain their positions against gravitational forces while allowing other external forces to move these joints to their desired positions. Unfortunately, force measurements are not possible on the NAO robot beyond its feet. The next best measurement is joint current, but there are two main issues with using current measurements from the NAO:

1) Current measurements are very noisy and error-prone.
2) Current measurements are always positive, making it impossible to determine which direction the joint is moving at any given time.

We first built a proof-of-concept compensator mock, deriving a basic function to map the position of the right shoulder pitch joint to the current required to maintain that position against the force of gravity. To determine this function, we experimentally measured the current against the force of gravity along the joint's full range of motion, building a graph mapping joint positions to minimum required currents. We then fit a variety of functions to the trending curve, achieving an r-value of 0.981 with a linear function of fixed y-intercept equal to zero. Using this function, we were easily able to derive a function to map any joint position to the desired stiffness, which control how much current is allowed at each joint, and the function was shown to be reliable for about 80% of the joint's full range of motion. In approximately 20% of possible joint positions, the current was overestimated, allowing the robot to move its right shoulder higher until it reached a more accurate current mapping.

As seen in Fig 1, the current measurements are extremely unreliable, even at static joint positions.

To perfect this approach, we needed a more accurate, nonlinear approach to deriving stiffnesses for any joint position. By controlling the current that passes through each joint, the bare minimum current can be used to counteract the gravitational gradient, providing enough givence for a human manipulator to modify the joint accordingly. Therefore, gravity compensation can be mocked by sending positional joint commands to a very large position, while limiting the current that can be used to reach that position based on a power function of the current position of the joint.

To map joint positions to stiffnesses, the torque vector at each main joint location must be determined based on the absolute positions of each of the related joints within a limb. We can then find the gravitational torque from these vectors.

The desired stiffness for each joint can be calculated from these torques, as well as the motor's geared torque, found from the NAO's manual.

We found that the stiffness needed to maintain the joint positions of the support leg were approximately double that calculated for any joint fightly only the force of gravity. This

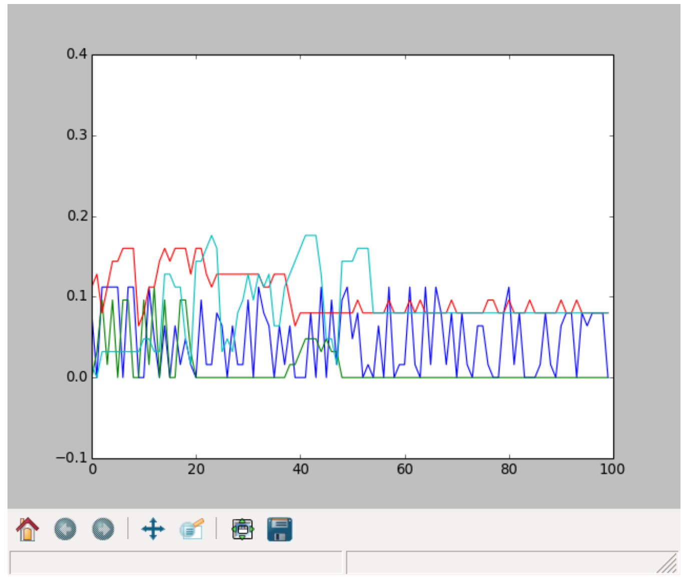

Fig. 1: A graph of the last 100 current readings for the four right arm joints.

is due to the additional weight force of the NAO's body, working along with gravitational force.

Once gravity compensation was implemented, we were able to create a new robot behavior (Fig 2) to streamline the keyframe teaching process. We segment the robot's four main joint sets – its arms and legs – and allow one joint set to be manipulated at a time, preserving the joint positions of the other sets throughout the teaching process. By doing so, we can easily position each joint set separately without worrying about other joint sets being modified by gravitational forces. We use the NAO's three head force controls to facilitate the teaching process and allow human demonstrators to select the joint set they wish to manipulate.

The gravity compensation teaching mode is able to also save the final poses into a yaml file on the NAO robot, allowing poses to be extracted into the codebase and used as part of keyframe sequences or poses.

IV. Evaluation

Although we do not have any quantitative evaluations to determine the accuracy of our gravity compensation model, we conducted some preliminary tests to evaluate the ease of use and subjective "acceptability" of our compensational teaching mode.

When applying gravity compensation to any joint that is disconnected from the ground and is feeling only the forces of gravity, we found that the joints successfully maintained the desired position at every point along their range of motion. Although the NAO's joint position jittered when reinstating joint stiffness at the end of a teaching segment, this was due only to a very minor current spike that quickly reverted back to its desired value and brought the joint position back into place.

In evaluating the ease of manipulation, we found that the NAO's upper joints were fairly easily movable to any

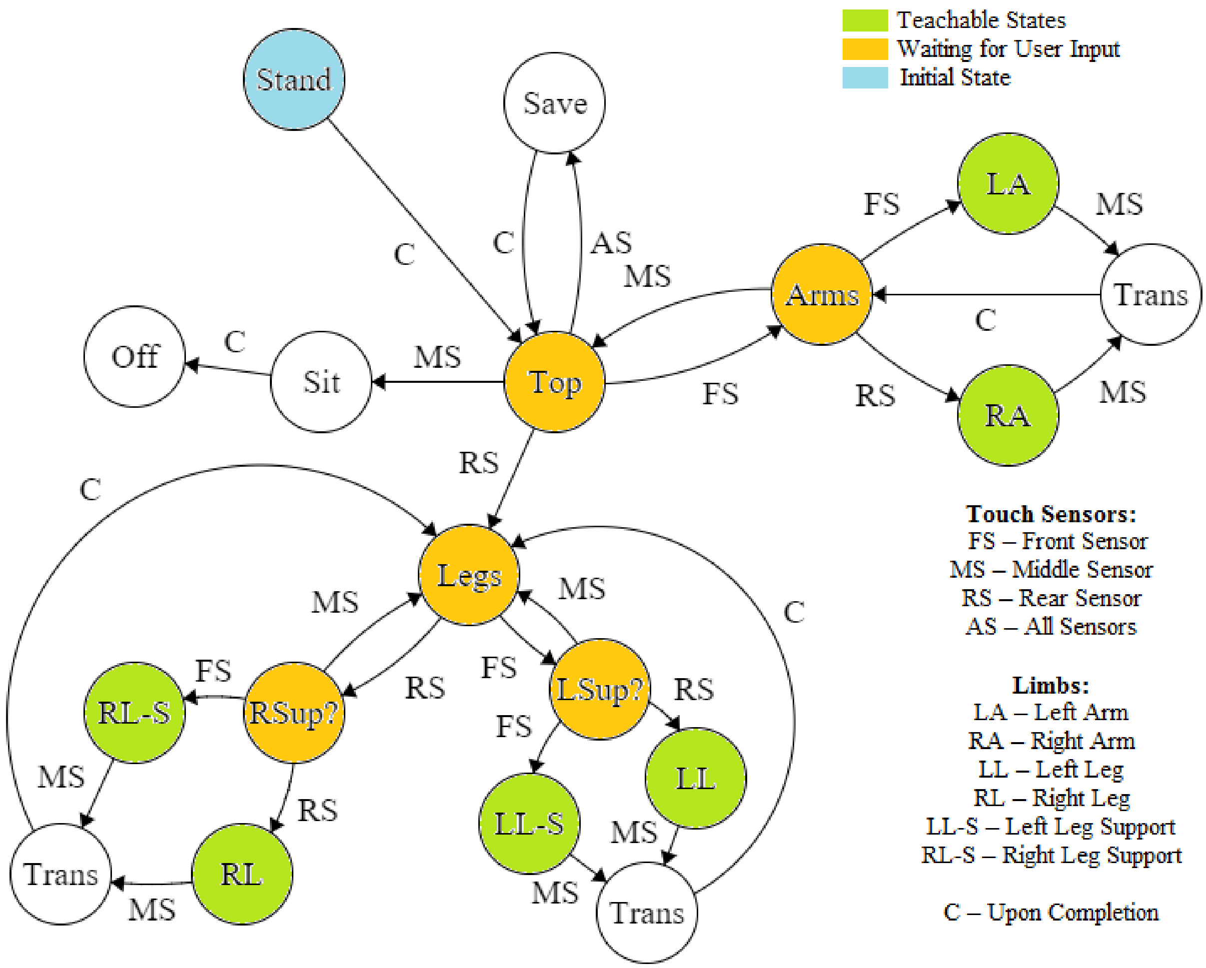

Fig. 2: The state machine for the NAO pose teaching behavior. TRANS nodes represent the reinstation of full stiffness.

position in which we they desired them to be. However, we found the ankle and hip rolls to be more difficult to move into the correct position due to the decreased ability to attain leverage overcoming the joint stiffness.

Finally, we evaluated the usefulness of our teaching behavior in finding stable positions for kicking motions. In previous projects, we found that finding a single stable position could take upwards of 15 minutes, and could be incredibly difficult without a human partner to help with holding joint positions and stabilization of the NAO. With our new teaching behavior, we were easily able to explore possible static positions and tweak joint positions until it was statically stable in approximately 3 minutes without external help from a secondary teacher. The ability to tweak the joint positions of one limb while holding the joint positions of other major limbs allows the teacher to more precisely position each joint in the desired manner.

V. Future Work

The proposed learning framework can be combined with the keyframe utility to more easily learn new kicks, quickening the optimization process significantly. In addition, the use of COM balancing to maintain desired poses as closely as possible, while maintaining balance in a single-support state, can provide a large step in human-robot interaction and training, utilizing the power of human demonstration intuition and control with adaptative optimizations by the robot.

It is also desired that multiple joint sets be manipulated concurrently in some demonstration cases, such as extending both legs away from the ground. This will make it easier to manipulate the robot in cases where two or more limbs are working in conjunction with one another to support and stabilize the robot.

A more complex, adaptative stiffness in the teaching mode could prove useful for making it easier to manipulate joints, while still providing reliable gravity compensation. A modified compensation controller that can model the changes in joint velocity over time and reduce stiffness as acceleration increases could allow the arm to move when desired, while gradually slowing towards a more stable state as the teacher's manipulations become more careful and precise. The monitoring of angular momentum and impulses can signify the start of a haptic command, allowing the arm

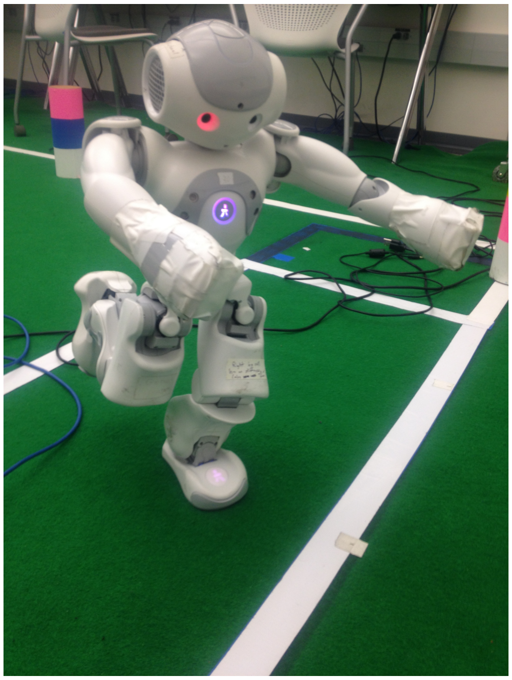

Fig. 3: An example of one of the statically-stable poses found within three minutes using a single human teacher.

to reduce antigravitational torque and release its position when desired.

VI. Discussion and Conclusion

In this paper, we proposed a gravity compensator that mimicked force control and positional joint stability against gravitational forces using the PD controller and stiffness controls provided by the NAO robot's high-level functionality. Although it is not as accurate as using actual force sensors or reliable current measurements, we were able to build a fairly reliable system to counteract the PD controller and maintain positional control at low stiffness levels. We also built a preliminary teaching behavior that has shown promise in quickening the process of pose exploration for the use of finding statically stable poses, and can be leveraged with online balancing using more sensitive foot force sensors and center-of-mass calculations to create a truly intuitive motion planning utility.

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