Humanoid Robot Orientation Stabilization by Shoulder Joint Motion During Locomotion

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Abstract— **Arm swing action is a natural phenomenon that emerges in biped locomotion. A shoulder torque reference generation method is introduced in this paper to utilize arms of a humanoid robot during locomotion. Main idea of the technique is the employment of shoulder joint actuation torques in order to stabilize body orientation. The reference torques are computed by a method which utilizes proportional and derivative actions. Body orientation angles serve as the inputs of this system. The approach is tested via simulations with the 3D full-dynamics model of the humanoid robot SURALP (Sabanci University Robotics Research Laboratory Platform). Results indicate that the method is successful in reducing oscillations of body angles during bipedal walking.**

Keywords—humanoid robot, biped locomotion, arm swing

I. INTRODUCTION

Humans swing their arms naturally in the course of biped locomotion [1, 2]. This suggests that arm motion can be utilized to enhance the bipedal robot walking naturalness. Nevertheless, achieving natural walk patterns is not the only motivation to include swing action of arms in locomotion. It is stated in [3-5] that swing action of arms has also stabilizing effects on the walk. Other recent studies suggest that swing of arms decreases metabolic cost of human locomotion [6-10]. [11] links speed of locomotion to arm swing action. A recent biological study [12] also suggests that there is an interaction between the leg and arm motion.

Although it is a trivial task for humans to swing their arms, comprehensive methods are required for humanoid robots to utilize arms for walking stabilization and control purposes.

[13] introduces a yawing moment compensation method based on Zero Moment Point (ZMP) stability criterion. Arm position references are computed as an integral part of trajectory synthesis. Another ZMP based approach is introduced in [14], which again uses position references to utilize arms during gait transitions. Reference [3] reports a method for passive dynamic walkers which counter angular momentum of the body by applying torques to shoulder axes.

Body orientation angles contain significant information about the stability of the walk. Body orientation angle references can be planned to undergo deliberate oscillations or can be kept constant at fixed values. For example the body pitch angle can be programmed such that the robot leans forward when walking forward. The constant body angle references can be zero too. This is typical for a humanoid robot carrying an object parallel to the ground. Majority of bipedal walking studies address the locomotion problem with upright body posture references.

This paper considers this case of zero desired body orientation angles and proposes an arm motion control method for keeping the roll, pitch and yaw angles of the humanoid body close to zero. Inspired by the off-line reference tuning method in [15], the approach relies on actuation torque reference generation for shoulder joints. It uses body roll and pitch angles along with the leg swing timing to create the torque references. The shoulder joints generate roll and pitch rotations. The proposed method is tested with 3D full-dynamics simulation of the humanoid robot SURALP [16] – a full–body human–sized 29 degrees–of–freedom humanoid robot (Fig.-1).

The paper is organized as follows. Section II presents details of the arm swing action method. Section III introduces the simulation environment. Simulations results follow in Section IV. Conclusions are drawn and future works are discussed in Section V.

II. SHOULDER REFERENCE TORQUE GENERATION

Most bipedal robots are designed with a resemblance to the human anatomy. The arms are in motion while a human is walking. Arm motion is in harmony with the locomotion actions of the legs. The upper extremity movements can be caused and actuated by the lower ones, as [12] implies. They can also aid the balance as in the extreme case of an acrobat who is walking on a rope or add to thrust as in the running athlete [2, 4, 12]. These phenomena motivate the use of the arms in a supportive role for humanoid robot walk. With the many DOF's (usually 6) of a humanoid arm, and with the control designer's creativity, obviously there is a multitude of approaches which could be applied for this purpose. This paper proposes a technique, inspired by the work in [15]. [15] is a paper on bipedal robot walking parameter tuning via simulations with a neuro-fuzzy learning systems called fuzzy identifiers. The simulation starts with random parameters and the parameters tuned gradually in a simulated long duration walk.

The difficulty in this framework of tuning is that the robot should continue walking without falling even with unsuitable walking parameters (so that walking can continue). This can be only accomplished with external support. Virtual torsional springs and dampers are attached to the simulated robot's body for support purposes. They follow the body during the walk and the robot with torques opposing deflections from upright posture (Fig.-2). It is observed that the virtual springs and dampers are very successful to support the robot and aid id keeping walking.

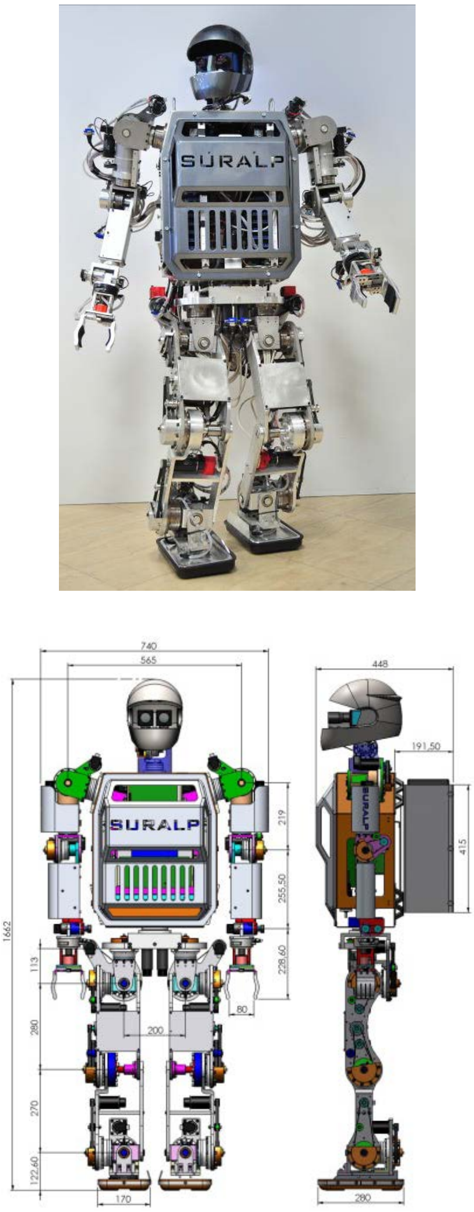


Fig. 1. SURALP, dimensions in mm

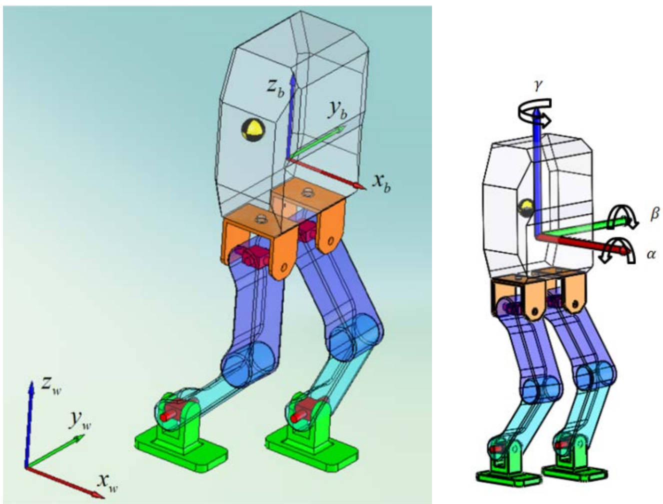


Fig. 2. The support scheme in [15]. The body orientation is described by roll-pitch-yaw angles α, β, and γ with respect to a world-fixed coordinate frame. Torsional springs and dampers about body frame coordinate axes force these angles to zero.

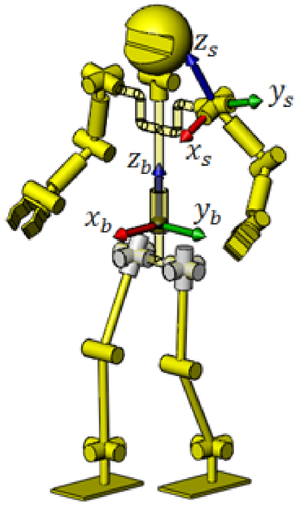


Fig. 3. Kinematic Arrangement of SURALP simulation.

Our main idea is: The torsional spring and damper support, what can enable the simulated robot keep walking with unsuitable walking parameters, should have the potential to be considered as an additional stability enhancement tool for bipeds with well tuned walking parameters too.

This idea requires agents which can apply torsional spring and damper effects, that is, spring and damper torques on the robot body. In a simulated environment, and for parameter tuning purposes, the virtual effects are suitable. However, for control scenarios, real tools (or their simulated versions) have to be employed for support torque generation. In our case we consider the arms attached to the robot body as agents which can generate the support with the action-reaction principle. For example, a shoulder pitch actuation torque proportional to and opposing the body pitch angle deviation from zero can generate a “torsional spring effect” which aids the balance of the robot.

On the other hand, attention has to be paid to the fact that application of actuator torques on shoulder joints does not only cause torque to be applied on the robot body. It also moves the arm. The motion range of the joints is limited in most of the robotic cases. Also, the motion of the arm can lead to accidental crashes of the hand or other arm links to the robot body. Therefore, the application of the shoulder torques has to be well planned and well timed before it can yield any benefit in balance enhancement.

Considering [15], shoulder torques for stabilization are obtained from orientation. Torque references are generated for the first two joints of the shoulders. The first angle is a rotation about the shoulder frame y axis (y_s) shown in Fig.-3. The second rotation takes place about the axis x_s.

The torque reference for the first joint (we term this torque as pitch torque) is obtained by using the body pitch angle (β) and rate of change of the body pitch angle ($\dot{\beta}$). This reference is applied to the motion driver unit. The timing of torque reference generation is in harmony with the leg swings. When the right leg is swung the computed torque is applied to the left shoulder in order to counteract the effect of the foot motion. A torque of the same magnitude as the one applied on the left shoulder, however with opposite sign, is applied on the right shoulder. A symmetric scheme is applied when it is the left foot which is swung. These shoulder rotations compensate Standard Deviations (SD) in body pitch angles. The torque reference $\tau_{1_{ref}}$, for shoulder pitch rotation is computed as:

$$\tau_{1_{ref}} = k_{p_1}\beta + k_d\dot{\beta} \quad (1)$$

In (1) k_{p_1} and k_d are constant tuning parameters.

The second torque reference (we would like to call it roll torque) is computed using body roll angle, and it is applied to the second shoulder joint. Again it is applied to the shoulder which is at the opposite side of the swing leg. Zero roll torque is applied to the other shoulder. It moves due to the gravitational force acting on it.

The following rule is used for the computation of the roll torque reference.

$$\tau_{2_{ref}} = k_{p_2}\alpha \qquad (2)$$

In (2) kp_2 is a constant tuning parameter.

The timing of the torque application explained above is in parallel with natural motion of the arms in human [17, 18].

III. Simulation Environment

The kinematic arrangement of the simulated robot consists of 29 DoFs: 7 at each arm and 6 at each leg, 1 at the hip and 2 at the neck. A snapshot of the animation window is shown in Fig.-4. Center of Mass (CoM) position trajectories for biped locomotion are created via ZMP stability criterion and preview control [19, 20]. Each joint trajectory is tracked by independent PID controllers except for the shoulder joints for which the torque references are generated. The foot trajectories as expressed in the world coordinate frame complete the locomotion references. An adaptive penalty based system is used to simulate ground contacts in the simulation [21].

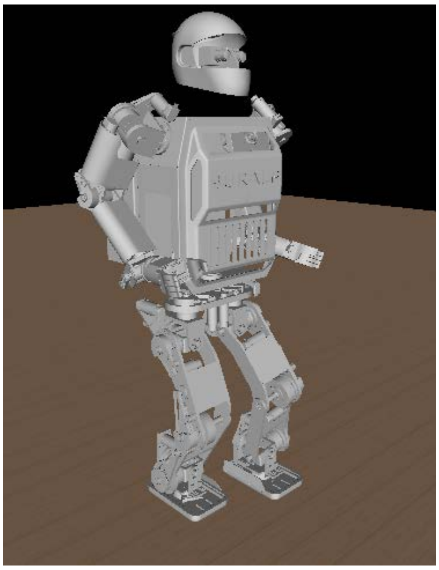


Fig. 4. Animation of simulation environment

IV. Simulations & Results

Five different simulation scenarios are used to test the effects of the shoulder joint actions of the robot's balance. In all simulations, the robot walks for 30 steps with a step size of 10 cm's. The difference between the scenarios is the combination of the control actions employed. In addition to the torque reference generation techniques explained in Section II, "position control", or "no control at all" were also applied and effects are observed. Table I summarizes the simulation scenarios. Control mechanisms employed and controller gains used for the five cases are detailed in this table.

Stability of the robot is ensured by body angles. Roll, pitch and yaw angles of the robot trunk for each simulation is shown in Fig.-5. Fig.-6 shows the required shoulder torques for the proposed control scheme which results in stable body angles during locomotion.

A. Simulations

The first simulation has no arm swing action. Arms are stationary at fixed positions with respect to the body frame throughout the walk. Roll, pitch and yaw angles obtained from the first simulation are presented in Fig.-5.a. Standard deviations (SD) of these data are shown in Table II. Fig.-6.a shows the generated torque reference curves for the left arm. The ones for the right arm are similar and not shown in this paper.

Second and third simulations are run by applying the torque obtained from (1) to the pitch axis of the shoulders. Remaining five axes track position references. Angles and their SD are shown in Fig.-4.b and Fig.-4.c and Table II respectively. The gain k_d is zero in the second simulation and there is no damping in the torque input.

Only $\tau_{2_{ref}}$, the is used in the fourth simulation. Body angles throughout the locomotion are shown in Fig.-4.d SD of body angles and simulation parameters are shown in fourth row of Table I and Table II.

For the fifth simulation both torques are applied to first two joints. Roll and pitch axes of shoulder joints are actuated and remaining four joints follow constant position references. Fig.-4.e, Table I and Table II represent body angles, SD and parameters of fifth simulation.

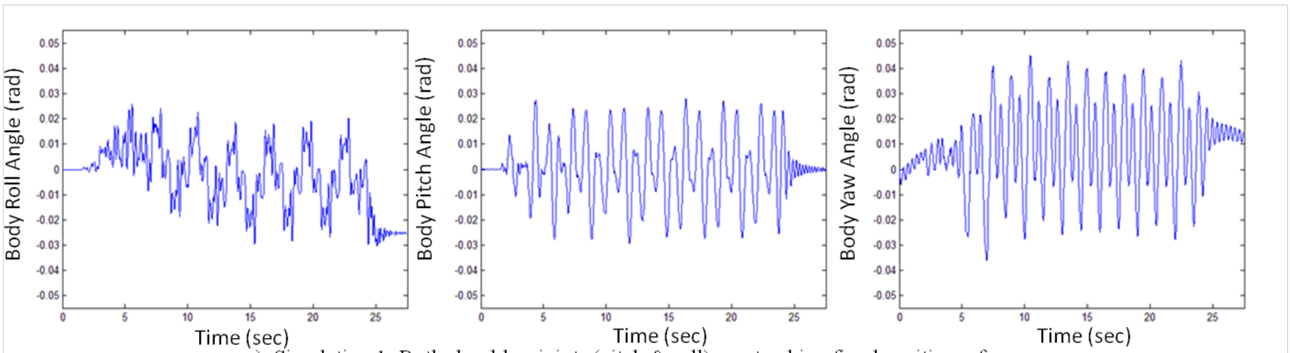
B. A Discussion of the Simulation Results

Second and third rows of Table II show a decrease in SD of body pitch angle and yaw angle, when only $\tau_{1_{ref}}$ is applied. The gain k_d is introduced in the third simulation, but it can be observed from rows 2 and 3 of Table II that effect of damping is not prominent.

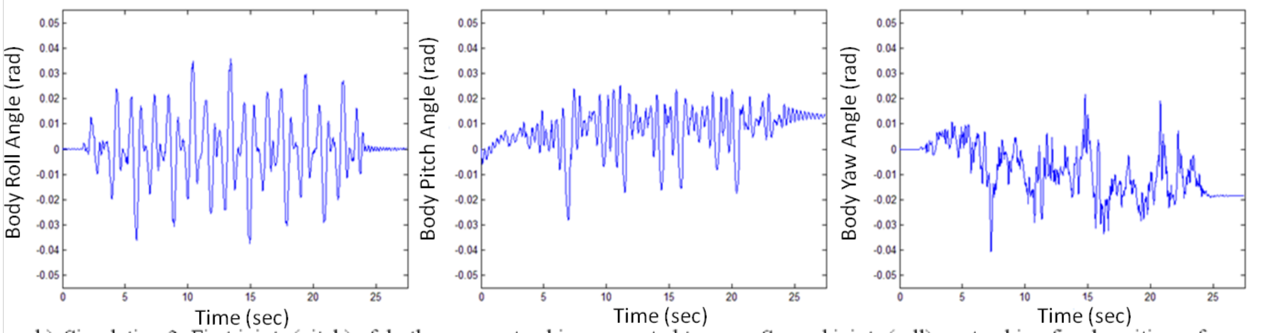
Only $\tau_{2_{ref}}$ is applied at fourth simulation. $\tau_{1_{ref}}$ is zero and all other joints track position references. First and fourth rows of Table II show that this action has compensation effect on SD values of roll pitch and yaw rotations.

Both torques are applied at fifth simulation, utilizing roll and pitch rotations for arms during locomotion. SD of all body angles decrease when shoulder joints are actuated in a way similar to natural swing action of human. SD of fifth simulation are lowest compared to other simulations.

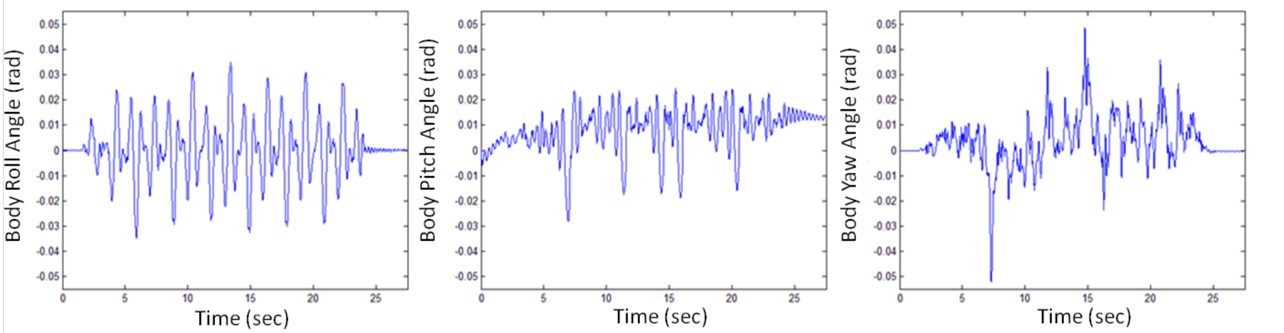
It is observed from Fig.-5 that time domain representation of robot body orientation for biped locomotion become more stable when reference torques $\tau_{1_{ref}}$ and $\tau_{2_{ref}}$ are applied to shoulder joints. Since every other locomotion parameter is kept same between different simulations except shoulder torques of joints one and two, the decrease in body angles can be attributed to the torque generated by swinging arms.



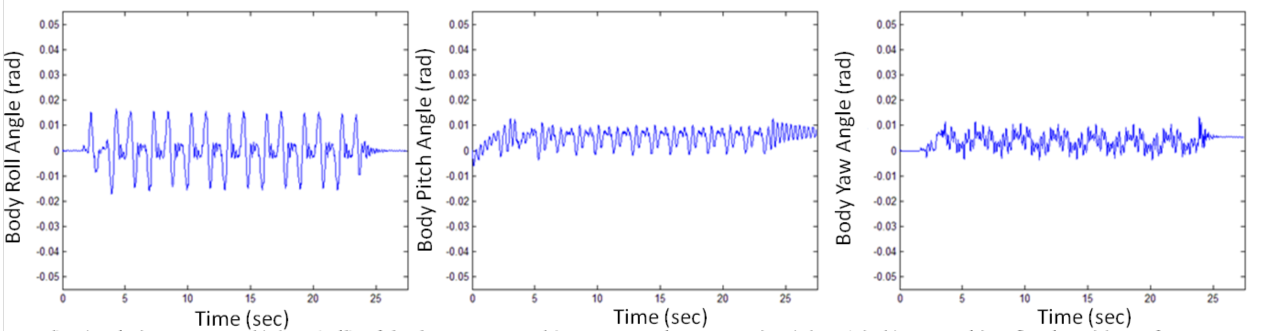
a) Simulation 1: Both shoulders joints (pitch & roll) are tracking fixed position references.



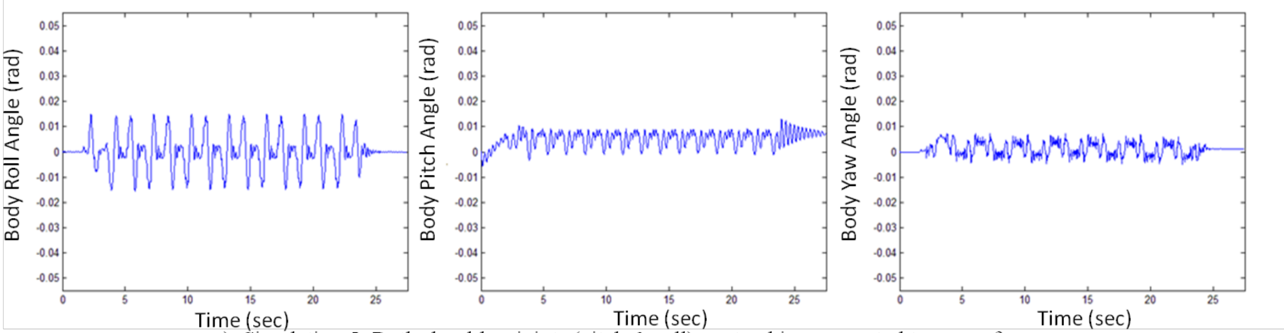
b) Simulation 2: First joints (pitch) of both arms are tracking generated torques. Second joints (roll) are tracking fixed position references.



c) Simulation 3: First joints (pitch) of both arms are tracking generated torques, damping is introduced. Second joints (roll) are tracking fixed position references.

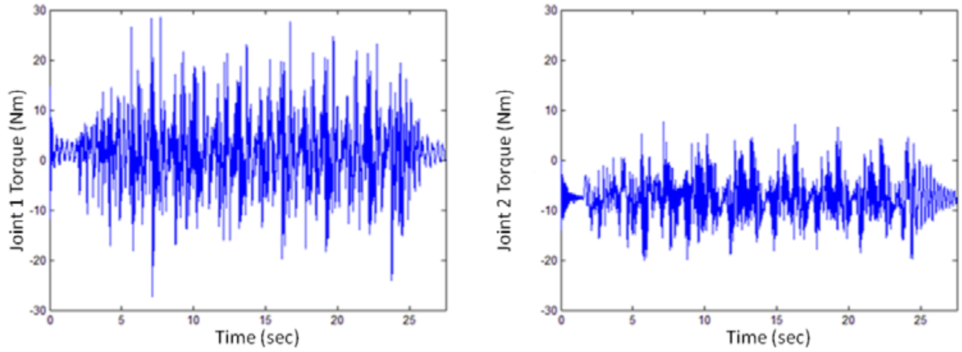


d) Simulation 4: Second joints (roll) of both arms are tracking generated torques. First joints (pitch) are tracking fixed position references.

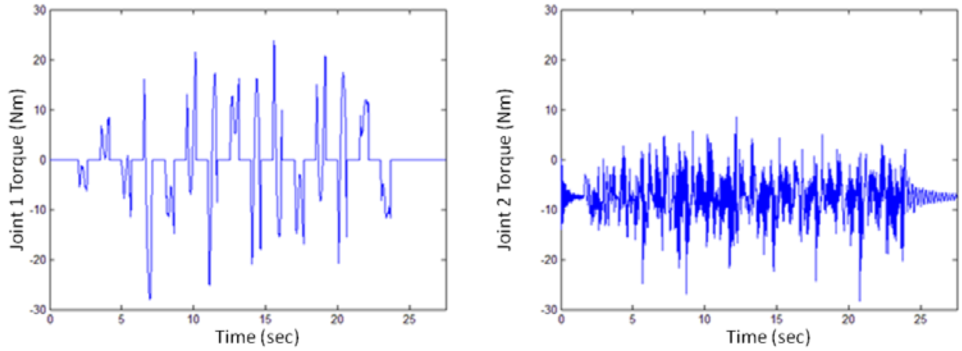


e) Simulation 5: Both shoulders joints (pitch & roll) are tracking generated torque references.

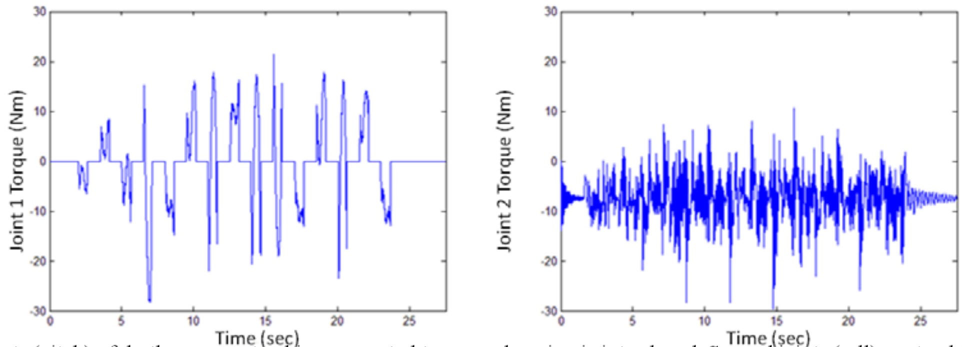
Fig. 5. Roll, pitch and yaw angles for 27.5 seconds of biped locomotion. Rows correspond to Simulations 1, 2, 3, 4 and 5



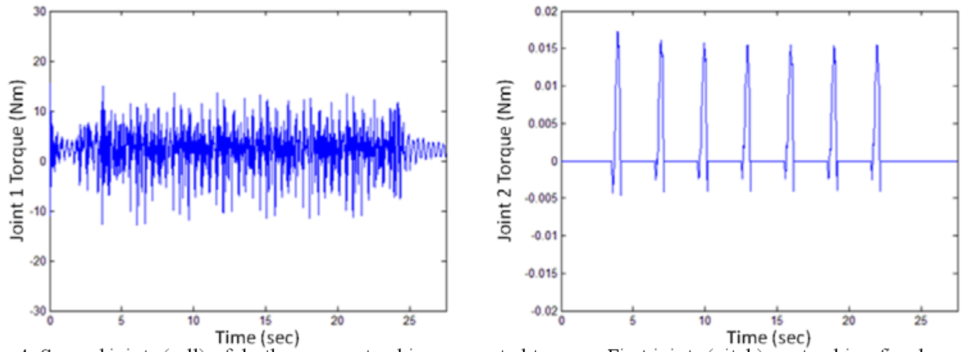
a) Simulation 1: Both shoulders joints (pitch & roll) are tracking fixed position references.



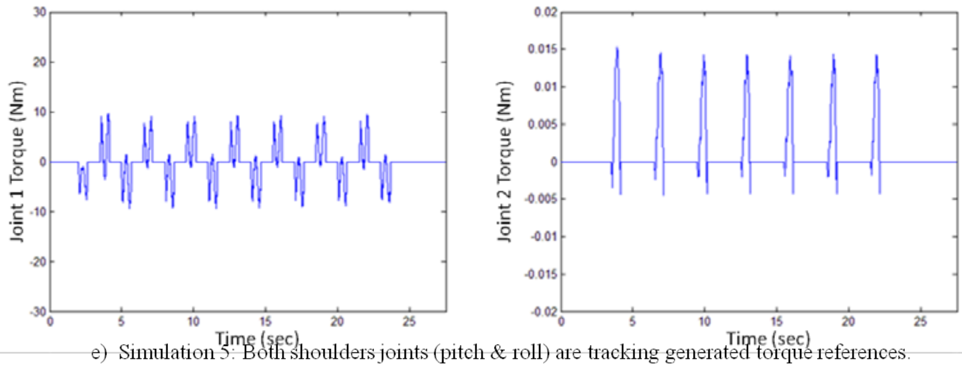
b) Simulation 2: First joints (pitch) of both arms are tracking generated torques. Second joints (roll) are tracking fixed position references.



c) Simulation 3: First joints (pitch) of both arms are tracking generated torques, damping is introduced. Second joints (roll) are tracking fixed position references.



d) Simulation 4: Second joints (roll) of both arms are tracking generated torques. First joints (pitch) are tracking fixed position references.



e) Simulation 5: Both shoulders joints (pitch & roll) are tracking generated torque references.

Fig. 6. Torques applied to first and second joints of shoulders. Columns 1 and 2 show Joint 1 and Joint 2, respectively. Rows represent Simulations 1, 2, 3, 4 and 5, respectively. Note that the vertical axis plotting limits are -0.02 and 0.02 Nm for Joint 2 in Simulations 4 and 5 instead of -30 and 30 Nm which are used for other plots in this figure.

TABLE I. Simulation Gains & Control Methods of First Two Joints of Arms

Simulation No	Simulation Gains	Joint1	Joint2
1	$k_{p_1} = 1000, k_{p_2} = 0, k_d = 0$	Fixed Under Position Control	Fixed Under Position Control
2	$k_{p_1} = 1000, k_{p_2} = 0, k_d = 0$	Moving Under Torque References	Fixed Under Position Control
3	$k_{p_1} = 1000, k_{p_2} = 0, k_d = 10$	Moving Under Torque References	Fixed Under Position Control
4	$k_{p_1} = 0, k_{p_2} = 1, k_d = 0$	Fixed Under Position Control	Moving Under Torque References
5	$kp_1 = 1000, kp_2 = 1, k_d = 10$	Moving Under Torque References	Moving Under Torque References

TABLE II. SD in Data in Radians

Simulation No	Roll SD	Pitch SD	Yaw SD
1	0.0124	0.0164	0.0126
2	0.0122	0.0086	0.0098
3	0.0119	0.0086	0.0097
4	0.0069	0.0033	0.0029
5	0.0067	0.0031	0.0025

Fig.-6 shows joint torques in each simulation. Energy cost of shoulder joints decrease whenever a joint is actuated with torque generated from body angles instead of tracking fixed positions. In Fig.-6.a both joints are tracking position references and excessive control torques are being applied. In Fig.-6.e both joints are actuated by $\tau_{1_{ref}}$ and $\tau_{2_{ref}}$. Excessive torques are not prominent in the fifth simulation.

V. Conclusion & Future Work

The results in this paper indicate that swing action of arms during biped locomotion has a stabilizing effect on body orientation. It also demonstrates that keeping arms at a fixed position during locomotion is more costly than relaxing the arms. Relaxed arms are more suitable to achieve a natural swing pattern.

We are motivated into developing and employing walking controllers which utilizes arms during locomotion of SURALP in later works. The current approach is simulated on a full dynamics 3D model, however experimental application to humanoid robot with arms is quite straightforward. We consider experimental verification as a future work.

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