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From Non-Reactive to Reactive Walking in Humanoid Robots

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***Abstract*— In this paper we report the implementation and the experimental validation of a controller to provide reactive walking gait capabilities of bipedal robots during the execution of predefined walking patterns. The proposed method is a cascade controller design to cope with external disturbances and to increase the robot stability. IMU states are used as inputs to generate modifications of the feet and the Center of Mass trajectories of the predefined walking gait. The method increases the walking stability minimizing the errors due to small terrain variations and external disturbances. The effectiveness of the proposed controller is validated in simulation and in real implementation on the full-body humanoid robot COMAN+.**

I. Introduction

The development of reactive walking gaits that are adaptable to heterogeneous terrains with small uncertainties and external disturbances, e.g. pushes, is fundamental for introducing bipedal robots in real world applications. Irregularities such as wires, bumps, and carpets can be present in structured environments for humans. To overcome these obstacles several methods have been developed that consider known trajectories to perform a stable walk [1]–[4]. However, given the model unknowns, the lack of complete model dynamics, terrain irregularities, and external disturbances, additional stability methods are required, like the ones referred to in [5]–[8]. Applying these controllers, the robot's walking pattern converges towards the desired gait making the gait execution stable. Other approaches propose re-planning of the walking patterns according to the robot's states [9]–[12]. These methods adapt the step time and/or the step position continuously such that the robot is able to walk in presence of contact force variations and external disturbances. However, to further increase the stability, feedback controllers are still needed. These low-level balancing controllers are able to reduce the effect of the different factors that increase the tracking errors and affect the gait execution in general.

Within these low level stabilizers, the one presented in [7] proposed a cascade controller with two consecutive phases. The first layer uses a Model based Predictive Control (MPC) that considers the future Center of Mass (CoM) trajectory and estimates the corresponding error according to the CoM dynamics model and actual states. In such a way, the controller is able to reduce tracking errors, avoid glitches and increase the bandwidth response. The second control layer is a PID control which modifies the Zero Moment Point (ZMP) reference adjusting the pelvis. This strategy modifies the CoM and pelvis trajectories to permit the proper execution of the original desired gait. However, the CoM and feet trajectories are not modified and the stability capabilities are given only by the applied torque at the ankles considering that the support polygon is not modified.

Another approach to stabilize a walking gait is presented in [13]. This control develops a compliant behavior through an admittance control that modifies the CoM reference such that the center of pressure converges towards the desired gait. This controller uses the six-axis force/torque measurements of the feet as feedback and generates a local CoM offset as output to provide the desired stable behavior. Given a fixed gait, the method does not modify the feet or CoM global frame trajectories, but still allows the robot to converge towards the desired walking gait.

In [8] the authors presented a full state feedback of the CoM, and modified the ZMP reference using the CoM/ZMP regulator presented in [14]. The new ZMP trajectory is the reference to a lower layer ZMP that distributes accordingly the forces on each foot. In that case, the robot's stability is guaranteed by the proper distribution of the feet forces such that the ZMP of the robot is assured. A balancing controller that can modify the feet orientation and position under disturbances during walking is given in [15]. It requires the gait generator to online update the walking pattern, which is not applicable to a predefined gait.

In this work, we develop a control to stabilize predefined walking gaits. In particular, we consider the strategy in [16] and develop a cascade control for stabilizing the generated bipedal walking. The proposed controller modifies the foothold references in both position and orientation. On one hand, we increase the stability region by providing a new rotation of the feet, that minimizes the tilting effect of external forces. On the other hand, the modification of the foot position increases the energy absorption capability of a single step. The controller uses the IMU signals as an estimation of the body orientation and provides the corresponding offset at the feet position and orientation references, and CoM reference. This strategy allows the robot to behave in a reactive way while performing a predefined walking algorithm.

II. Problem Description

Considering a bipedal walking gait that is fixed. i.e, the step length and the step timing are predefined, it is possible to analyze the maximum disturbance that the robot can dissipate without modifying the foot position [17]. Using the Linear Inverted Pendulum Model (LIPM) to approximate the

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dynamics of the robot and assuming a constant CoM height, the dynamic equations can be linearized. Then, the future position $x(t)$ and the velocity $\dot{x}(t)$ of the biped CoM can be obtained analytically [17].

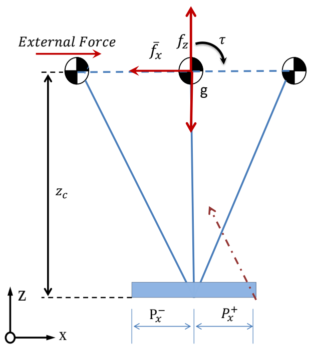

Fig. 1. Ground reaction force acting on the LIPM.

Considering that the system behaves as a LIP as represented in Fig. 1, the dynamics of the system is:

$$\ddot{x} = g\frac{x}{z_c}, \tag{1}$$

where z_c is the height of the CoM.

Solving the second order differential equation, we can find the solution of the system behavior from a known initial condition [17]:

$$x(t) = x(0)\cosh(\frac{t}{T_c}) + T_c\dot{x}(0)\sinh(\frac{t}{T_c}), \tag{2}$$

$$\dot{x}(t) = \frac{x(0)}{T_c}\sinh(\frac{t}{T_c}) + \dot{x}(0)\cosh(\frac{t}{T_c}), \tag{3}$$

$$T_c = \sqrt{z_c/g}. \tag{4}$$

Therefore, if we assume that no additional energy is introduced into the system [17], it is possible to express the orbital energy [18] for the LIP with a fixed pivot as:

$$E = \frac{\dot{x}^2}{2} - \frac{g}{2z_c}x^2, \tag{5}$$

where $\frac{\dot{x}^2}{2}$ represents the normalized kinetic energy and $\frac{g}{2z_c}x^2$ represents the normalized potential energy. From (5), we can estimate the future CoM state during the present step under the assumption that the orbital energy is conserved.

When the external disturbance is applied, the orbital energy is changed. To compensate for this variation, the energy error with respect to the desired energy of the gait $E_d = \frac{1}{2}\dot{x}_d(t_0)^2 - \frac{x_d(t_0)^2}{2z_c}g$, needs to be computed. On a specific time t_0, this error is expressed as:

$$E_{error} = E_d - \frac{1}{2}\dot{x}(t_0)^2 - \frac{x(t_0)^2}{2z_c}g. \tag{6}$$

Since we are considering a fixed gait, therefore, the foothold modification we applied is to maintain the relation of $x(t_0) = x_d(t_0)$. Thus, (6) becomes

$$E_{error} = \frac{1}{2}\left(\dot{x}(t_0)^2 - \dot{x}_d(t_0)^2\right).$$

On the other hand, from the energy error we have:

$$\int_{x_0}^{x_f} F_n \delta r = mE_{error}. \tag{7}$$

So, from (7) the required force F_n that compensates for this energy error without further modifications is:

$$F_n = \frac{mE_{error}}{2(x_f - x(t_0))}, \tag{8}$$

where x_f is the final CoM position defined by the desired step length.

By considering the size of foot $P_x^{\pm}$ as in Fig. 1, the force that can be applied to the system by changing the center of pressure of the biped [17] is:

$$\bar{f}_x = \frac{mgP_x^{\pm}}{z_c}. \tag{9}$$

Therefore, in order to re-establish the gait symmetry of the biped during a fixed gait, at any time t during a walking step, the condition (10) must be satisfied:

$$P_x^- < \frac{E_{error}z_c}{2g(x_f - x(t))} < P_x^+ . \tag{10}$$

If condition (10) does not hold, the foot placement must be modified to recover the periodic gait.

Given that we are considering fixed walking pattern generators, it is necessary to modify the foothold x_f while affecting as little as possible the original gait. As it is seen in Fig. 2, when an external force is applied to a fixed gait, and assuming that no additional stabilizers (e.g. joint/Cartesian torque controller), are available, the robot will tilt on its support foot. As an effect of this body rotation, the motion will result in an early landing with the foot not flat to the ground. To minimize this effect, we propose a control strategy that modifies the step landing position and the swing foot rotation such that the early landing effect is minimized and the landing foot is more parallel with respect to the ground. This will result in a more stable state towards the subsequent steps. Notice that the fixed gait pattern generators assume that the ZMP relies in the center of the stance foot. During disturbances, if no correction is applied at the swing foot, the ZMP will not be in the foot's center after landing, compromising the overall stability. By applying the foothold correction, we are driving the ZMP after landing to be closer to the foot's center. On the other hand, if a large correction of the swing foot is applied, a new ZMP and CoM trajectories will be needed which is beyond the fixed gait generators' capabilities. Given that our proposal only applies to fixed gaits, the additional stability it can provide is limited.

III. Control Strategy

To generate the desired reactive capabilities, we propose two combined strategies: (i) swing and standing feet orientation, and (ii) landing foot position modification. Within the first control strategy, the swing foot rotation allows a better landing of the foot minimizing the effect of the applied disturbances on the gait. Therefore, during the recovery

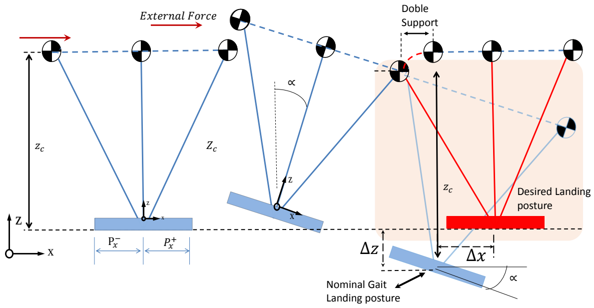

Fig. 2. Swing foot reactive modification strategy.

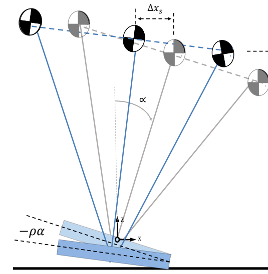

Fig. 3. Support foot orientation adaptation.

phase, both the torque applied by the ankles and the gait stabilizer have more effect with respect to the case where the foot is tilted. The standing foot rotation minimizes the tilting of robot's body. This strategy decelerates the robot once it starts tilting and reduces the required correction that is applied. The second strategy is the landing foot position modification. As depicted in Fig. 2, to give continuity to the gait in the sagittal direction, a modification in the axis x, z is required. Δx and Δz correspond to the modifications of the swing foot placement. As can be seen, these are directly related to the tilting angle of the robot. During the double support phase, the new standing leg is extended, recovering the desired gait.

A. Feet Orientation Modification

In this controller we use the IMU readings as feedback. Since the IMU is located at the robot's waist, this measurement provides an estimation of the orientation of the robot. Therefore, the rotation matrix of the waist R_w is a function of the IMU angles $\mathbf{\Psi}$ as: $R_w(\alpha, \beta, \gamma)$. Leaving apart the analysis of the yaw angles at the feet, the rotation of the swing foot which is defined w.r.t the pelvis ${}^pR_f$ with respect the global frame w, i.e. with respect to the ground, can be written as:

$$^wR_f \quad = \quad {}^wR_p *^p R_f, \tag{11}$$

where ${}^pR_f$ is the foot rotation w.r.t the pelvis and ${}^wR_p$ is the pelvis rotation w.r.t the world. From (11), and considering that the desired ${}^wR_f$ is flat with respect to the ground, we can write:

$$^pR_f = {}^wR_p{}^{-1} I = {}^wR_p{}^T, \tag{12}$$

where I is an identity matrix. Since $R(\mathbf{\Psi})^T = R(-\mathbf{\Psi})$ and given the rotation matrix properties:

$$^pR_f = {}^wR_p{}^T(\mathbf{\Psi}) = {}^wR_p(-\mathbf{\Psi}). \tag{13}$$

According to (13) the desired swing foot rotation, such that the landing foot is flat with respect to the ground, is equivalent to the IMU measurement with opposite sign. By not following precisely the IMU measurement, the ZMP will remain at the foot edge, so that the robot can fully use the recovery torque to keep balance. However, if no action is applied, when the landing of the swing foot happens, the stance foot orientation with respect to the ground will generate a tilting back motion that makes difficult to recover the stability. In addition to the swing foot rotation compensation, we consider a modification of the standing foot as well. The purpose of this action is to minimize the tilting angle of the robot, assuming a rigid foot. As can be seen in Fig. 3, if the robot is tilting on the positive α rotation, a negative proportional $\rho \in (0, 1)$ rotation applied at the stance foot will permit the robot to reduce the height modification of the CoM which permit original assumptions on the fixed gait to hold. Moreover, it will also reduce the travel distance due to the body tilting. To show that the rotation of the body is corrected once a rotation is applied to the stance foot, following a similar analysis as for (13), we can write:

$$\begin{aligned} {}^wR_w &= {}^wR_p *^p R_f \text{ for } R_f = I \\ {}^wR_w &= {}^wR_p(\mathbf{\Psi}) *^p R_f(-\rho\mathbf{\Psi}) \; for \; \Psi \in (0,1) \\ {}^wR_w &< {}^wR_p(\mathbf{\Psi}); \end{aligned} \tag{14}$$

notice that this modification should be smaller than the IMU avoiding fast dynamic behavior and conserving the original gait.

The same analysis is done for the roll correction angles.

B. Landing Foot Position Modification

It is straightforward from Fig. 2 the landing height and the longitudinal corrections are both a relation of the CoM height and the tilting angle of the body. Then, to compensate the landing position in the sagittal plane of the foot:

$$\begin{aligned} \Delta x &= z_c sin(\alpha) * \kappa_x, \\ \Delta z &= z_c - z_c cos(\alpha) * \kappa_z, \end{aligned} \tag{15}$$

where κ is a proportional gain. In order to avoid slips during the landing phase, these modifications are not considered during the landing phase. In addition, as depicted in Fig. 2, during the double support phase the CoM height is recovered such that the original z_c parameter is restored. A similar analysis was done to extend this strategy in the lateral plane.

IV. Simulation Results

To evaluate the performance of our controller, we implement the proposed approach using gazebo in the robot COMAN+ [19] whose dimensions are comparable to those of an adult human. It is 170 cm height from the sole to the head, 60 cm between shoulders, and the depth at the torso level is 30 cm. The robot's weight is 70 Kg and it has 28 degrees of freedom.

We test our method by applying a disturbance of 80 N in the hip of the robot for 0.3 s while performing two different walking gaits. For both cases we compare the obtained gait with and without the application of our controller in addition to the pre-planned walking generator of [16]. The implementation of the proposed approach makes use of the whole body inverse kinematics solver *OpenSoT* [20].

A. Walking in Place

The first evaluated case is a walking in place task. The step timing is set to 0.8 s, the step length to 0 cm and the clearance of the foot to 4 cm. As it is shown in Fig. 4, the robot applies small corrections at the foothold from the beginning. These corrections are in the range of 1 cm compensating the upper body tilting during the motion. After 14.5 s, a disturbance in the forward direction is applied and a bigger reactive step of 2.3 cm can be observed followed by a second bigger step of 4 cm, and a final recovery step of 2 cm. This sequence of steps absorbs the applied disturbance and recovers the original walking gait. Given that the gait is an in place gait, the foot reference is always zero and it is not reported in Fig. 4. As can be seen, the original gait is shifts due to the simulated contact forces that modify the original stepping conditions. However, these modifications are on the mm range. In addition, in Fig. 5 we show the feet

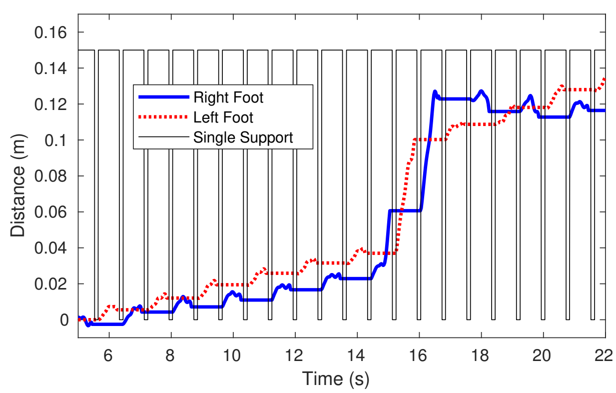

Fig. 4. Reactive foot position for a walking in place task.

rotation during the gait execution. As can be seen, the IMU pitch has opposite sign with respect to the feet orientation in the global frame, which agrees with the proposed control strategy. Before introducing additional energy to the gait, the IMU detects a motion of 1° which is reflected in the foot orientation. It can be seen that the magnitude of the foot rotation is smaller than the IMU measurements as desired. As can be seen in Fig. 5, in the step at time 10 s, the right foot pitch has a positive and a negative component. This means that the robot is swaying back and forth, as can be also seen from the IMU readings. Once the disturbance is applied, the swinging foot rotates to compensate for the disturbance at the landing phase. During the double support phase, the feet rotation converges to 0° to recover the original gait. As it can be noted, during the disturbance rejection at 16 s, both the swing foot and the stand foot modified their orientations. The stand foot variation is smaller compared with the swing foot correction as it was already discussed in Sec. III-A.

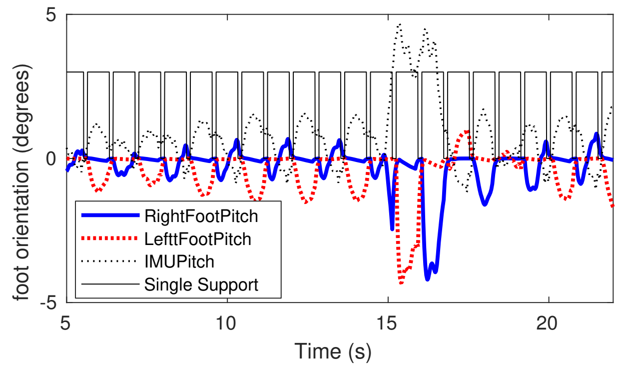

Fig. 5. Reactive foot rotation for a walking in place task.

B. Walking Gait with 10 cm Step Length

In this case the given task is a straight walk with step timing of 0.8 s, a step length of 10 cm, and a foot clearance of 4 cm. As it is shown in Fig. 6, the planned gait is followed precisely by the robot, and no foothold corrections are introduced by the controllers. When a disturbance is introduced at 11.2 s, the reactive strategy allows the robot to perform a step correction of 6.1 cm followed by a second step 2 cm bigger than nominal gait. After this reactive action, the robot recovers the gait.

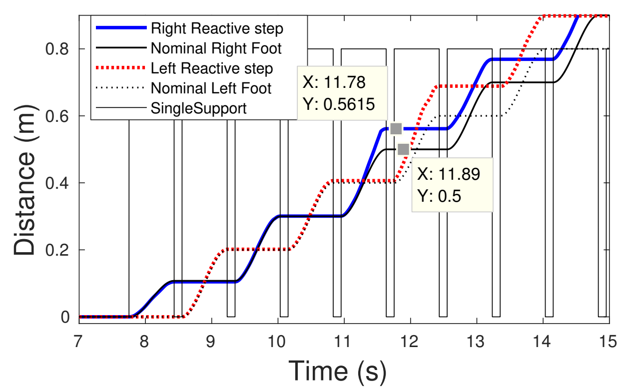

Fig. 6. Reactive foot position for a 10-cm-step walking task.

As can be seen in Fig. 8, the rotation reference of the feet is changing from the first step compensating the pitch IMU readings. These changes are not appreciated in the foothold position as was already pointed out. Similar to the results for the walking in place case, the initial foot rotation modification is close to 1°. When the disturbance is applied, the tilting angle of the robot increases up to 6.5°, and the foot rotation controller acts accordingly to compensate the disturbance and recover the gait. Note that during the steps at time 11 s and 12 s, both feet, support and swing, change the rotation reference as described previously.

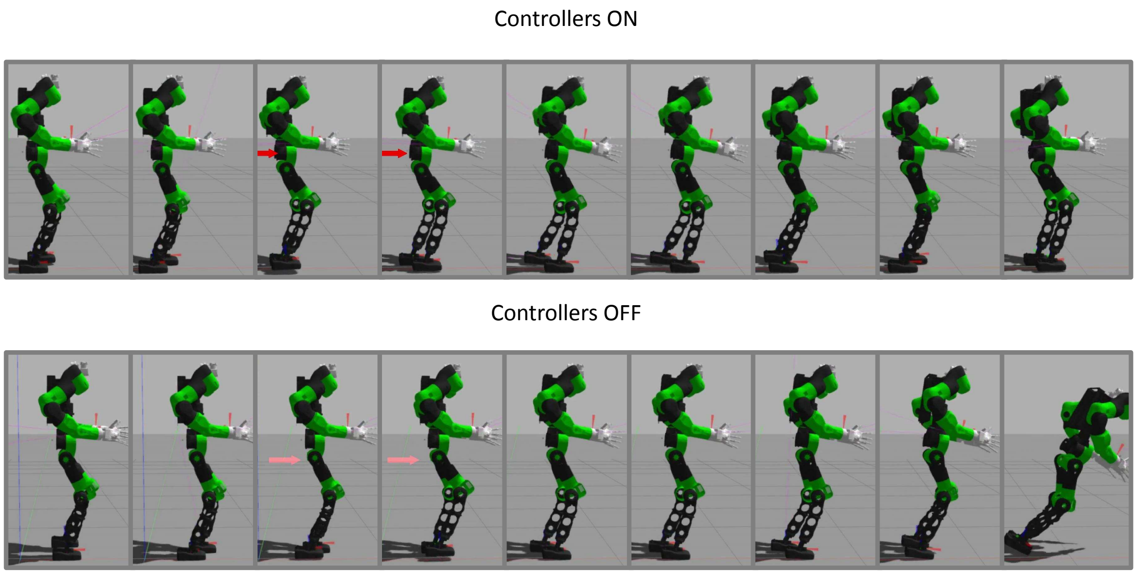

Fig. 7. Snapshots of COMAN+ walking in simulation.

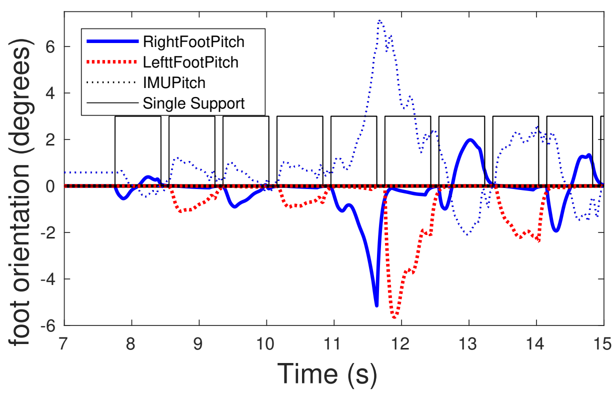

Fig. 8. Reactive foot rotation for a 10-cm-step walking task.

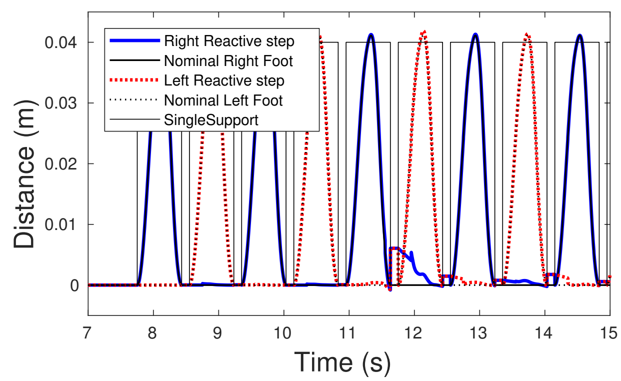

Fig. 9. Reactive foot height for a 10-cm-step walking task.

As shown in Fig. 9, the clearance of the support foot is changing during the recovery steps starting at time 11.8 s. During the implementation, we consider the CoM height as 0.8 cm, and according to Fig. 8, the maximum IMU deviation is 6° leading to a correction of 0.5 cm. Even though the change is relatively small, it affects the performance of the gait and allows a faster recovery. This agrees with the theoretical results and the observed behaviors during the development of the given strategy.

As seen in Fig. 7, COMAN+ is pushed and the upper body tilts forward. When the controllers are active (ON), the robot compensates the disturbance by stepping further and rotating the landing foot. On the other hand, when the controllers are deactivated (OFF), the robot performs its nominal step, but the tilting is not compensated. This leads to a loss of stability, and as a consequence the robot falls.

V. Experimental Results

Finally, we implement our controller in the biped robot COMAN+; as depicted in Fig. 10, the reactive capabilities on the fixed walking pattern generator make the steps of the robot smaller with respect to the nominal gait. This behavior is obtained due to the IMU angles which are seen in Fig. 11. Before the gait starts, the pitch of the robot tilts backwards by $0.5°$, which makes the reactive controllers generate smaller steps. It is also seen in Fig. 11 that the rotation of the feet is constantly changing during the corresponding swing phase, and the magnitude of the rotation is following the IMU, in agreement with the desired behavior. A video showing simulations and experiments on the COMAN+ robot can be found at [1]

VI. Conclusions

The presented work implements a control strategy to stabilize predefined walking gaits like the one in [16]. Our

[1] https://youtu.be/ifRDD5qgMb8

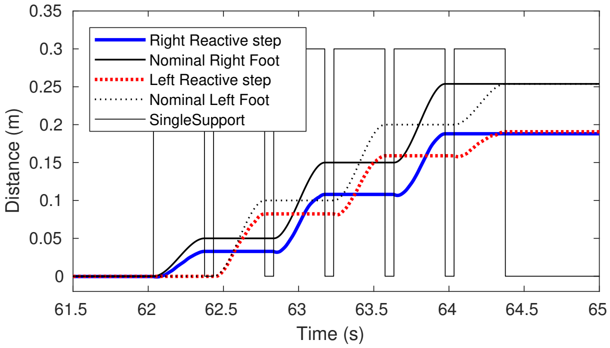

Fig. 10. Reactive foothold for a 10 cm walking task in COMAN+ real robot.

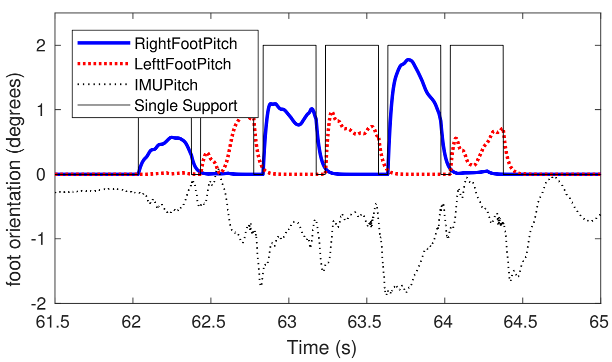

Fig. 11. Reactive foot rotation for a 10 cm walking task in COMAN+ real robot.

controller modifies the original foot and CoM trajectories of the walking pattern generator increasing the stability of the robot in the presence of external disturbances.

We tested our method with the robot COMAN+ in simulation and in real experiments. The obtained behavior shows a better dissipation of the external applied energy and a better recovery of the original walking pattern. This performance provides to nonreactive walking pattern generators reactive capabilities that minimize the falling risk for bipedal robots.

More in detail, the rotation of the feet provides a better landing and minimizes the bumping due to early landing during walking. In addition, the effectiveness of the ankle torque when the foot is not tilting with respect to the ground gives a better support region to the feet after the disturbance is applied. This results in a walking pattern that can better deal with the added energy in the gait. Moreover, the modification of the landing foothold permits further dissipation of energy during the recovery phase. Finally, the clearance of the landing foot minimizes the effect of an early landing.

Even though, the method was tested only in a non-reactive walking scheme, we consider that similar control strategies can be developed towards more reactive gait capabilities also for reactive walking pattern generators. The proposed controller does not affect the higher control levels. Therefore, it can be implemented over different walking pattern generators providing similar capabilities to them.

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