Closed-Loop Balance Control for a Humanoid Robot

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Abstract— **This paper examines the balancing problems a humanoid robot could face while manipulating an object. A proposal of balancing strategies are proposed and developed. The main approach towards these developments concern the control over the humanoid robot's center of mass within the support polygon. We devise two different ways of balancing: sitting and hip-ankle. Both strategies are utilized in an experiment where the robot is disturbed while manipulating an object, the success rate and projection of the center of mass are recorded and compared. The results indicate that the hip-ankle strategy proves to be more effective than the sitting strategy. Further suggestions include whole-body motion planning for stabilized walking, better experimental design that is more scientific and quantification of the disturbance to the robot.**

I. INTRODUCTION

A humanoid robot would be comprised of rigid bodies interconnected with joints that can be actuated actively or passively, it possesses a human-like locomotion, this poses a higher risk for falling when a biped locomotion is disturbed. A human model for pushing motion has been devised in the past [1] suggesting that the center of mass must remain inside the support polygon for stable balance, here we would like to try and implement a balancing controller using said model.

The question of balance in this case would depend on the manipulation task, some have worked on whole-body motion planning for tasks such as pulling a drawer or grabbing an object [2]. For our purposes, we will be making the robot push a cardboard box for the manipulation task.

With a humanoid robot applying force to a box, there is undue momentum that is absorbed through friction by the box. When we remove the object thus disturbing the balance, that undue momentum would force the robot forward in the direction of the box. The displacement of the robot's center of mass outside of its support polygon will cause the robot to fall.

In this research, we want to develop a balancing controller that would help Aldebaran's NAO V4 maintain its balance. For a biped locomotion, a stable balance can be achieved by controlling the NAO's center of mass. Our approach takes monitors the NAO's center of mass projection and dynamically adjust the joints torques in such a way that the NAO remains upright. We hope to measure the effectiveness of the balance controller by devising an experiment that disturbs the NAO and forcing the balance controller to execute the balancing mechanism.

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II. METHOD

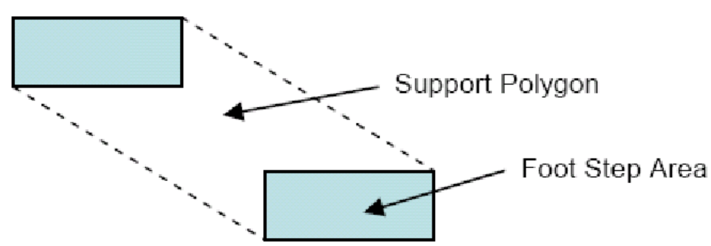
The overall behavior of the NAO is be walking forward with its arms up, this is our choice for the pushing motion. The balance controller is packed into a thread running in the same main program, it is started before initiating the locomotion. A function called **CoMBalancing** is called with an infinite loop to continually monitoring the robot's sensor data and perform calculations.

The source code of our program can be found at: `https://github.com/awingray/nao-balance`

A. Formulating Support Polygon

Since NAOqi SDK does not provide a built-in function for retrieving the NAO's support polygon, we decided to formulate our own using the robot's foot positions to form a simple rectangle. The process begins by determining which foot is in front of the other, this would help us define the highest point of the polygon. We can retrieve the position of the robot's feet relative to its frame of reference. The tip of both feet are used to compute a line that serves as the upper limit of the support polygon. With this, we can modify the line such that the computed area is smaller than the actual support polygon allowing us to experiment with different parameters. In our experiment we conclude that at 60 percent minimized, the computed support polygon is optimal for balancing.

Fig. 1. Support polygon



B. Development of balancing strategy

As the balance controller monitors the center of mass projection, we define a boundary by which the balancing strategy is executed once the center of mass exceeds this boundary. Both strategies utilize both legs of the NAO. The joint **HipPitch** is dynamically updated as the walking motion is executed, this is essential because we need to link the leg joints in such a way that the NAO remains fixed on the ground. The equation linking leg joints that we have developed is:

$$HipPitch \approx -1 \times KneePitch - \frac{AnklePitch + NewAngle}{2} \quad (1)$$

We precompute the new HipPitch joint angle before executing the strategies using (1). The variable **NewAngle** are also used as parameters set according to which foot is forward to ensure that both feet are proper flat out.

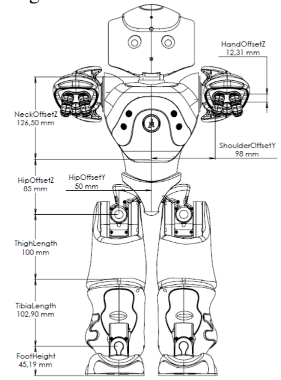
1) Sitting Strategy: The main idea in this strategy is to lower the center of mass thus maintaining balance [4]. We achieve this by manipulating the **KneePitch** and **AnklePitch**. By changing the angle of the knees, the robot will lower its center of mass considerably. In our balance controller, we set the robot's **KneePitch** to its maximum angle with maximum torque to lower the center of mass as quickly as possible. The strategy also employ cartesian control of the NAO's torso, we set the **Torso** end-effector in **FRAME_ROBOT** to initial position (upright position).

2) Ankle-Hip Strategy: The Ankle-Hip Strategy utilizes two joints: **AnklePitch** and **HipPitch**. This idea was proved to be quite effective in another research done on balance maintenance [3]. The idea is manipulate the translation of the robot on the x-axis of the robot (leaning forward or backward). To maintain upright, we can manipulate the ankle joint of the NAO such that it leans in the opposite direction of an intended direction of momentum. However, in cases where the NAO reaches beyond a certain point out side of the calculated support polygon, the ankle joint reaches maximum torque and therefore creating even more momentum in the opposite direction. We mitigated this issue by incorporating the hip as well as the ankle, this can be seen as an extension to the sitting strategy.

III. EXPERIMENTS

For the experiments we use a V4 NAO humanoid. The height of the robot is 57.4 cm, depth - 31.1cm and width - 27.5 cm. NAO has 25 DOF. Total mass of the robot is 5.3 kg. In the following experiments our program were executed on a standard desktop CPU. Both experiments were conducted separately for two different strategies(Sitting strategy, Ankle-Hip strategy). In the beginning of the experiments NAO was put into initial position marked with black tape with box right in front of the robot. Box was a normal cardboard box of the following size - height: 70cm, width - 40cm, depth - 25cm. To add some weight to the box we put a laptop inside. The total mass of laptop+box was approximately 1.5kg.

Fig. 2. NAO humanoid robot



A. Controlled Walk

The goal of the first experiment is to check stability of the undisturbed pushing of the box. After the program was executed NAO tried to push the box for 1.5 meters in forward direction. Distance was controlled using NAO API function **getRobotPosition** that gave as absolute coordinates of the NAO in real world.

B. Disturbance

In the second experiment we evaluated the success rate of our balancing mechanism in case when the box was suddenly removed while NAO was trying to push it. Since we pulled the box away ourselves it was difficult to do it at the same moment, hence the experiment was conducted with pulling the box away in an arbitrary position of the walk. The desired result was to reach maximum stability during the disturbance and continue walking even when the box is removed.

IV. RESULTS

We performed 10 trials for each program for both experiments. Results of the 10 attempts of undisturbed walk can be found in table 1. If box is not disturbed NAO successfully pushed the box for 1.5 meters in forward direction 100% of the time. Moreover the time of pushing was almost the same in all trials, meaning that normal walk is robust, but was slower than it could have been to prevent balancing problems. In the first experiment there was no difference between two strategies, because during undisturbed walk NAO was stable and none of the balancing functions were activated.

Strategy	Success rate	Average time(s)
Sitting strategy	100%	157.8
Hip-ankle strategy	100%	157.5

TABLE I

EXPERIMENT 1.

For the second experiment we also performed 10 trials for each strategy. Results are summarized in Table 2.

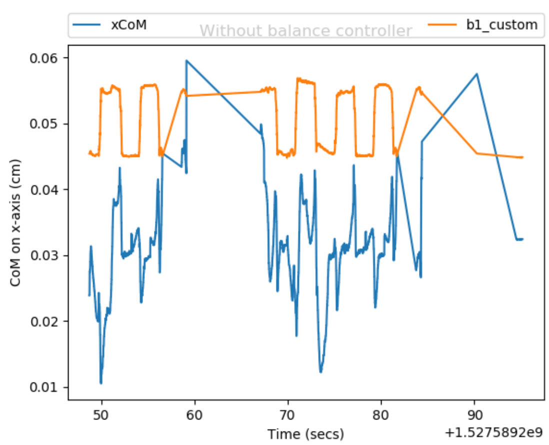
Strategy	Success rate	Activation of balancing.
Sitting strategy	30%	70%
Hip-ankle strategy	50%	80%

TABLE II
EXPERIMENT 2.

After conducting the second experiment we can conclude that our program can predict that it is going out of balance with high accuracy(70 and 80 percent). Moreover sometimes balance function was not activated because disturbance was too week and center of mass stayed within our restricted support polygon. Both strategies used the same mechanism for identifying balance, so there should not be any difference in balance activation and this difference can be explained by removing the box in arbitrary position. Since the box was removed more or less randomly sometimes robot stayed stable even after the box was removed.

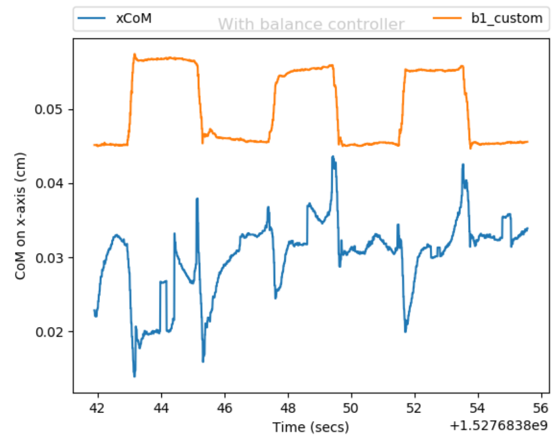
We also examine the projection of the center of mass in the x-axis when the robot is disturbed. *It is important to note that the robot continues its pushing motion after falling because we manually support it to prevent damage.* Here,

Fig. 3. Projection of CoM without balance controller



the robot falls when it is disturbed as evidence by the rapid change in the projection of center of mass. During the time interval between 60 and 70 seconds of the behavior, the robot's center of mass exceeds the support polygon (in this case it lunged forward too much). Here, the robot maintains its balance as seen by the fluctuations of the xCom (center of mass on x-axis) never exceeding the lines of the support polygon. As opposed to the first condition, the projection of the center of mass rises (lunged forward) but is quickly recovered back (by balancing strategy).

Fig. 4. Projection of CoM with balance controller



V. CONCLUSIONS AND DISCUSSION

Here the results conclude that the Hip-Ankle strategy proves to be far more effective than the sitting strategy. However, we must note that the experiments are more empirical than scientific since quantification of the disturbance caused can be too inaccurate to be done. We were successful in identifying when COM of NAO goes out of support polygon, but our reaction to the disturbance was not ideal. One of the reason for it is reactive type of our balancing mechanism. Most of the time balancing activated when NAO was already in some very unstable position. On top of it our balancing mechanism does not fully use the current position of NAO, hence quite often the fall happened because of our balance reaction. The box was removed in some random position and sometimes our reaction was too strong and by trying to balance we created even more unbalanced situation. Hip-ankle strategy was more successful because its counter-reaction to fall was not that strong and as a result it did not create more unbalanced situations.

One of the possible ways of improving the current program is use of more complicated programming software like in one of the original research. For example with the use of MoveIT! framework in ROS can give us more ways of determining the counter-disturbance action. With MoveIT planning capabilities we can identify exact new position that robot has to reach to stay in balance. Planning can also improve the activation of balancing mechanism. Right now quite often our reaction to the disturbance is too slow, because we have to wait until center of mass will go outside of our restricted support polygon and that leaves us less time to properly react. Further restriction of support polygon is impossible since it will be activated even during normal walk without disturbance and we would like to avoid it. With new planning mechanism we could identify that robot is about to go out of support polygon before it actually goes out. That gives us more time to react, hence our reaction should not be that extreme and we will create less unbalanced situations while trying to avoid the falling. Another possible improvement that can be achieved with the use of planning is the speed of the walk. Right now our walk is pretty slow because the walk itself is part of the balancing measures. We tried to create as stable walk as possible so it would not be easily disturbed but as a result the speed fell significantly. Maybe with the use of planning the speed can be increased.

The use of NAO was another limitation. NAO's low sensing capabilities give us delayed, noisy and biased data. On top of that slow control rate(10ms) reduces our balancing options.

On of the disadvantages of our experiment is low reproducibility. Since we removed the box in an arbitrary position it is pretty difficult to measure the disturbance, since it depends on many parameters like current position of most joints, their velocities and acceleration and some of them can not be obtained using NAO sensors. As a result even with 10 trials we theoretically could be lucky/unlucky with our disturbance timing hence results are not that precise. Possible improvement is redesigned experiment. For example if we used pendulum that hits NAO in certain position we could have easily measure the disturbance and conducted better experiment.

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