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From Template to Anchor: A Novel Control Strategy for Spring-Mass Running of Bipedal Robots*

Behnam Dadashzadeh, Hamid Reza Vejdani and Jonathan Hurst, *Member, IEEE*

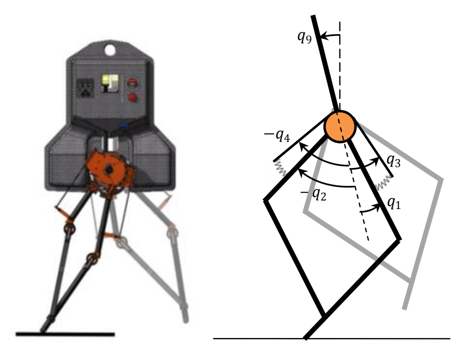
Abstract— **In this paper, we present a novel control strategy for running of bipedal robots with compliant legs. To achieve this goal and to take advantage of the characteristics of the template, we match the dynamics of the full multibody model of a real biped robot with the dynamics of a well-known running template called spring loaded inverted pendulum (SLIP) model. This can be viewed as a template and anchor approach. Because the SLIP model is theoretically conservative, it always operates at a constant energy level. However, real robots operate at various energy levels due to the positive and/or negative work done by the motors, inherent damping/friction of the components and more importantly, the regular ground impact that occurs during the running process. As a case study the proposed controller was implemented on a simulation of the bipedal robot called ATRIAS. The full dynamic equations for running of the ATRIAS robot are derived using the Lagrangian approach. To make our multibody biped robot run with a steady and stable gait that tracks the SLIP model dynamics, a two-level controller is proposed. The upper level controller in stance phase is designed with feedback linearization to make the active SLIP model follow the SLIP model trajectory. The lower level controller in stance phase is designed for the multibody model to track the toe force profile of the active SLIP model. Two active SLIP architectures are proposed for locked and unlocked torso cases of the robot. Simulation results demonstrate stable running based on this strategy for both cases of the ATRIAS model with locked and unlocked torso angle. Matching the SLIP dynamics on running biped robots not designed for spring-mass gaits is impossible due to actuator limitations, or, at best, inefficient.**

I. Introduction

The spring loaded inverted pendulum (SLIP) [1], consisting of a point mass as the body and a massless spring as the leg, is a simple and effective physical model to describe the dynamics of bipedal running. Biomechanical studies show that the SLIP model appropriates the center of mass (CoM) trajectory and the ground reaction force (GRF) profile for running of a large variety of animals and humans [2]. Despite the simple structure of this model, it can be used well to model both bipedal walking and running [3], yielding insights into the principles of legged locomotion. The SLIP model, with properly chosen parameters and initial conditions, can reject disturbances and return passively to the stable limit cycle of running in a constant energy level [3]. Also unstable running gaits or disturbed energy level of the SLIP model can be stabilized using some simple control laws [3],[6]-[10]. From the self-stability [4] and energy efficiency point of view, the SLIP model can be considered a promising template [5] to control running robots.

Several control strategies have been proposed to stabilize SLIP running or raise its settling rate and increase its basin of attraction. Koepl *et al* [6] proposed a force control technique for an actuated SLIP model to reject the various disturbances. Their controller matches the actuated model's impulse profile to that of the SLIP model during stance phase. Dead-beat controllers can reject disturbances during a single step of running by adjusting attack angle or spring stiffness [7]. Swing leg retraction is a bio-inspired strategy for flight phase in which the front leg starts to rotate backwards with a constant angular velocity from the apex instance [8]. A similar strategy is utilized by animals during running to synchronize front toe and ground speed [8]. A simple control strategy for flight phase is to update each touch-down angle equal to the negative value of the previous take-off angle. This strategy stabilizes the overall SLIP running gait [9]. Schmitt *et al* proposed a control strategy for stance phase in which the length of the stance leg is varied as a sinusoidal function [10].

Despite all the advances in the field of legged locomotion, robots are not yet able to walk and run as efficiently and robustly as animals in natural environments. Stability, robustness, and energy efficiency of actuated SLIP models encourages researchers to take advantage of their dynamical characteristics, as a template for biped robots. This is not a simple task because multibody robots have higher degrees of freedom (DOF), more complicated dynamics, energy losses and discontinuities due to touch-down impact, while the SLIP model does not. There are some proposed methods in the



(a) (b)

Figure 1. (a) A view of ATRIAS in sagittal plane, and (b) its stance phase generalized coordinates

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Behnam Dadashzadeh is with the School of Engineering-Emerging Technologies, University of Tabriz, Tabriz, Iran, and was a visiting researcher at the Dynamic Robotics Laboratory, Oregon State University, Oregon, USA, (corresponding author to provide phone: +98-411-339-3877; e-mail: b.dadashzadeh@tabrizu.ac.ir).

Hamid Reza Vejdani is with the Dynamic Robotics Laboratory, Oregon State University, Oregon, USA, (e-mail: hrvn@engr.orst.edu,).

Jonathan Hurst is with the Dynamic Robotics Laboratory, Oregon State University, Oregon, USA, (e-mail: jonathan.hurst@oregonstate.edu).

literature to do this task. In [11] the CoM trajectory of the SLIP model has been used as hybrid zero dynamics (HZD) for an asymmetric SLIP model with a torso and a motor in the hip, and generated stable hopping for it. This method has been generalized in [12] for the same biped model with nontrivial torso pitch. An operational space controller was proposed in [13] that projects the behavior of the SLIP model onto the dynamics of a segmented robotic leg. Feedback linearization was used in [14] to track SLIP CoM trajectory by a three link rigid hopper. Inheritance of SLIP running stability by a simple biped model with leg mass and damping was discussed in [15], however their method is not general enough to be applicable easily to general multibody robots.

In this work, we present a control strategy for the running of multibody model of biped robots, as an anchor, on the sagittal plane to follow the corresponding SLIP dynamics, as a template. Without loss of generality, we implement our controller on the simulated full-dynamic model of the real biped robot ATRIAS [18] shown in Fig. 1. ATRIAS having almost massless legs and series springs with motors has been designed to have a similar structure to the SLIP model. The utility of the anchor dynamics close to the template can minimize control effort by using the passive dynamics effectively. We propose a two level controller to return the system to the desired energy level and generate stable running. The control idea of this work using force control is its main contribution. Our work is different from the previous works in that it provides a relatively simple control strategy for real robots with all real world limitations to track SLIP dynamics and generates stable and robust running gaits; Previously, SLIP embedding controllers were applied to some simple and restricted biped models [11]-[15]. Also since our strategy uses force control in its lower level, it will have the advantage of rejecting ground disturbances as shown in [6] for a simple model.

II. Dynamic Modeling

ATRIAS 2.1 is a human-scale, series elastic driven bipedal robot which aims to walk and run efficiently outdoors [20]. Running gaits consist of stance phase, take-off event, flight phase, and touch-down event. In this section we derive the full dynamical equations for ATRIAS running in the sagittal plane. Fig. 1 shows the stance phase generalized coordinates which is a 9D vector. Each leg consists of a four-bar mechanism which is actuated by two DC motors at the hip. A leaf spring, acting as rotational spring, is mounted between each motor and its corresponding leg link. Having taken all counter-clockwise angles positive, q_1 and q_2 are angles of thigh and shin of leg 1 with respect to the torso, q_3 and q_4 are angles of their corresponding motors, q_5 to q_8 are corresponding angles of leg 2 and q_9 is the angle of the torso with respect to the vertical. The leaf springs have a linear behavior, so the torques applied to the thigh and shin are proportional to (q_3-q_1) and (q_4-q_2). In the dynamic model of the robot, we have considered inertia and damping of the rotors, inertia and damping of the harmonic drives, mass and inertia of the springs, mass and inertia of the legs links, and mass and inertia of the torso. To confine ATRIAS' motion to the sagittal plane, the torso is connected to a boom which prevents its roll and yaw rotations. Also torso pitching can be free or locked by the boom. We consider the ATRIAS model in two cases: In case $'a'$ the torso angle is locked i.e. $q_9 \equiv cte$ and the stance phase DOF is $n_s = 8$ and the flight phase DOF is $n_f = 10$. In case $'b'$ the torso angle is unlocked and the stance phase DOF is $n_s = 9$ and the flight phase DOF is $n_f = 11$. Using Lagrange's equation, the stance phase dynamic model is derived in the form

$$\left[\boldsymbol{D}_s(\mathbf{q}_s)\right]_{n_s\times n_s}\cdot\left[\ddot{\mathbf{q}}_s\right]_{n_s\times 1}+\left[\boldsymbol{C}_s(\mathbf{q}_s,\dot{\mathbf{q}}_s)\right]_{n_s\times 1}=\left[\boldsymbol{B}_s\right]_{n_s\times 4}\cdot\left[\mathbf{u}\right]_{4\times 1}. \quad (1)$$

in which $\boldsymbol{D_s}$ is the inertia matrix, $\boldsymbol{C_s}$ contains Coriolis, gravity and elastic forces, and $\mathbf{u}$ is motor torques vector.

Take-off occurs when the GRF reaches zero, and the flight phase begins. The flight phase has two more DOFs than the stance phase, and its two additional components of the generalized coordinates are selected to be x_{cm} , y_{cm}. Although the CoM of the robot follows a ballistic trajectory during the flight phase, we need the multibody dynamic model of the robot to control angles of the legs. The flight phase dynamic equation is written as

$$\left[\boldsymbol{D}_f(\mathbf{q}_f)\right]_{n_f\times n_f}\cdot\left[\ddot{\mathbf{q}}_f\right]_{n_f\times 1}+\left[\boldsymbol{C}_f(\mathbf{q}_f,\dot{\mathbf{q}}_f)\right]_{n_f\times 1}=\left[\boldsymbol{B}_f\right]_{n_f\times 4}\cdot\left[\mathbf{u}\right]_{4\times 1}. \quad (2)$$

The touch-down event takes place at the moment of first intersection of the toe and terrain profiles. The contact of the toe and ground is assumed fully plastic with no rebound. Using Lagrange's impact equation the touch-down map is written as

$$\mathbf{q}_s^+ = \Delta_f^s\left(\mathbf{q}_f^-\right). \quad (3)$$

in which superscript plus and minus denote post contact and pre contact, respectively. Equations (1-3) constitute the hybrid dynamic model of ATRIAS planar running. More details about dynamic equations can be found in [19].

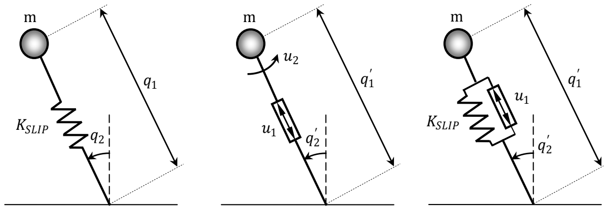
III. Control Strategy

Our control strategy is based on toe force control inspired by [6]. To follow the dynamics of a template, the ATRIAS motors are commanded to generate the same toe force profiles as the template. Since the SLIP running is not stable for most gaits, tracking it causes unstable running gaits for ATRIAS. This is because starting from the desired stance initial state, there will be a deviated state for ATRIAS at the beginning of subsequent steps, causing error accumulation and eventually falling down. To overcome this problem, we propose a two level controller: In the upper level, an active SLIP model is controlled to follow the trajectory of a SLIP model. The active SLIP model has the same initial condition as ATRIAS in each step and the SLIP model has the desired initial condition. In the lower level controller, ATRIAS is commanded to follow the toe force profile of the active SLIP model.

A. Upper Level Controller for the case 'a' with locked torso

1) Stance Phase:

In this case the torso pitch angle is locked and the torso has only translational motion, making ATRIAS structure more similar to the SLIP model. ATRIAS loses energy during running steps and starts the next step with a deviated initial condition. To compensate for the initial condition errors and to prevent their accumulation, an active SLIP model is used to design the upper level controller. An active SLIP model with a force actuator in the leg and a torque



(a) (b) (c)

Figure 2. (a) The SLIP, (b) The proposed active SLIP model for the case 'a', (c) The proposed active SLIP model for the case 'b'

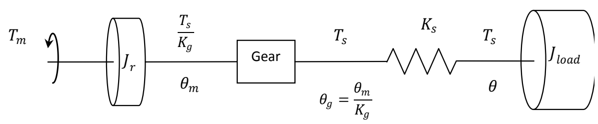


Figure 3. ATRIAS drive system

actuator in the hip is proposed as shown in Fig. 2b. This model could have a spring parallel or series to the actuator with no effects on the final results for the main robot. So, we neglect the spring and still call this model 'active SLIP'. This model has the same deviated initial condition as the CoM of ATRIAS. The goal of the upper level controller is to return the active SLIP to the trajectory and energy level of the desired SLIP gait. By choosing stance phase generalized coordinates as in Fig. 2, the stance phase dynamic model for SLIP model is written as

$$\left[\mathbf{D}(\mathbf{q})\right]_{2\times 2} \cdot \left[\ddot{\mathbf{q}}\right]_{2\times 1} + \left[\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\right]_{2\times 1} = 0 \tag{4}$$

and for the active SLIP it is written as

$$\left[\mathbf{D}'(\mathbf{q}')\right]_{2\times 2} \cdot \left[\ddot{\mathbf{q}}'\right]_{2\times 1} + \left[\mathbf{C}'(\mathbf{q}',\dot{\mathbf{q}}')\right]_{2\times 1} = \left[\mathbf{B}'\right]_{2\times 2} \cdot \left[\mathbf{u}\right]_{2\times 1} \tag{5}$$

The error function is defined as $\mathbf{e} = \mathbf{q}' - \mathbf{q}$, so

$$\ddot{\mathbf{e}} = -\mathbf{D}'^{-1}\mathbf{C}' + \mathbf{D}'^{-1}\mathbf{B}'\mathbf{u} + \mathbf{D}^{-1}\mathbf{C} \ . \tag{6}$$

To have $\ddot{\mathbf{e}} + \mathbf{K}_d\dot{\mathbf{e}} + \mathbf{K}_p\mathbf{e} = 0$, control effort is derived using feedback linearization as

$$\mathbf{u} = \mathbf{B}'^{-1}\left(\mathbf{C}' - \mathbf{D}'\mathbf{D}^{-1}\mathbf{C} - \mathbf{D}'\mathbf{K}_d\dot{\mathbf{e}} - \mathbf{D}'\mathbf{K}_p\mathbf{e}\right) \tag{7}$$

where $\mathbf{K}_d$ and $\mathbf{K}_p$ are 2 by 2 matrices that can be suitably chosen to generate an asymptotically stable response with the desired overshoot and rise time.

2) Flight Phase:

Due to the massless leg in the SLIP model, the control effort in flight phase is zero and the leg turns simultaneously to any desired angle before touch-down. The running gait of the SLIP model with a constant touch-down angle for all steps is unstable for most equilibrium gaits. But it can be stabilized using a simple control law for flight phase. This control law defines the attack angle of each step equal to the negative of take-off angle of the previous step [9].

$$\alpha_{TD} = -\alpha_{TO} \tag{8}$$

According to our simulations, although the active SLIP model can be stabilized using only the stance controller (7), we will use the flight control law (8) as well to increase the basin of attraction of ATRIAS running.

B. *Upper Level Controller for the case 'b' with unlocked torso*

1) Stance Phase:

The active SLIP architecture shown in Fig. 2b with a torque actuator at the hip cannot generate a stable and steady running motion in case 'b'. Because the unlocked torso of the main robot cannot exert any arbitrary torques to the legs and meanwhile keep itself upright. In this case we use an active SLIP m odel with only one force actuator in the leg, as shown in Fig. 2c. To accommodate perturbations and return system to the nominal energy level, we use an SLIP energy level control law that was also used in [10] as

$$u_1(t) = -K_p^E \frac{x_c\dot{x}_c + y_c\dot{y}_c}{\sqrt{x_c^2 + y_c^2}}\left[E(t) - \bar{E}\right] \tag{9}$$

in which K_p^E is a positive gain, x_c, y_c is the position of the point mass, $E(t)$ is the total mechanical energy, and $\bar{E}$ is the nominal energy. Other than the control law (9) to compensate energy losses, another controller is needed to keep the ATRIAS' torso upright. To do so, we use a PD controller to deviate the angle of the desired GRF by:

$$\delta\theta_{GRF} = K_p^F\left(q_{s9} - \bar{q}_{s9}\right) + K_d^F\left(\dot{q}_{s9}\right) \tag{10}$$

in which K_p^F and K_d^F are proportional and differential gains, q_{s9} is ATRIAS' torso angle, and $\bar{q}_{s9}$ is the desired torso angle. This control part causes a net torque around ATRIAS CoM and return the torso angle to the desired value.

2) Flight Phase:

We use Raibert's event-based controller to regulate the forward speed of the active SLIP model,

$$\alpha = \bar{\alpha} + K_p^v\left(\dot{x}_c^- - \bar{\dot{x}}_c\right) \tag{11}$$

in which $\bar{\alpha}$ is the nominal touch-down angle, K_p^v is a positive gain, $\dot{x}_c^-, \bar{\dot{x}}_c$ are the actual and nominal forward speeds in touch-down [11].

C. *Lower Level Controller*

The lower level controller commands ATRIAS to follow the active SLIP model. In this manner, ATRIAS will follow the energy level and trajectory of the SLIP by an intermediary. In this section, virtual legs of ATRIAS are considered as lines connecting the CoM to the toe points.

1) Stance Phase:

At the beginning of the stance phase, the CoM of ATRIAS and the active SLIP model have the same states. We control the magnitude and direction of ATRIAS' toe force to track the toe force profile of controlled active SLIP model. When the CoMs of the two systems have the same initial condition and the same external forces applied they will have the same dynamics.

To track the toe forces we first need to map them to hip torques. Assuming massless legs for ATRIAS which is reasonable given their low mass, this would be a simple static map. The mapped torques are ATRIAS' spring torques to be applied to thigh and shin. If the masses of legs are not negligible for other robots, then this map will be a set of differential equations that can be combined with the differential equations of the drive system.

Because the rotor inertia has considerable effects at high speeds, generating the mapped hip torques is a dynamical problem. We use a PID controller to control output torques of the motors. Fig. 3 shows a schematic view of ATRIAS' drive system. T_m is motor torque which is the control input of the system, J_r is rotor inertia, T_s is spring torque, K_g is the gear reduction ratio, and K_s is the torsional spring ratio of ATRIAS. The rotor equation of motion is

$$K_g J \ddot{\theta}_g = T_m - \frac{T_s}{K_g}. \tag{12}$$

By assuming right hand side of (10) as control input u, a PID controller for this system is written as

$$T_m = \frac{K_s}{K_g}\Delta\theta_s + K_p\left(\frac{T_{sd}}{K_s} - \Delta\theta_s\right) + K_i\int\left(\frac{T_{sd}}{K_s} - \Delta\theta_s\right)dt + K_d\left(\frac{\dot{T}_{sd}}{K_s} - \Delta\dot{\theta}_s\right) \tag{13}$$

in which T_m is the stance leg motor torque, $\Delta\theta_s$ is spring deflection, and T_{sd} is the mapped desired spring torque at the hip. In this controller, proportional and derivative components control the toe force value to track the active SLIP force profile, and the integral part controls the impulse. Since in any practical control system there is some deviation between controlled value and desired value, impulse control is important because the applied impulse to a system and the initial velocity determines its final velocity.

Equation (13) is the control law for stance leg motors. For swing leg motors on which there is no load, the controller formula becomes

$$T_m = K_p\left(\theta_{gd} - \theta_g\right) + K_i\int\left(\theta_{gd} - \theta_g\right)dt + K_d\left(\dot{\theta}_{gd} - \dot{\theta}_g\right) \tag{14}$$

Different PID coefficients will be needed for the stance and swing leg. The stance leg PID coefficients should be tuned on a running gait on the robot's dynamic model, because there is not a constant value for J_{load} in Fig. 3 and its estimation is almost impossible.

We plan symmetric motions for ATRIAS legs in the running gait. During the stance phase, the length and angle of the virtual swing leg are defined in terms of stance leg length and angle as

$$\begin{aligned} \alpha_{swing,d} &= -\alpha_{stance} \\ L_{swing,d} &= 0.93\, L_{stance} \end{aligned} \tag{15}$$

This policy guarantees the swing leg clearance from ground, and generates suitable initial conditions for the legs to start flight phase.

2) Flight Phase:

In flight phase both legs are swing legs and control law (14) is used to control them but first we need to plan the desired length and angle of ATRIAS' virtual legs in this phase. The desired touch-down angle is updated in each step according to (8) or (11) and the desired lengths and angles of legs are defined as

$$\begin{aligned} \alpha_{2d} &= \alpha_{TD},\ \alpha_{1d} = -\alpha_{TD} \\ L_{2d} &= L_0,\ L_{1d} = 0.93\, L_0 \end{aligned}, \tag{16}$$

in which legs 2 and 1 are front and rear legs respectively and L_0 is the free leg length of the SLIP.

IV. Simulation Results and Discussion

Simulation results show that the proposed control strategies for the both cases 'a' and 'b' with carefully chosen controller parameters can reject disturbances and stabilize ATRIAS running around a desired SLIP running gait. Our controller needs considerably less calculations than previous methods for biped running control like HZD in [21]. Stick diagram of 4 typical steps of the sustained running gait for ATRIAS with unlocked torso is shown in Fig. 4, which also depicts CoM trajectories. There are three curves in stance phases, the dashed red curve stands for the desired SLIP model, dotted cyan is for the active SLIP model which tracks the red curve, and the solid blue curve is for ATRIAS CoM which follows cyan by toe force profile tracking. Small tracking error between blue and cyan curves is because of the toe force tracking errors due to motors torque saturation, but they are small enough to be compensated in the next step and generate a stable running gait for ATRIAS. To save space we neglect to show the stick diagram for case 'a' with locked torso. In case 'a' the active SLIP model is fully actuated whereas in case 'b' it is underactuated. So, in case 'a' the active SLIP tracks the SLIP better than in case 'b'. In case 'a' at the end of stance phase trajectories of active and passive SLIP model are coincident but in case 'b' they have a small observable error. With tuned controller parameters, the ATRIAS model can run stably and steadily. Convergence of x and y components of ATRIAS CoM velocities at touch-down for 50 steps of running are shown in Fig. 5. In case 'a', where the torso angle is fixed, ATRIAS converges to its limit cycle in only 3 steps as shown in Fig. 5a. In case 'b', with unlocked torso angle, there are more disturbance sources and the steady state ATRIAS touch-down velocity has small fluctuations around the desired value as shown in Fig. 5b. According to Fig. 5b, the robot's CoM velocity in the second step is deviated %44 from its nominal gait, due to complicated dynamics of the underactuated system and actuators limitations, and then the controller stabilizes the system around the nominal gait. This shows the robustness of our controller to external disturbances of the system that can cause similar deviated initial condition in each step.

The tracking errors for upper level controllers in cases 'a' and 'b' are shown in Fig. 6a and b, respectively. In case 'a' the tracking error includes leg length and leg angle error of the active SLIP and in case 'b' it includes its mechanical energy error. Toe force profiles are shown in Fig. 7. Dashed lines

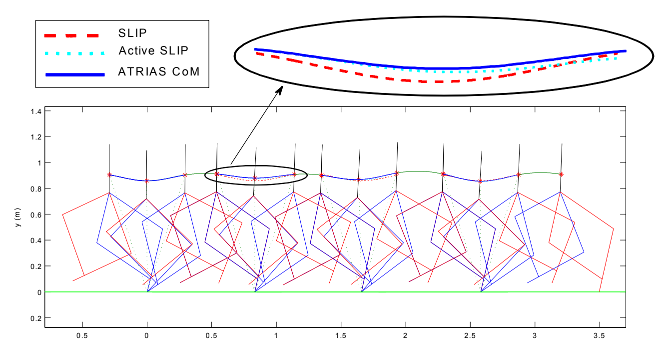
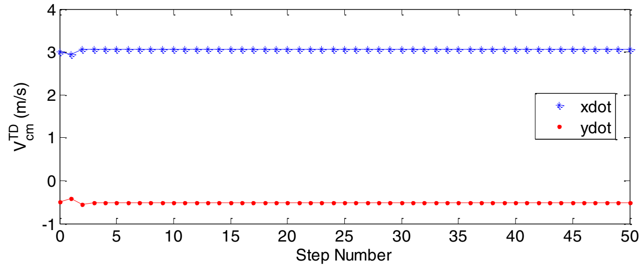
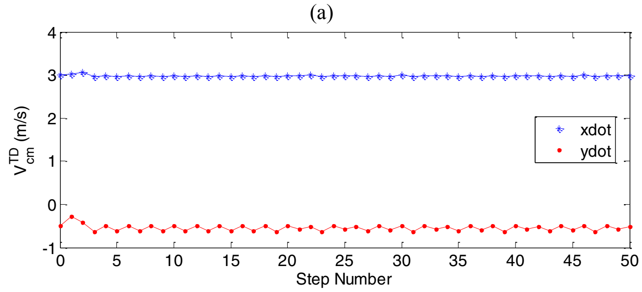


Figure 4. Stick diagram of 4 steps of ATRIAS running with unlocked torso

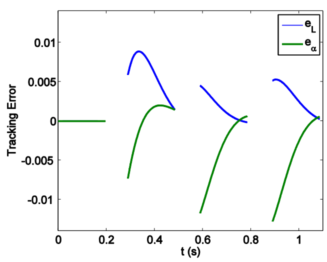


(a)



(b)

Figure 5. Components of ATRIAS post-touchdown CoM velocities for 50 steps (a) for locked torso (b) for unlocked torso



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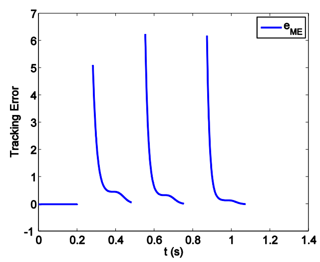
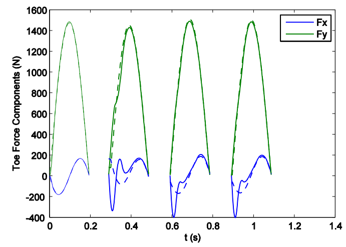


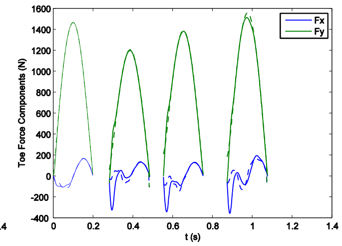
(b)

Figure 6. Tracking error of active SLIP model in stance phases of 4 steps of running (a) for locked torso (b) for unlocked torso

stand for toe force profiles of the active SLIP model which are also desired values for ATRIAS toe force and solid lines are ATRIAS toe force components. In case 'b' the active SLIP force profile has more fluctuations than case 'a'. This is because in case 'a', the active SLIP toe force is deviated from the SLIP only according to (7) to track the SLIP trajectory; whereas in case 'b', it is deviated from the SLIP according to (9) to track the SLIP energy level as well as (10) to keep ATRIAS' torso upright. Blue lines show force components in *x* direction and green shows *y* direction. In the first step, the active SLIP and ATRIAS have the same initial condition as the SLIP model and so the force profile for the first step is very close to the SLIP force profile and ATRIAS tracks it very well. But at the beginning of the stance phase of the subsequent steps ATRIAS has a deviated initial condition, so the upper level controller generates force profiles for the active SLIP model (dashed lines) that are different than the SLIP force profiles. ATRIAS CoM returns to the desired trajectory by tracking the active SLIP force profiles. The deviated initial condition of stance phase is due to positive or negative works of motors in a multibody system, damping, touch-down impact, non-perfect force profile tracking, imprecise touch-down state due to small flight time, and ATRIAS series springs with motors. Series springs have the advantage of isolating and protecting motors from touch-down impact, but they cause unintended vibration in the swing leg causing touch-down condition errors.

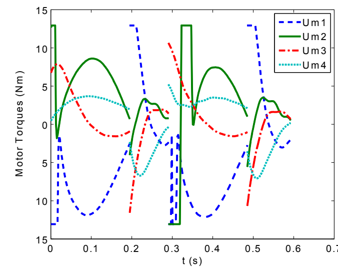


(a)

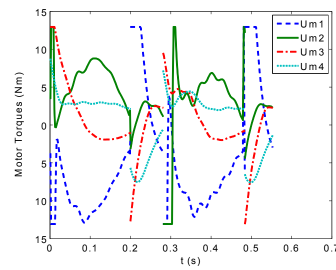


(b)

Figure 7. The desired and actual toe force profiles for ATRIAS following SLIP dynamics (a) for locked torso (b) for unlocked torso



(a)



(b)

Figure 8. Control effort for 2 steps of ATRIAS running by following SLIP dynamics (a) for locked torso (b) for unlocked torso

Fig. 8 shows ATRIAS motor torques for 2 typical steps of the sustained running gait. Stance time is *0.25 s* and flight time is *0.07 s*. In stance phase, motors 1 and 2 are for stance leg, shown by dashed blue and solid green lines, and motors 3 and 4 are for swing leg, shown by dash-dot red and dotted cyan lines respectively. In SLIP model vertical hopping with nonzero flight phase, maximum GRF is more than *2mg* and so the maximum GRF for ATRIAS running gait will be greater than *1214N*. For the chosen running gait in this paper, touch-down velocities are $V_x = 3m/s$, $V_y = -0.5\, m/s$ which generates a max GRF of 1462 *N*. Fig. 8 shows that the peak torque for motor 1 in mid-stance is close to saturation value of 13 *Nm*. So, this is the minimum saturation value of motor torques needed for running of our robot with total mass of 61.9 *kg* with the chosen velocities. Increasing touch-down velocity V_y to have longer flight phase will cause motor torque saturation and force tracking errors in mid-stance. This plot shows that there are inevitable motor saturations at the beginning of each stance and flight phase.

The most challenging issues in the control of biped robot running actuated by electric motors are motor torque limitations and rotor inertia. At the beginning of each phase of running the motors need an impulsive torque to change the rotor velocity to a desired value, so the motor torques are saturated at the beginning of each phase (Fig. 8) and it causes tracking errors for a finite interval of time (Fig. 7). Also in some steps at mid-stance where maximum GRF is needed, a stance leg motor is saturated. To resolve this problem, PD gains for active SLIP controller, PID gains for force profile tracking controller, and horizontal and vertical velocities at the beginning of the running gait should be chosen carefully, using optimization, trial and error, and some considerations. Our simulations for case 'a' show that when PD gains for the upper level controller are chosen such that the active SLIP model has a settling time of less than the desired stance time, then the active SLIP tracks the SLIP very fast but ATRIAS cannot track its toe force profiles and fails to run. That is because most of the control effort to return the system to the desired SLIP trajectory is needed at the first half of the stance time which ATRIAS' motor torque limitations do not allow. To avoid this problem, the PD gains in (7) are chosen such that the rise time of the controller is equal to the stance time, then the upper level controller acts gradually during stance time, as shown in Fig. 6a, and ATRIAS' motors are able to follow its force profiles that are shown in Fig. 7a. Also the proportional gain in (9) for case 'b' is chosen in a similar manner.

V. CONCLUSION

Having known the advantages of the SLIP model to generate energy efficient and stable running gaits, a two level control strategy was developed to make real robots, as anchors, act like the SLIP model, as a template. In the proposed control strategy, an active SLIP model tracks the trajectory or the energy level of the desired SLIP model in the upper level, and the multibody robot tracks the force profiles of the active SLIP in the lower level. The controller was implemented on ATRIAS simulation. Despite deviated initial conditions for each stance phase of the robot due to underactuated and complicated dynamics of the real robot, simulations show that our controller can reject disturbances and return the system to the desired gait. For instance, the controller could settle down and stabilize a %44 deviated initial velocity of the robot in our simulations. We proposed two different active SLIP models for cases 'a' and 'b'. In case 'a' the real robot has locked torso so we proposed a fully actuated active SLIP that can be stabilized easier and faster. However in case 'b' putting a torque actuator on the hip of active SLIP would cause instability of the main robot. The robot in case 'a' can be controlled by the controller 'b', but it would be inefficient and less robust. We also used the flight phase controller (8) or (11) to increase the basin of attraction and the convergence speed. The proposed control strategy has a good performance for robots like ATRIAS that have dynamics close to the template. The performance of the controller would be weaker for rigid biped robots because they do not have compliant elements in their structure and due to the physical limitations of actuators (like inertia and torque saturation) they cannot track the dynamics of the SLIP model well.

In future work, this controller can be used for transient running velocities by properly choosing the desired SLIP gait for each step. It can be done using a lookup table of SLIP running gaits to choose a gait according to touch-down condition. Also, the proposed control strategy containing the force controller is very promising to reject disturbances of ground level and ground damping [6]. Studying effects of modeling uncertainties on the controller robustness is another potential work for future. Our next step is to put the controller on the real robot. At present, the amplifiers on ATRIAS don't provide sufficient torque to allow running gaits. They will be upgraded in the near future, and we plan to test these controllers when the amplifiers are replaced.

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