

Bipedal Hopping Pattern Generation for Passively Compliant Humanoids: Exploiting the Resonance

Barkan Ugurlu, *Member, IEEE*, Jody A. Saglia, *Member, IEEE*, Nikos G. Tsagarakis, *Member, IEEE*, Stephen Morfey, *Member, IEEE*, and Darwin G. Caldwell, *Member, IEEE*

Abstract—This paper describes a novel technique to analytically generate feasible hopping trajectories that can be applied to passively compliant bipedal humanoid robots. The proposed method is based on exploiting the inherent passive compliance through a reduced model, while the dynamic balance is maintained via the ZMP criterion. To begin with, a computational resonance frequency analysis and a system identification routine are performed for the actual robot, so as to determine the base resonance frequency, which is of special interest. Subsequently, the vertical component of the center of mass trajectory is generated by using a periodic function in which the aforementioned resonance frequency is utilized. The horizontal component of the center of mass trajectory is generated via the ZMP concept to ensure the dynamic balance. Having analytically generated both vertical and horizontal elements of the center of mass trajectory, joint motions are computed through the utilization of translational and angular momenta constraints. Applying the proposed method, a series of periodic forward hopping experiments are conducted on our actual compliant bipedal robot. As the result, we observe repetitive, continuous and dynamically equilibrated forward hopping cycles with successful landing phases.

Index Terms—humanoid, legged hopping, trajectory generation, passive compliance, resonance frequency.

I. INTRODUCTION

STARTING from 1970s, humanoid robots have evolved in many aspects and various operational principles have been exploited on several prototypes. To mention a few, researchers developed novel minimal graspers [1], walking controllers [2], [3] and jumping pattern generators [4], [5]. In the light of these recent advances, humanoid robots are expected to be adapted within the dynamic human environment in the current decade.

Observing such a human environment, people may walk, run, jump and interact with others. Therefore, a well-adapted humanoid should function in a human-like dexterous manner. This goal naturally includes fast motion capabilities, such as, running and jumping, when necessary. Being one of the main prerequisites of bipedal running, hopping motion appears to be

a very important index in the humanoid robot technology. Furthermore, humanoid robots may have to perform small jumps to stabilize their posture when they are subject to external forces. Sufficient hopping ability also enables humanoids to jump over small obstacles. Considering these facts, hopping motion deserves to be carefully analyzed as it potentially provides insights in improving the modern-day humanoids.

A. Background

In demonstrating running and jumping motions, many researchers conducted simulations and experiments on robots with rigid joint structures [4]–[6]. The predominant approach is to make use of non-backdrivable, stiff transmission systems that are combined with high gain servo controllers. Although non-backdrivability and large stiffness properties provide high precision, the resulting large output mechanical impedance makes them inherently unsafe when interacting with humans. Moreover, safety is not the only feature being compromised in these stiff robots. Compared to biological systems, they have significant performance handicaps, particularly related to their ability to interact with the environment and energy efficiency.

Biological systems, for instance, store and release elastic potential energy into/from muscles and tendons during daily activities; such as walking, running, jumping and so on [7] [8]. The management of the elastic potential energy that is stored in these biological structures is essential for reducing the energy consumption, achieving mechanical power peaks and adapting to the outer environment. These tasks are less likely to be handled using a stiff structure. The lack of compliance in present-day conventional humanoids does not allow these robots to make use of natural dynamics and storage of energy during cyclic locomotion. As a result, these robots have difficulties in interacting with the environment and do have higher energy demands since more effort is required both for the control system and the actuators.

Findings in biomechanical studies also do support the importance of compliance, especially during human locomotion. Ishikawa et al. experimentally verified the fact that managing the elastic potential energy is quite important during human walking [8]. As another example, Seyfarth et al. defended that properly adjusted leg stiffness is one of the key requirements of stabilized running motion [9]. The significance of resonance frequency during human hopping was stressed by Blickhan [10]. He stated that a human hopper selects a frequency within the range of physiologically feasible frequencies to maximize the elastic energy storage. In this context, Buchli and Ijspeert

Manuscript received October 25, 2012; revised September 20, 2013; accepted November 30, 2013.

Copyright (c) 2013 IEEE. Personal use of this material is permitted. However, permission to use this material for any other purposes must be obtained from the IEEE by sending a request to pubs-permissions@ieee.org.

B. Ugurlu is with the Department of Brain Robot Interface, Computational Neuroscience Laboratories, Advanced Telecommunications Research Institute International (ATR), 619-0288, Kyoto, Japan. (e-mail: barkanu@ieee.org).

J. A. Saglia, N. G. Tsagarakis, and D. G. Caldwell are with the Department of Advanced Robotics, Istituto Italiano di Tecnologia (IIT), 16163, Genova, Italy. (e-mail: {jody.saglia, nikos.tsagarakis, darwin.caldwell}@iit.it).

S. Morfey is with SRI International, Menlo Park, CA, 94025, US. (e-mail: stephen.morfey@sri.com).

also utilized the resonance frequency for efficient quadruped locomotion [11]. The outcomes of these studies, especially Blickhan's [10], inspired our current approach.

In the light of the facts discussed above, roboticists make use of compliance, from micro/nano robotic systems to legged locomotors. Following the same trend, our research activities are aimed at exploring the benefits which can be gained by the incorporation of compliance in humanoid robots. To this end, we developed a humanoid robot with passive and active compliant joints [12], as a part of the European AMARSi project [13]. The main objective of the AMARSi project is to achieve a qualitative leap toward rich motion skills in robotic systems by rigorously following a systematic approach in novel mechanisms with compliance. Efficient hopping locomotion is considered to be one of the goals, as compliant systems possess clear advantages in exploring fast motion generation techniques.

B. Related Works and Our Approach

Within the aforementioned connection, perhaps, one of the most prominent jumping motion demonstrations over the years was provided by Raibert et al. [14]. Applying a similar strategy and considering energy transformations, Ahmadi and Buehler succeeded in monopod running using an electrically-actuated mechanism with springs [15]. Despite these successful works, researchers may face difficulties when directly applying Raibert's control laws to fully-actuated legged robots with relatively heavy legs. On this matter, Xu and Kawamura demonstrated that these control laws are efficient when the target robot mass is cumulated around its hip [16]; thus, might not be suitable for a wider range of humanoids.

In addition to physical springs, actively compliant joints also play an important role for robots while adapting to different environmental conditions. This feature was exploited in several humanoid robot projects without the support of passive compliance [17]–[19]. Though this approach proved to be efficient in improving the force and impedance control, the bandwidth of the active compliance is limited due to the delays caused by motor inertia, sensory data process, and real-time control [20]. This may cause it to be inherently unsafe for human-robot interaction. Moreover, passive compliance is inevitably needed to achieve elastic potential energy management for efficient locomotion generation.

Speaking of energy-efficient pattern generation, one alternative way is to make use of natural dynamics on systems that can exhibit passive locomotion characteristics [21]. On this matter, fully actuated 3D robots like ours may not be physically suitable to exhibit such movements.

In providing sufficient compliance for humanoid robots, pneumatic artificial muscles appear to be a very promising actuation technology. Using an antagonistic setup, researchers from Vrije University demonstrated walking and jumping motion on a planar bipedal robot [22]. Hosoda et al. also followed a similar trend with a 3-D robot that is powered by antagonistic McKibben pneumatic actuators [23]. In addition to the numerous advantages, pneumatic actuation has its own drawbacks. Slow dynamics, the constant requirement of pressurized air,

inevitable hysteresis and nonlinear characteristics are typical difficulties to overcome when utilizing these actuators [24]. In response to these issues, we implement an electrical actuation system in our compliant joint mechanism.

Electrical actuators can also be utilized in an antagonistic configuration. From the energy efficiency point of view, a recent study from our research group [25] have revealed that SEAs (Series Elastic Actuators) are advantageous over antagonistic setups. This fact motivated us to develop and implement a SEA-powered mechanism for our compliant bipedal robot's pitch axis ankle and knee joints [12], [26]. In addition to passive compliance at these joints, all individual joints are equipped with built-in torque sensors and multiple position sensors to achieve active compliance in a similar manner as proposed in [17]. We believe that the combination of passive and active compliance at the joint level provide a versatile experimental hardware. Active compliance is expected to be beneficial mostly for environmental adaptation tasks though it may not help storing elastic potential energy. Thus, this paper does not focus on active compliance while generating hopping locomotion trajectories.

In accordance with the goals stated within the AMARSi project, we develop an analytical hopping trajectory generation method that can be applied to bipedal robots with passive compliant structures. The proposed method utilizes the inherent passive compliance while maintaining the dynamic balance through the use of ZMP (Zero Moment Point) concept. As partially inspired by Blickhan's studies [10], we make use of the base resonance frequency at which the total elastic potential energy storage is expected to be maximized. All in all, the proposed method enables us to acquire feasible, repetitive, continuous and dynamically-equilibrated hopping cycles in which the base resonance frequency is exploited to maximize hopping locomotion efficiency.

C. Novelty

Although some research groups successfully demonstrated single or intermittent jumping cycles on robots with artificial pneumatic muscles [22], [23]; a systematic method is still lacking to generate continuous hopping trajectories for a general class of bipedal robots with passive compliance. Therefore, we would like to highlight the fact that this paper mainly focuses on this issue. That being said, the novelty of this paper can be divided in two main directions.

To our knowledge, our bipedal robot is one of a few examples of a passively compliant and fully actuated bipedal robot. This privilege allows us to present one of the first experimental attempts on a passively compliant and fully actuated bipedal robot to analytically exploit the resonance frequency for the continuous hopping motion generation task. In the proposed method, there is no hardware-specific parameter for the pattern generation. One can easily apply the proposed method as long as the experimental robot's base resonance frequency is determined.

CoM trajectory generation is realized by analytical functions. Usually, the horizontal component of CoM can be analytically obtained for bipedal walking while the vertical

TABLE I
MECHANICAL SPECIFICATIONS

Size	Upper Leg length: 226.63 [mm] Lower Leg length: 203.3 [mm] Ankle-sole length: 60.3 [mm]
Weight	Each Leg: 6.816 [kg] Waist: 4.41 [kg] Total : 17.772 [kg]

component is kept constant. This is not applicable for bipedal hopping motion; the vertical component should vary to meet the jumping conditions. In this context, we analytically derived a vertical CoM trajectory generation method for robots with passive compliance, for the first time to our knowledge. Furthermore, initial velocity and support time parameters are tuned in a way to generate feasible jumping patterns, so that the method becomes systematic and easy-to-apply for a wider class of passively compliant and fully actuated bipedal robots.

An early version of this study including preliminary discussions is appeared in [27]. The current paper is a significantly expanded and improved version to provide a thorough and complementary archival report. Enhancements over [27] include the following: i) exhaustive review of the related works, ii) detailed explanations on the mechatronic hardware and passively compliant joint structure, iii) mathematical analysis of resonance frequencies and related discussions, iv) additional experimental results concerning 4 distinct non-resonant frequencies and ankle joint torque-angular position characteristics, v) further discussions on potential benefits and limitations of the proposed method.

The paper is organized as follows. In section II, we introduce our bipedal humanoid robot with a special emphasis on its passive compliant joint structure. Methodology, base resonance frequency analyses, and hopping pattern generator are respectively presented in sections III, IV and V. Experimental results are discussed thoroughly in section VI. Finally, the paper is concluded in section VII by stating the remarks and addressing the future directions.

II. COMPLIANT BIPEDAL ROBOT

A. General Overview on the Passive Compliant Biped

In order to explore compliant humanoid characteristics, we developed a bipedal robot at the Italian Institute of Technology, as a part of the AMARSi project. Table I summarizes its mechanical specifications. The robot has a total of 15 DoF (Degrees of Freedom); 6 DoF in each leg, and 3 DoF at the waist to be able to obtain greater motion flexibility. Each active joint incorporates three position sensors (one relative and two absolute encoders) and one torque sensor. The robot is also equipped with 6-axis Force/Torque sensors at the ankles and five 1-axis load cells on the feet soles. In addition, it has a triaxial rate gyro sensor and an accelerometer, located at the pelvis. In its electronic hardware structure, the main controller is an Intel Core 2 Duo 1.5 GHz dual processor with 3.0 GB RAM, running on a 32-bit GNU/Linux operating system that includes real-time Xenomai extension. Data communication is performed via a real-time Ethernet protocol called RTnet. Fig. 1 displays the actual robot and its joint configuration.

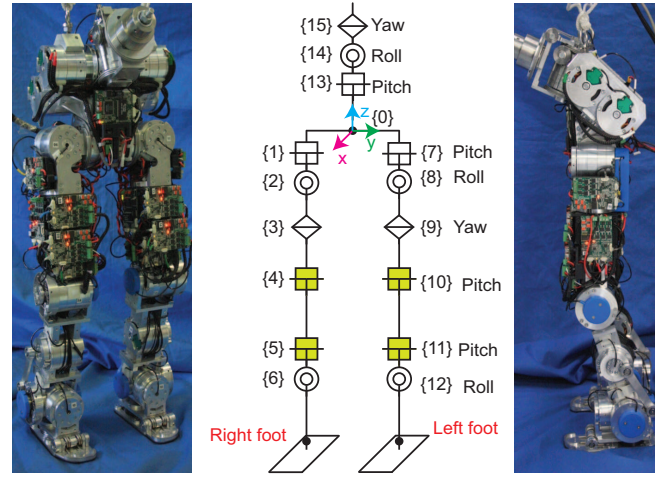


Fig. 1. The mechanical assembly of our robot and its joint configuration.

In this first prototype, only pitch axis ankle and knee joints are equipped with passive compliant elements, i.e., springs (see Fig. 1, frames with green color). However, torque sensing and versatile position sensing elements are placed in all the joints to enable active compliance control.

B. Compliant Joint Structure

For the compliant actuation system in our bipedal robot, the main objective is to satisfy dimensional and weight requirements while achieving high rotary stiffness within a compact structure. Regarding these requirements as well as with the previously discussed issues in mind, the SEA module [12], [25], [26] appears to be a very suitable candidate and it is presently implemented in our robot.

Our compliant actuation solution is based on an elastic mechanism which includes a three-spoke output component, a circular input pulley and six linear springs. The input pulley is fixed to the output of the reduction drive. The output pulley (three-spoke element) rotates on bearings with respect to the input pulley and is coupled to this by six springs. Fig. 2 displays this module's 3-D CAD section, its physical appearance and the torque sensing module.

At the zero passive deflection configuration between the input pulley and the three-spoke output pulley, six linear springs experience a pre-contraction equal to half of the maximum acceptable deflection. Deflections larger than the maximum allowable are not permitted by means of mechanical pin based locks. The motor and the reduction drive adopted for the robot's lower body compliant module uses a combination of harmonic drives (CSG series, 100:1 ratio for all joints) and a Kollmorgen RBE series brushless frameless motor. The motor, gears and joint sensing elements have been highly integrated to optimize the weight and dimensions of the joint, as displayed in Fig. 2. The sensing system of the compliant actuator includes three position sensors and one torque sensor. One optical encoder monitors the position of the motor, while two absolute magnetic encoders measure the position of the input pulley (harmonic drive output) and the position of the three spoke structure (link side). A torque sensor based on

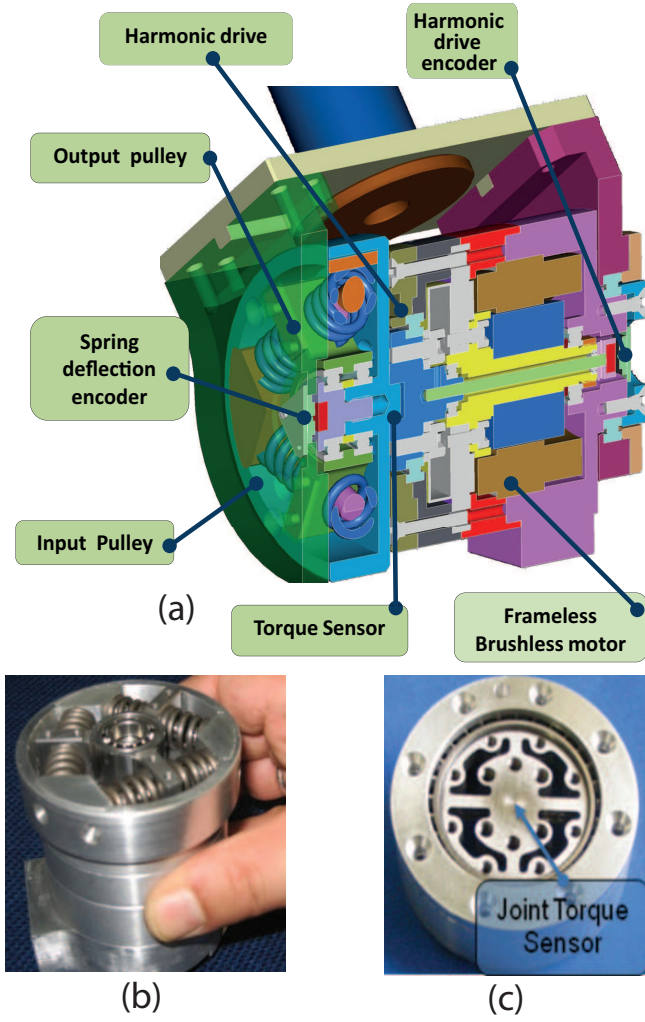


Fig. 2. Compliant actuation system SEA. a) The 3-D CAD section and the compact physical prototype along with the torque sensor module. The third encoder (relative) is placed at the motor side (before the harmonic gear) and not shown above. b) The physical SEA module. c) Torque sensor.

a custom load cell structure, instrumented by semiconductor strain gauges measures the torque generated at the output of the actuator. The output stiffness of the joint, k_s , can be derived as a function of the module parameters [26].

$$k_s = 6k_a r^2 \cos 2\theta_s \quad (1)$$

In (1), θ_s is the deflection angle of the three spoke element (output pulley) with respect to the input pulley. r and k_a stand for the length of the spoke arm and linear spring stiffness, respectively. For stiffness profiles and other details, refer to [25] and [26].

In order to perform energy analysis, we are in need of formulating the elastic potential energy that can be stored in a passive compliant joint. As understood by (1), stiffness is a function of deflection, meaning that it is not constant. Therefore, the elastic potential energy, E_{ep} , can be yielded through the following integration.

$$\begin{aligned} E_{ep} &= \int \theta_s k_s d\theta_s = 6k_a r^2 \int \theta_s \cos 2\theta_s d\theta_s \\ &= 3k_a r^2 (\theta_s \sin 2\theta_s + 0.5 \cos 2\theta_s) \end{aligned} \quad (2)$$

III. METHODOLOGY

The main idea in our approach is to determine a hopping frequency at which the elastic potential energy storage is maximized. That being the case, we perform an analysis and a system identification routine on our actual bipedal robot to determine such a feasible frequency (base resonance frequency) within the range of physically realizable frequencies. Subsequently, the vertical CoM trajectory is analytically generated via the utilization of the base resonance frequency. The horizontal CoM trajectory is also analytically derived using the ZMP criterion. Finally, given the CoM trajectory, joint motions are obtained via translational and angular momenta constraints. Prior to the step by step explanation of these stages, let us state the conditions that are considered throughout the construction of the hopping trajectory generator.

In the current version of our bipedal robot, only pitch axis ankle and knee joints are equipped with passive compliant elements. Due to this fact, we focus on two legged hopping motion generation, in which the robot moves on the sagittal plane, i.e., yaw axis and roll axis joint positions are set to zero. Only pitch axis hip, knee and ankle joints are activated. This postulate also enables us to give our full attention to generate hopping trajectories on a relatively abstracted model. Note that we do not physically constraint the robot motion and it can move in the lateral plane if it is subject to an external force. In other words, all experiments are conducted in 3D, without any mechanical limitation.

As the mechatronic hardware is manufactured with great precision in our institute, both legs can move in a sufficiently synchronized manner during two-legged hopping; the angular position difference between the corresponding leg joints are negligibly small.

Even though pitch axis hip joint is not equipped with a spring element, we model the whole system as a 3-DoF robot with elastic joints. In this case, hip joint stiffness is substituted relatively large by considering the stiffness profile of the harmonic gear and the elasticity of the cable drive.

While the robot is in a support phase, its feet are assumed to be stationary, i.e., no slippage occurs. On the actual system, robot feet are equipped with custom made pads to increase friction, so that this assumption may have a physical equivalence during support phases.

IV. DETERMINING THE RESONANCE FREQUENCIES

A. Computational Analysis

In order to gain insights regarding the base resonance frequency of the system, a computational analysis is conducted, prior to the experimental identification procedure. Even though we utilize the experimentally-identified base resonance frequency value during locomotion generation, a computational analysis is of importance for two reasons: i) To

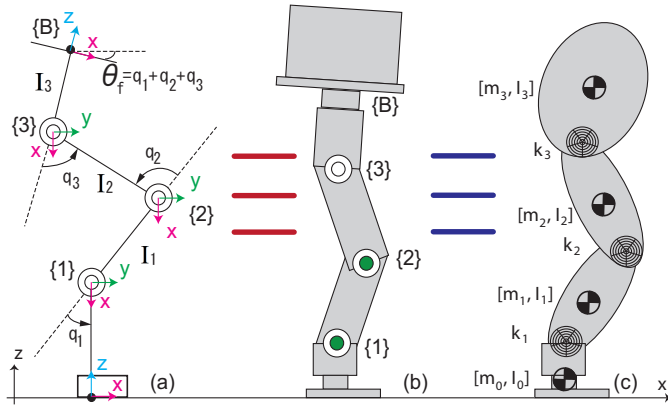


Fig. 3. a) Kinematic structure of the robot in the sagittal plane. Associated joint frames are indicated. θ_f denotes the pitch axis body tray orientation. b) Actual robot representation in the sagittal plane. Only pitch axis ankle and knee joints have passive compliant elements (green joints). c) The whole system can be considered as a 3-DoF robot with elastic joints.

double-confirm experimental identification results. ii) To see whether the elasticity properties of the system would yield a physically realizable base resonance frequency, prior to the identification procedure.

Keeping these in mind, the robot may be modeled as a 3-DoF system with elastic joints. Fig. 3 provides an illustration for this model. Considering this case, the system dynamics can be expressed using Spong's formulation [28].

$$\tau = I_r(q)\ddot{q} + C_r(q, \dot{q})\dot{q} + G_r(q) - \rho\dot{q} \quad (3)$$

$$= I_m\ddot{\theta} + B_m\dot{\theta} + \kappa(\theta - q) \quad (4)$$

In (3) and (4), τ is generalized joint torque vector while q and θ respectively denote link side and motor side angular position vectors. $I_r(q)$, $C_r(q, \dot{q})$, $G_r(q)$ are inertia, coriolis/centrifugal, and gravitational force terms, regarding the reduced model presented in Fig. 3(c). ρ is a diagonal matrix that represent link side friction terms, and it may be identified via the method proposed in [29]. I_m and B_m are diagonal matrices that store rotor inertia and friction constants, which are appropriately scaled via respective gear ratios. κ refers to the diagonal joint stiffness matrix.

Referring to [30], natural frequencies of this system are determined while generalized coordinates, q , converge to the equilibrium configuration that is defined as $q_e = \theta$. That being said, we utilize Jacobian of the gravitational force term, $\Psi_{G_r}(q)$, that can be computed via partial differentiation with respect to joint motion; $\Psi_{G_r}(q) = \partial G_r(q)/\partial q$. Basically, the Jacobian $\Psi_{G_r}(q)$ maps the variations in $G_r(q)$ to variations in joint motions as follows [31].

$$\Delta G_r(q) = \Psi_{G_r}(q)\Delta q \quad (5)$$

Around the equilibrium configuration, the variations in joint motion points out $\Delta q = q - q_e$. Therefore, $G_r(q)$ in can be expressed in terms of the gravitational force at equilibrium, namely, $G_r(q_e)$, while performing a linearization around the equilibrium (q_e).

$$G_r(q) = \Psi_{G_r}(q_e)(q - q_e) + G_r(q_e) \quad (6)$$

Combining (3), (4) and (6) in the equilibrium state ($q_e = \theta$), together with the above-mentioned linearization, the following is yielded.

$$I_r(q_e)\ddot{q} + [C_r(q_e, \dot{q}_e) - \rho]\dot{q} + [\kappa + \Psi_{G_r}(q_e)]q = I_m\ddot{q}_e + B_m\dot{q}_e + [\kappa + \Psi_{G_r}(q_e)]q_e - G_r(q_e) \quad (7)$$

If we call the right hand side of (7) F_e , it becomes analogous to the general multi-DoF vibration system,

$$M\ddot{X} + B\dot{X} + KX = F_e \quad (8)$$

where, $M \equiv I_r(q_e)$, $B \equiv [C_r(q_e, \dot{q}_e) - \rho]$ and $K \equiv [\kappa + \Psi_{G_r}(q_e)]$ respectively correspond to mass, damping and stiffness matrices of the general multi-DoF vibration system. In this case, the eigenvalue problem associated with (8) may be interpreted as a λ -matrix problem [32].

$$\Lambda_j^2 M u_j + \Lambda_j B u_j + K u_j = 0 \quad (9)$$

In (9), Λ_j and u_j are the j^{th} eigenvalue and eigenvector. With the help of approximate decoupling method described in [32], eigenvalues may be computed by solving the related characteristic polynomial equation; however, omitting the damping term greatly simplifies computations and does not create any significant deviation. Using this information, natural frequencies, ω_j , and resonance frequencies, δ_j , defined at the equilibrium are given as follows.

$$\omega_j^2 = \Lambda_j; \quad \delta_j = \frac{1}{2\pi} \sqrt{\Lambda_j}. \quad (10)$$

Hence, it is possible to compute resonance frequencies for a given set of joint configurations, elasticity properties and inertial parameters of the robot. Utilizing (10), base resonance frequency, δ_1 , is computed to be within 0.925~1.04 [Hz] band. Fig. 4 depicts its correlation with respect to the knee joint angle where the maximum deviation is less than 5%. Similar variations could also be observed for hip and ankle variations. Keeping this in mind, the base resonance frequency is considered as a constant value, since it does not vary greatly with respect to the given joint configuration.

Computing the second and third resonance frequencies using (10), δ_2 appears to be within 8~11 [Hz] band, while δ_3 vary between 92~101 [Hz]. Consequently, we only make use of the base resonance frequency in the proposed hopping generator. There are two main reasons behind this decision: i) In multi-DoF systems with elasticity, only the first resonance mode makes the whole system move in a synchronous manner. In other words, if the system is excited at the frequency of δ_1 , both springs deflect accordingly, so that energy storage/release cycles can be maximized. In other vibration modes, springs move against each other and create unfavorable characteristics for energy storage/release cycles. ii) In our specific case, both δ_2 and δ_3 are out of the band of interest for the target hopping

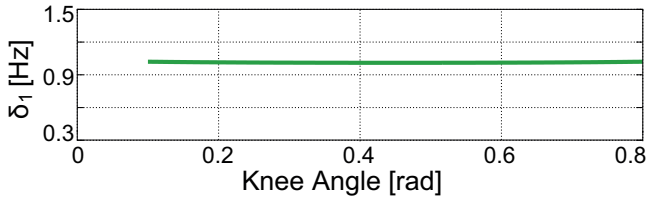


Fig. 4. Base resonance frequency variation with respect to knee angle. This plot indicates that it does not greatly depend on knee angle variation.

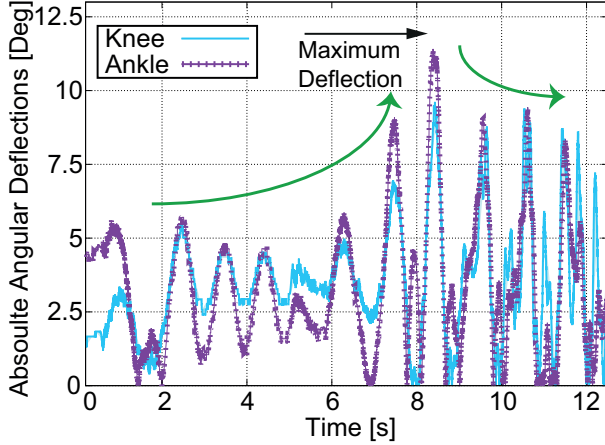


Fig. 5. System identification results on pitch axis ankle and knee joints. Angular deflections are measured for left leg's pitch axis ankle (solid purple) and knee (solid cyan) joints. Identical results are also obtained for the right leg. The actual experimentation period is longer than 12 [s]; however, the data is truncated after the twelfth second to display the worthwhile portion.

locomotion. They are also outside of the physically realizable frequency range.

B. Experimental Identification

Despite the fact that (10) provides a systematic way to determine the base resonance frequency, theoretical computation of resonance frequencies might not be sufficiently precise for practical applications. Due to the compliance at the feet soles, harmonic gear stiffness, servo controller gains and several other factors, resonance frequencies may differ from their theoretical representations. Moreover, resonance frequencies are computed via reduced dynamics equations, which may potentially introduce modeling errors. In regard to these facts, we performed a system identification routine on our bipedal robot, so that the base resonance frequency can be determined experimentally to validate our computations.

For this purpose, we firmly attached the robot's feet to a rigid platform. Subsequently, the robot is excited through the vertical direction, using a chirp signal with frequencies ranging from 0.25 [Hz] to 8 [Hz]. Within this frequency range, we plotted angular deflections both for pitch axis ankle and knee joints as depicted in Fig. 5, and sought for maximum deflections.

As observed in Fig. 5, ankle and knee joints' angular deflection reaches to its maximum value slightly after the eighth second. This corresponds to a frequency value of

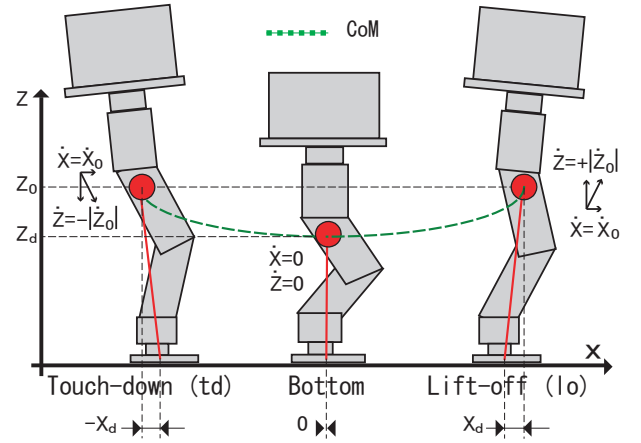


Fig. 6. Illustration of a single support phase period. It includes three main phases; a) Touch-down (from the previous flight phase), b) Bottom, c) Lift-off (for the next flight phase). Elastic potential energy is stored during touch-down - bottom period and then released throughout bottom - lift-off period. During support phases, the foot is stationary and its center is considered to be the origin. The offsets in x-axis are left only for illustrative purposes. Since the foot sole center is substituted as origin, the CoM trajectory is determined with respect to this point. In order to prevent slips, we placed pads at the feet soles and did not consider large forward velocities.

0.985 [Hz]; the base resonance frequency (δ_1). As previously stated, our theoretical computation returned 0.925~1.04 [Hz], a frequency band that spans within the vicinity of the experimentally obtained value¹. Furthermore, frequencies greater than δ_1 creates gradually decreasing angular deflections as well. As a consequence, we obtain a profile that is similar to a Gaussian distribution for both joints.

Considering the fact that experimentally identified δ_1 appears to match well with our theoretical computations, we choose to vertically excite the robot body at 0.985 [Hz]. What is more, the joint deflections in ankle and knee joints are in harmony with each other when the frequency is at this value, meaning that both joints' deflections are around their highest values. The end result is that if we vertically excite the robot body using this resonance frequency, we can hypothetically maximize the angular deflection, and therefore the potential energy storage.

V. HOPPING TRAJECTORY GENERATION

A. CoM Trajectory Generation during Support Phase

For the CoM motion generation task during support phases, we make use of ZMP concept, a widely used dynamic balance criterion for legged robots. Firstly, let us analyze x-axis ZMP equation [4].

$$X_{zmp} = x - z \frac{\ddot{x}}{\ddot{z} + g} - \frac{\dot{L}_y}{m(\ddot{z} + g)} \quad (11)$$

In (11), x and z symbolize horizontal and vertical CoM positions, L_y is pitch axis intrinsic angular momentum, m is the total mass and g is the gravitational acceleration. To simplify the motion generation task, $\dot{L}_y$ is omitted. We later

¹Base resonance frequency is inadvertently miswritten in [27].

include this term in the joint computation stage, in a similar manner as performed in [6].

With the aforementioned assumption, (11) may be re-written as below.

$$\omega = \sqrt{\frac{\ddot{z} + g}{z}} \quad (12)$$

$$\ddot{x} = \omega^2(x - X_{zmp}) \quad (13)$$

The ω parameter in (12) is called the natural frequency of equivalent pendulum in ZMP modeling [6]. The core idea is that if we utilize the base resonance frequency via ω term in this model ($\omega = 2\pi\delta_1$), we can maximize the elastic potential energy during hopping. Being second order differential equations, (12) and (13) can be analytically solved for constant ω values to obtain the CoM trajectory. In the following subsections, we explain this motion planning for vertical and horizontal components, respectively.

1) *Vertical CoM Motion Planning*: Eq. (12) can be re-written in a way to move the highest order to the left hand side.

$$\ddot{z} = \omega^2 z - g \quad (14)$$

For a constant ω value, we may analytically solve (14), without the loss of generality.

$$z = \left(z_0 - \frac{g}{\omega^2}\right) \cosh \omega t + \frac{\dot{z}_0}{\omega} \sinh \omega t + \frac{g}{\omega^2} \quad (15)$$

In (15), z_0 and $\dot{z}_0$ are initial position and velocity values, t is the time parameter. If we differentiate this equation, we can obtain the vertical CoM velocity as well.

$$\dot{z} = \left(\frac{\omega^2 z_0 - g}{\omega}\right) \sinh \omega t + \dot{z}_0 \cosh \omega t \quad (16)$$

At this stage, we would like to highlight the fact that the reason for obtaining vertical CoM trajectory by solving (14) is to make sure that ω parameter is constant. One may think that another periodic function could also be employed for the vertical CoM trajectory. However, in that scenario, (12) does not hold valid for constant ω values; it varies with time. Since we use the ZMP model in generating the forward motion, vertical CoM motion needs to obey (12). In that sense, such a condition can only be met via (15).

As previously stated, our strategy is to create a vertical pattern with constant excitation frequency, i.e., the base resonance frequency. This is due to the fact that the passive compliant joints in our robots have approximately constant stiffness profiles (see Fig. 4). Furthermore, biomechanical studies also indicate the utilization of constant stiffness during stance phases [9], [10]. Therefore, we are in need of vertical CoM patterns in which the excitation frequency is constant as well. Consequently, this condition allowed us to yield (15) and (16), through the analytical solution of (14).

In order to obtain periodic elastic energy transformation routines using (15) and (16), it is desirable to obtain a vertical motion profile in which the robot moves downwards and

upwards in a cyclical fashion. Together with Fig. 6, Fig. 7(a) and Fig. 7(b) depict this kind of vertical position and velocity profiles throughout the desired support period. As observed in these figures, the robot starts from an initial position, z_0 , with a negative initial velocity, $-\dot{z}_0$, at the moment of t_0 , then decelerates downwards. In the middle point of the support phase ($t = t_{mz}$), the CoM reaches its minimum value, z_d . Between t_0 and t_{mz} , the springs store elastic potential energy. After the t_{mz} moment, the robot releases the elastic potential energy and accelerates upwards. It lifts off at the end of the support phase, t_e . Because the motion is symmetric, the vertical initial position is equal to the vertical lift-off position. Moreover, the vertical initial and lift-off velocities have the same magnitude with different signs.

As noted by Blickhan [10], the number of independent parameters are less than the constraints in jumping motion. This causes limitations in the parameter space in which a feasible jump can be performed. Therefore, proper tuning of jumping parameters is crucial. In our method, we determine z_0 and z_d values by considering the mechanical capabilities of our robot. ω is equalized to the base resonance frequency as previously explained; $\omega = 2\pi\delta_1$. Other parameters, namely, initial velocity ($\dot{z}_0$) and support time period (T_s), are computed by using z_0 , z_d and ω values to make sure that we obtain the motion profile shown in Fig. 7(a) and Fig. 7(b).

In Fig. 7(a), we can observe that the vertical position function has a minimum when $t = t_{mz}$. In other words, the velocity function is zero at this moment. If we call support time period T_s , and initial time (t_0) is zero², t_{mz} simply becomes $T_s/2$.

$$\dot{z}|_{t=T_s/2} = \frac{\omega^2 z_0 - g}{\omega} \sinh \omega \frac{T_s}{2} + \dot{z}_0 \cosh \omega \frac{T_s}{2} = 0 \quad (17)$$

From (17), T_s can be expressed in terms of ω , z_0 and $\dot{z}_0$.

$$T_s = \frac{2}{\omega} \tanh^{-1} \frac{\dot{z}_0 \omega}{g - \omega^2 z_0} \quad (18)$$

Additionally, the z-axis CoM position is equal to z_d when $t = t_{mz} = T_s/2$.

$$\begin{aligned} z|_{t=T_s/2} &= \frac{\omega^2 z_0 - g}{\omega^2} \cosh \omega \frac{T_s}{2} \\ &+ \frac{\dot{z}_0}{\omega} \sinh \omega \frac{T_s}{2} + \frac{g}{\omega^2} = z_d \end{aligned} \quad (19)$$

Combining (18) and (19), and solving the outcome for $\dot{z}_0$, the following relation is obtained.

$$\dot{z}_0 = \mp \sqrt{(z_0 - z_d)(\omega^2 z_0 - 2g + \omega^2 z_d)} \quad (20)$$

Even though we have two solutions, we need to choose the one with the minus sign, in order to comply with the desired vertical motion profile.

Utilizing (20), we can compute the initial vertical CoM velocity, $\dot{z}_0$, for a given set of z_0 , z_d and ω . Subsequently, we can compute the support time period, T_s , using (18).

²For non-zero initial time values, resulting equations can simply be shifted in time through t_0 , without the loss of generality.

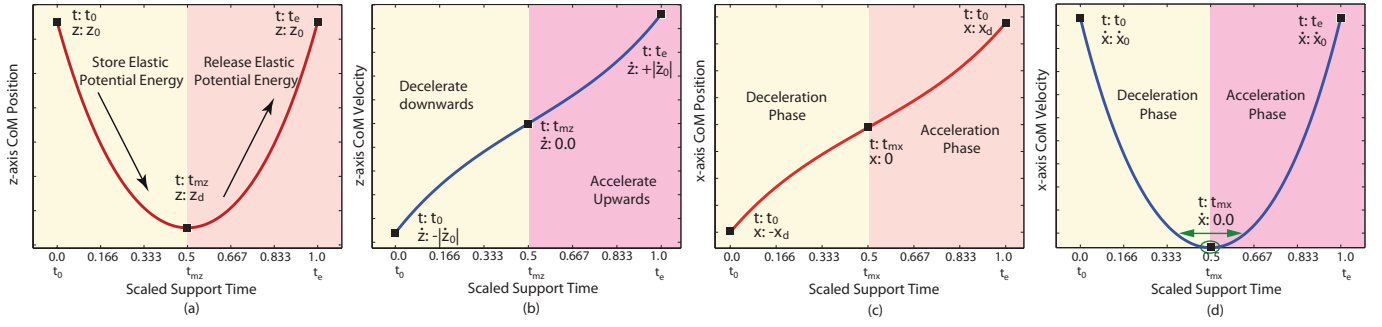


Fig. 7. Feasible CoM position and velocity profiles. a) z-axis CoM position. b) z-axis CoM velocity. c) x-axis CoM position. d) x-axis CoM velocity.

Inserting all these parameters into (15) and (16), vertical CoM position and velocity trajectories are yielded. To this end, we later provide a simple and sequential algorithm to generate trajectories.

2) *Horizontal CoM Motion Planning*: Having obtained the vertical CoM trajectory, we follow a similar strategy for the horizontal CoM trajectory. Keeping in mind that ω is constant and equal to $2\pi\delta_1$, we can solve (13) for a constant X_{zmp} as below.

$$x = (x_0 - X_{zmp}) \cosh \omega t + \frac{\dot{x}_0}{\omega} \sinh \omega t + X_{zmp} \quad (21)$$

Initial position and velocity are denoted with x_0 and $\dot{x}_0$. Differentiating (21) once and twice, we can obtain x-axis velocity and acceleration functions as well.

$$\dot{x} = \omega (x_0 - X_{zmp}) \sinh \omega t + \dot{x}_0 \cosh \omega t \quad (22)$$

$$\ddot{x} = \omega^2 (x_0 - X_{zmp}) \cosh \omega t + \omega \dot{x}_0 \sinh \omega t. \quad (23)$$

When there is a requirement to generate ZMP-based feasible x-axis CoM trajectories, it is desirable to obtain a motion profile in which the robot decelerates and accelerates within a cyclical manner. Together with Fig. 6, Fig. 7(c) and Fig. 7(d) depict the horizontal position and velocity profiles for this kind of trajectory generation. In these figures, the deceleration phase is defined between t_0 and t_{mx} while the acceleration phase is defined between t_{mx} and t_e . Depending on the desired deceleration/acceleration strategy, t_{mx} can be assigned between t_0 and t_e . In the case of substituting t_{mx} as the middle point, deceleration/acceleration periods become equal to each other. The CoM then moves forward by keeping its average pace and its terminal velocity becomes equal to the initial velocity. Fig. 7(c) and Fig. 7(d) demonstrate such a situation. Because the motion is symmetric, the horizontal initial velocity equals to the horizontal lift-off velocity.

As may be observed in Fig. 7(d), velocity function has a minimum point when $t = t_{mx}$. Hence, its derivative, the acceleration function, is zero at that moment.

$$\begin{aligned} \ddot{x}|_{t=t_{mx}} &= \omega^2 (x_0 - X_{zmp}) \cosh \omega t_{mx} \\ &+ \omega \dot{x}_0 \sinh \omega t_{mx} = 0 \end{aligned} \quad (24)$$

Using (24), we can express $\dot{x}_0$ as follows.

$$\dot{x}_0 = \omega ((X_{zmp} - x_0) \coth \omega t_{mx}) \quad (25)$$

During single support phases, it is also possible to substitute an average forward velocity, v_m . Assigning this parameter, the terminal position, x_d , can simply be obtained by the following formula.

$$x_d = v_m T_s + x_0. \quad (26)$$

In the case of cyclic motion, the x_0 parameter in (26) equals to the lift-off position with a minus sign ($-x_d$) as illustrated in Fig. 6. If the robot starts jumping from a stationary motion, i.e., the beginning of an experiment, it could be substituted as zero or a relatively small value.

The x_d parameter in (26) also corresponds to the position when $t = t_e$:

$$\begin{aligned} x|_{t=t_e} &= x_d = (x_0 - X_{zmp}) \cosh \omega T_s \\ &+ \frac{\dot{x}_0}{\omega} \sinh \omega T_s + X_{zmp}. \end{aligned} \quad (27)$$

Inserting (25) and (26) into (27), we may compute X_{zmp} .

$$X_{zmp} = \frac{x_0 \sinh(\omega(T_s - t_{mx})) + x_d \sinh(\omega t_{mx})}{\sinh(\omega(T_s - t_{mx})) + \sinh(\omega t_{mx})}. \quad (28)$$

In a basic sense, (26), (28) and (25) enable us to respectively compute X_{zmp} and $\dot{x}_0$ parameters for a given set of x_0 , ω , v_m and t_{mx} profile. Having obtained x_0 , $\dot{x}_0$ and X_{zmp} , we can generate the horizontal CoM position and velocity trajectories by utilizing (21) and (22). On this matter, we later provide an easy-to-implement algorithm.

B. Trajectory Generation During Flight Phase

1) *Vertical Motion Planning*: When the robot is in the air, it is subject to projectile motion dynamics. That being said, z-axis CoM simply follows a parabola.

$$z = z_0 + \dot{z}_0 t - \frac{1}{2} g t^2 \quad (29)$$

$$\dot{z} = \dot{z}_0 - g t \quad (30)$$

Initial conditions of a flight phase simply equals to terminal conditions of the preceding support phase. As may be observed

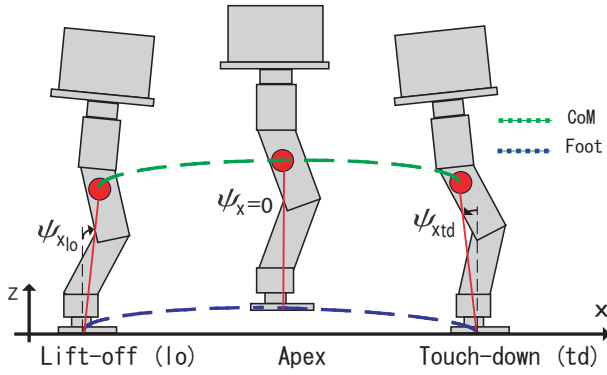


Fig. 8. Illustration of a single flight phase period. ψ indicates the angle between x-axis and z-axis when the robot is in the air. The foot trajectory can be generated in a way that ψ angles at the lift-off and touch-down are equalized with different signs; $\psi_{xtd} = -\psi_{xlo}$.

in Fig. 6, Fig. 7(a) and Fig. 7(b), initial and terminal positions are the same during support phases. Initial velocities are also the same with a minus sign. Therefore, initial position and velocity parameters of a flight phase are known in advance for a designated support phase. In addition, one may define a foot trajectory for vertical axis (z_f) to extend flight phase time; however, we do not use it in this work.

Note that flight time period depends on the lift-off velocity (initial velocity of a flight phase):

$$T_f = 2 \left| \frac{\dot{z}_0}{g} \right| \quad (31)$$

2) *Horizontal Motion Planning*: In this case, horizontal CoM velocity is constant due to the fact that x-axis translational momentum is conserved. That being the case, CoM motion is expressed as in the following.

$$x = -x_0 + \dot{x}_0 t \quad (32)$$

$$\dot{x} = \dot{x}_0 \quad (33)$$

Similarly, initial conditions in (32) and (33) are determined via terminal conditions of the preceding support phase. If we observe Fig. 6, Fig. 7(c) and Fig. 7(d), initial and terminal velocities are the same for a support phase. Terminal position is also equal to initial position with a minus sign, with respect to foot position. Therefore, x-axis initial position and velocity values can be obtained beforehand for a given support phase and they appear to be $-x_0$ and $\dot{x}_0$.

Fig. 8 illustrates a flight phase, where the angle between x-axis and z-axis is denoted with ψ . At the moment of lift off, this angle can be obtained using z_0 and x_0 ; $\psi_{lo} = \tan^{-1} \frac{x_0}{z_0}$. For the purpose of symmetrical motion patterns, it is desired to land with the same angle with minus sign; $\psi_{xtd} = -\psi_{xlo}$. Moreover, it should be zero at the apex point. Using these conditions, ψ trajectory can be derived using polynomials. Finally, horizontal foot trajectory, x_f , can be computed as follows to make sure that necessary foot placement planning can be achieved.

$$x_f = x - (z - z_f) \tan \psi \quad (34)$$

C. Joint Motion Computation Scheme

Having computed all the necessary components of CoM trajectories, we now proceed to the joint computation scheme. As we stated previously, only the joints in sagittal plane are equipped with passive compliant elements. Therefore, we focus on jumping motion in which pitch axis ankle, knee and hip joints are actuated, i.e., 3 DoF. Fig. 3(a) displays the kinematic structure and joint frames.

At this point, we can easily derive an analytical inverse kinematics solution that maps CoM position and upper body pitch axis orientation (x, z, θ_f) with joint positions (q_1, q_2, q_3). On the other hand, this approach cannot characterize the rotational inertia, an important characteristic of the robot dynamics [5]. Considering this fact, we utilized x-axis and z-axis CoM translational momenta (P_x, P_z) and pitch axis CoM angular momentum (L_y) for the joint motion computation task, in accordance with the method proposed in [27].

VI. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Evaluation of Experimental Results

Utilizing the proposed pattern generation technique, a set of forward hopping experiments were conducted on our actual bipedal robot. In these experiments, initial vertical and horizontal CoM positions (z_0, x_0), minimum vertical CoM position (z_d), and average forward velocity (v_m), were substituted as 0.36 [m], 0.005 [m], 0.3015 [m], 0.11 [m/s], respectively. The base resonance frequency (δ_1) was previously determined as 0.985 [Hz]. t_{mx} parameter was considered as the middle point during the support period; $t_{mx} = 0.5(T_s + t_0)$. Other necessary parameters were computed in accordance with the algorithm presented above; namely, flight time (T_f), support time (T_s), and referential ZMP input (X_{zmp}) were respectively calculated as 0.12 [s], 0.48 [s], 0.0314 [m].

In Fig. 9(a) and Fig. 9(b), horizontal and vertical CoM trajectories are depicted. As seen in these figures, consecutive support and flight phases are connected seamlessly. Note that trajectories are plotted with respect to the foot sole center. Therefore, x-axis trajectories seem periodic although the robot performs forward hopping.

x-axis ZMP response is illustrated in Fig. 9(c). In this figure, solid red line denotes actual x-axis ZMP measurements while dashed green and blue lines symbolize the support polygon. As it may be observed, the ZMP response is always within the support polygon, indicating that we obtained dynamically equilibrated forward jumping cycles. What is more, ZMP is undefined during the flight phase and these periods are covered with yellow hatched areas.

Vertical GRF response can be examined in Fig. 10(a). Similar to Fig. 9(c), yellow hatched areas symbolize flight phase periods in which GRF response is observed to be zero. Based on this fact, we may claim that we obtained successful flight phases with certain foot clearances. Moreover, touch-down impacts are measured to be around 350 [N]. This impact

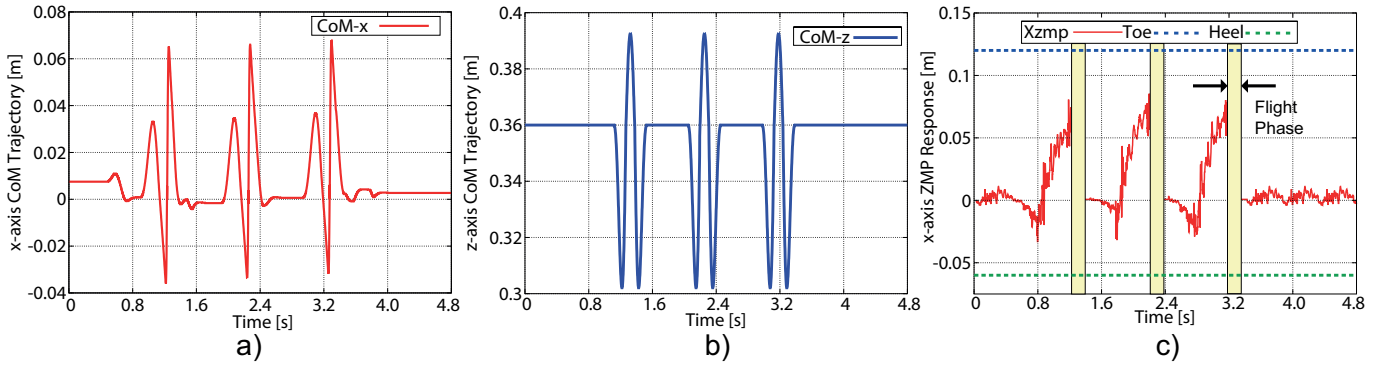


Fig. 9. a) x-axis CoM trajectory. b) z-axis CoM trajectory. c) x-axis ZMP response.

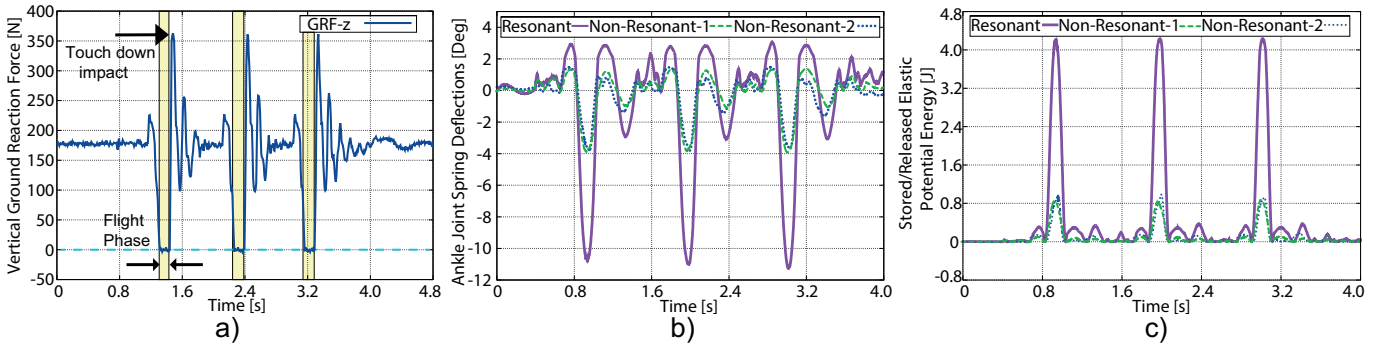


Fig. 10. a) Vertical GRF response. b) Ankle joint spring deflections. c) The total elastic potential energy variations.

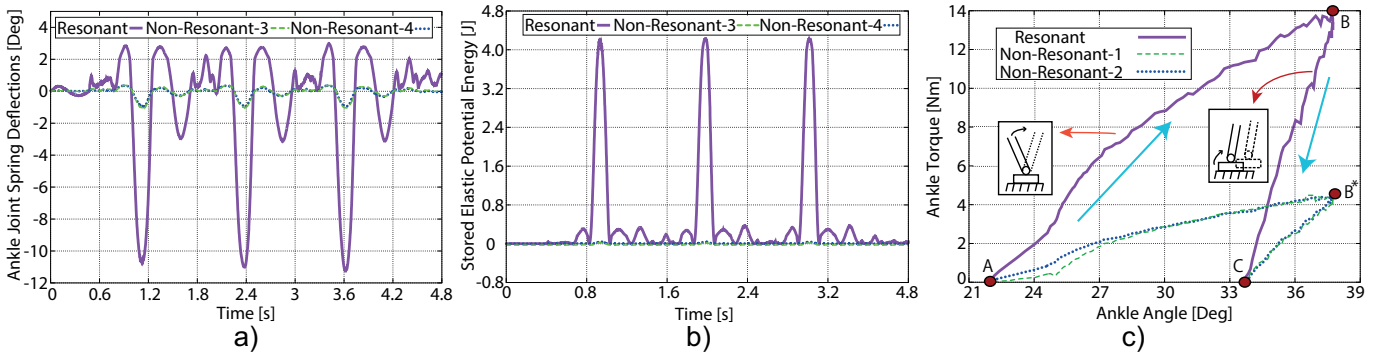


Fig. 11. a) Ankle joint spring deflections. b) The total elastic potential energy variations. c) Ankle joint, torque-angle profile (link side), stance phase

force appears to be twice the amount of the overall robot weight. In Ugurlu's previous works on a stiffly controlled one legged robot, jumping experiments with relatively similar characteristics (jumping height etc.) were conducted [4]. In those experiments, touch-down impacts were measured to be 4 to 5 times greater than that of the rigid robot's weight. As a comparison, it is obvious that compliant robots are intrinsically advantageous over their rigid counterparts in reducing touch-down impacts. Thus, one may develop any kind of motion trajectory for compliant robots without having additional concerns to reduce touch-down impacts. Note that force and ZMP measurements were estimated using on board sensory information and floating base inverse dynamics.

In order to investigate hopping at the resonance frequency,

we conducted 4 additional experiments in which the vertical CoM trajectory is generated by using non-resonant frequencies ($\varphi_1, \varphi_2, \varphi_3, \varphi_4$). Non-resonant frequencies are chosen equidistantly from the base resonance frequency; $\varphi_1 = 0.75\delta_1$, $\varphi_2 = 1.25\delta_1$, $\varphi_3 = 0.5\delta_1$, $\varphi_4 = 1.5\delta_1$.

Fig. 10(b) displays the ankle joint spring deflections. Solid purple, dashed green, and dotted blue lines respectively represent deflection variations in resonant, non-resonant-1 and non-resonant-2 hopping experiments. As seen in the figure, the highest deflection peak is obtained during the experiment that is conducted at the resonance frequency. It is measured to be around -11 degrees which is quite close to the maximum limit; -11.45 degrees. On the other hand, the highest deflection during non-resonant jumping experiments was measured to

be about only -4 degrees, which is 65% smaller than the maximum allowable deflection range. Identical results are observed for knee joint deflections as well.

Using eq. (2) and removing the trend, we also computed the total elastic potential energy. Fig. 10(c) depicts these elastic potential energy variations. Similarly, solid purple, dashed green, and dotted blue lines respectively indicate elastic potential energy variations in resonant, non-resonant-1 and non-resonant-2 jumping experiments. Not surprisingly, elastic potential energy storage/release is maximized in the case for resonant jumping. The peak value is measured to be around 4.2 [J]. In contrast, elastic potential energy variations in non-resonant jumping experiments exhibited 80.7% less peak values, in comparison with the resonant jumping case.

In addition, Fig. 11(a) and Fig. 11(b) display ankle joint spring deflections and elastic potential energy variations for hopping experiments conducted at the base resonance frequency (solid purple), non-resonant-3 frequency (dashed green) and non-resonant-4 frequency (dotted blue). As the excitation frequencies are chosen farther, spring deflections get much smaller. They are measured to be less than 1 degree, which is 91% smaller than the maximum allowable deflection range. Accordingly, potential energy variation is around 0.1 [J]. This value corresponds to 98% less amount of energy that is stored when the robot is excited at the base resonance frequency.

It can also be observed that the spring deflection and elastic potential energy variations are quite identical in non-resonant-1 (φ_1) and non-resonant-2 (φ_2) hopping experiments. Similarly, non-resonant-3 (φ_3) and non-resonant-4 (φ_4) hopping experiments reveal identical spring deflection and elastic potential energy variation profiles. Indeed, this result is expected since the frequencies utilized in these experiments are chosen equidistantly from the base resonance frequency (δ_1). This also proves that δ_1 is able to represent the resonance frequency, so that the system reacts in accordance with the Gaussian distribution. Table II summarizes resonant and non-resonant frequency hopping experiment results.

What is more, non-resonant-1 and non-resonant-2 hopping experiments partially succeeded; the robot demonstrated premature flight phases with no obvious foot clearances. This is expected since non-resonant frequencies cannot fully utilize the springs to maximize the deflections and potential elastic energy variations. In non-resonant-3 and non-resonant-4 hopping experiments, the robot simply did not hop vertically at all. On the other hand, the robot successfully exhibited continuous forward hopping cycles with obvious foot clearances when it is excited at the base resonance frequency.

Ankle joint's link side torque-angle curve is provided for a single stance period in Fig. 11(c). The curve A-B-C illustrates the resonant jumping experiment result (solid purple) while A-B*-C curves display the non-resonant-1 and non-resonant-2 hopping experiments results (dashed green and dotted blue). Non-resonant-3 and non-resonant-4 hopping experiment results are excluded as they generate very low torque profiles. From point A to point B, the robot body moves forward. Between points B and C, the robot pushes down the ground and lifts off after the C point. These results are quite similar to

TABLE II
RESONANT NON-RESONANT EXPERIMENT RESULTS

	Maximum Deflection [Deg]	Stored Elastic Potential Energy [J]
δ_1	11.12	4.2
$\varphi_1 = 0.75\delta_1$	3.98	0.82
$\varphi_2 = 1.25\delta_1$	3.92	0.8
$\varphi_3 = 0.5\delta_1$	0.96	0.1
$\varphi_4 = 1.5\delta_1$	1.0	0.12

Hansen et al.'s study involving human ankle joint torque-angle measurements during fast motions [33]. In their work, we may observe that the A-B curve gets steeper when the human subject moves faster. This is in accordance with our torque-angle curve measurements; A-B curve is steeper than that of A-B*. Based on this result, we may hypothesize that the robot may exhibit human-like natural torque-angle characteristics thanks to its passively compliant structure.

B. Potential Benefits and Limitations

We would like to highlight the fact that the robot is not able to perform hopping without the passive compliance (e.g. with no springs), because of hardware limitations. Therefore, it is clear that the proposed method fully utilizes its passive compliance to achieve hopping motion. Keeping this in mind, the proposed method can be used to enable low-power humanoids to succeed in efficient jumping and hopping locomotion scenarios when they are supported with passively compliant elements.

In order to augment the hopping height, it is either possible to modify the mechanical stretching capabilities of the legs to increase the amplitude or to replace current springs with their softer counterparts. In other words, hopping performance highly depends on the spring selection which requires careful analysis beforehand. In relation to that matter, series elastic actuators may not store a high amount of energy since the control bandwidth must be prioritized. Therefore, this aspect appears to be a limitation concerned with operational difficulties.

It should also be noted that the initial velocity must be non-zero at the beginning of support phase. In the case of first hop, the joints may suffer a discontinuous velocity profile; however, this is less likely to cause excessive torque peaks within the presence of passive compliance.

VII. CONCLUDING REMARKS

To summarize, this paper proposes an analytical jumping trajectory generation method that can be implemented on bipedal robots with passively compliant structures. The proposed method is independent from the hardware-specific parameters, so that it might be applicable for a wider class of passive compliant bipedal robots. CoM trajectory generation algorithm is based on analytically derived equations, in which the resonance frequency is utilized for the vertical component, and the ZMP criterion is employed for the horizontal component. Therefore, the method ensures the creation of efficient elastic potential energy storage/release cycles, while

the dynamic balance criterion is concurrently met. What is more, initial conditions are tuned in a way to generate feasible jumping patterns, making the proposed method systematic and easy-to-apply for real-time applications. Finally, translational and angular momenta constraints are used to obtain joint angles in which the rotational inertia is characterized.

Even though we make use of the passive compliance at the joint level, one may use any other passively compliant structure -such as a limb [21]- to generate vertical CoM trajectories as long as the corresponding resonance frequency is physically realizable. In this context, using passive compliance at the joint level enabled us to measure and compute deflection and potential energy variations. Therefore, the performance can be evaluated in a convenient way.

Implementing the proposed method, we conducted a set of periodic forward hopping experiments using our passively compliant bipedal robot. As a result, we obtained repetitive, continuous and dynamically equilibrated forward jumping cycles with successful landing phases. Up to our knowledge, this paper presents one of the first jumping experiments through the utilization of resonance frequency, conducted on a fully actuated and passively compliant 3D bipedal robot. It also reports a novel trajectory generator in which the vertical CoM trajectory is analytically derived for the hopping pattern generation task.

In our future work, we are planning to utilize series elastic actuators in all the robot joints. That being said, we will generalize the proposed technique for 3D bipedal running upon the hardware reconfiguration. Hence, our next report will be about efficient bipedal running in which the base resonance frequency is exploited.

ACKNOWLEDGEMENTS

This work is supported by the European Commission FP7, "AMARSi" project ICT-248311. The authors would like to thank Gianluca Pane, Phil Hudson, and IIT Advanced Robotics team engineers for their continuous support and assistance. This work was completed while Barkan Ugurlu and Stephen Morfey were with the Department of Advanced Robotics, Istituto Italiano di Tecnologia, Genova, Italy.

REFERENCES

- [1] J. Jin, S. L. Yuen, Y. H. Lee, C. Jun, Y. B. Kim, S. Lee, B.-J. You, and N. L. Doh, "Minimal grasper: A practical robotic grasper with robust performance for pick and place tasks", in *IEEE Trans. on Industrial Electronics*, vol. 60, no. 9, 2013, pp. 3796-3805.
- [2] Y. Hong, C. Park, and J. Kim, "Stable bipedal walking with a vertical center of mass motion by an evolutionary optimized central pattern generator", in *IEEE Trans. on Industrial Electronics*, vol. 61, no. 5, 2014, pp. 2346-2355.
- [3] S. Shimmyo, T. Sato, and K. Ohnishi, "Biped walking pattern generation by using preview control based on three-mass model", in *IEEE Trans. on Industrial Electronics*, vol. 60, no. 11, 2013, pp. 5137-5147.
- [4] B. Ugurlu, and A. Kawamura, "ZMP-based online jumping pattern generation for a one-legged robot", in *IEEE Trans. on Industrial Electronics*, vol. 57, no. 5, 2010, pp. 1701-1709.
- [5] B. Ugurlu, and A. Kawamura, "On the backwards problem of legged robots", in *IEEE Trans. on Industrial Electronics*, vol. 61, no. 3, 2014, pp. 1632-1634.
- [6] T. Sugihara, and Y. Nakamura, "Enhancement of boundary condition relaxation method for 3D hopping motion planning of biped robots", in *Proc. IEEE Conf. on Intelligent Robots and Systems*, San Diego, US, 2007, pp. 444-449.
- [7] T. J. Roberts, R. L. Marsh, P. G. Weyand and C. R. Taylor, "Muscular force in running turkeys: The economy of minimizing work" in *Science*, vol. 275, no. 5303, 1997, pp. 1113-1115.
- [8] M. Ishikawa, P. V. Komi, M. J. Grey, V. Lepola and G. P. Bruggemann, "Muscle-tendon interaction and elastic energy usage in human walking" in *Journal of Appl. Physiology*, vol. 99, no. 2, 2005, pp. 603-608.
- [9] A. Seyfarth, H. Geyer, M. Gunther, and R. Blickhan, "A movement criterion for running," in *Journal of Biomechanics*, vol. 35, no. 5, 2002, pp. 649-655.
- [10] R. Blickhan, "The spring-mass model for running and hopping," in *Journal of Biomechanics*, vol. 22, no. 11-12, 1989, pp. 1217-1227.
- [11] J. Buchli, and A. J. Ijspeert, "Self-organized adaptive legged locomotion in a compliant quadruped robot," in *Autonomous Robots*, vol. 25, no.4, 2008, pp. 331-347.
- [12] B. Ugurlu, N. G. Tsagarakis, E. Spyarakos-Papastravridis, and D. G. Caldwell, "Compliant joint modification and real-time dynamic walking implementation on bipedal robot cCub," in *Proc. of IEEE Int. Conf. on Mechatronics*, Istanbul, Turkey, 2011.
- [13] A. Soltoggio, and J. J. Steil, "How rich motor skills empower robots at last: Insights and progress of the AMARSi project," in *Kunstliche Intelligenz*, vol. 26, no.4, 2012, pp. 407-410.
- [14] M. H. Raibert, H. B. Brown Jr., and M. Chepponis, "Experiments in balance with a 3D one-legged hopping machine," in *Int. Journal of Robotics Research*, vol. 3, no. 2, 1984, pp. 75-92.
- [15] M. Ahmadi, and M. Buehler, "Controlled passive dynamic running experiments with the ARL-Monopod II," in *IEEE Trans. on Robotics*, vol. 22, no. 5, 2006, pp. 974-986.
- [16] F. Xu, and A. Kawamura, "3-D Simulation study concerning a one legged jumping robot with force control," in *Proc. Japan Ins. of Electrical Eng., Tech. Meeting on Industrial Instrumentation and Control*, IIC-08-70, Tokyo, Japan, 2008, pp. 7-12, (in Japanese).
- [17] C. Ott, M. Roa, and G. Hirzinger, "Posture and balance control for biped robots based on contact force optimization," in *Proc. of IEEE Int. Conf. on Humanoid Robotics*, Bled, Slovenia, 2011, pp. 26-33.
- [18] B. Ugurlu, T. Kawasaki, M. Kawanishi, and T. Narikiyo, "Continuous and dynamically equilibrated one-legged running experiments: Motion generation and indirect force feedback control", in *Proc. of IEEE Conf. on Intelligent Robots and Systems*, Algarve, Portugal, 2012, pp. 1846-1852.
- [19] S. Hyon, "Compliant terrain adaptation for biped humanoids without measuring ground surface and contact forces," in *IEEE Trans. on Robotics*, vol. 25, no.1, 2009, pp. 171-178.
- [20] M. Zinn, O. Khatib, B. Roth, and J. Salisbury, "Playing it safe [human friendly robots]," in *IEEE Robotics and Automation Magazine*, vol. 11, no. 2, 2004, pp. 12-21.
- [21] X. Yu, and F. Iida, "Minimalistic models of an energy-efficient vertical-hopping robot," in *IEEE Trans. on Industrial Electronics*, vol. 61, no.2, 2014, pp. 1053-1062.
- [22] B. Vanderborght, R. Van Ham, B. Verrelst, M. Van Damme, and D. Lefeber, "Overview of the Lucy project: Dynamic stabilization of a biped powered by pneumatic artificial muscles," in *Advanced Robotics*, vol. 22, no. 10, 2008, pp. 1027-1051.
- [23] K. Hosoda, T. Takuma, A. Nakamoto, and S. Hayashi, "Biped robot design by antagonistic pneumatic actuators for multi-modal locomotion," in *Robotics and Autonomous Systems*, vol. 56, no. 1, 2008, pp. 46-53.
- [24] R. Van Ham, T. G. Sugar, B. Vanderborght, K. W. Hollander, and D. Lefeber, "Compliant actuator designs," in *IEEE Robotics and Automation Magazine*, vol. 16, no. 3, 2009, pp. 81-94.
- [25] M. Laffranchi, N. G. Tsagarakis, F. Cannella, and D. G. Caldwell, "Antagonistic and series elastic actuators: A comparative analysis on the energy consumption," in *Proc. of IEEE Conf. on Intelligent Robots and Systems*, St. Louis, US, 2009, pp. 5678-5684.
- [26] N. G. Tsagarakis, M. Laffranchi, B. Vanderborght, and D. G. Caldwell, "A compact soft actuator unit for small scale human friendly robots," in *Proc. of IEEE Conf. on Robotics and Automation*, Kobe, Japan, 2009, pp. 4356-4362.
- [27] B. Ugurlu, J. A. Saglia, N. G. Tsagarakis, and D. G. Caldwell, "Hopping at the resonance frequency: A trajectory generation technique for bipedal robots with elastic joints", in *Proc. IEEE Conf. on Robotics and Automation*, St. Paul, US, 2012, pp. 1436-1443.
- [28] M. Spong, "Modeling and control of elastic joint robots," in *ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 109, no. 4, 1987, pp. 310-318.
- [29] T. Murakami, F. Yu and K. Ohnishi, "Torque sensorless control in multidegree-of-freedom manipulator", in *IEEE Trans. on Industrial Electronics*, vol. 40, no. 2, 1993, pp. 259-265.

- [30] F. L. Moro, N. G. Tsagarakis, and D. G. Caldwell, "Walking in the Resonance with the COMAN Robot with Trajectories based on Human Kinematic Motion Primitives (kMPs)", in *Autonomous Robots*, 2013, Forthcoming article.
- [31] F. Ghorbel, and R. Gunawardana, "A uniform bound for the Jacobian of the gravitational force vector for a class of robot manipulators", in *ASME Journal of Systems, Measurement, and Control*, vol. 119, no. 1, 1997, pp. 110-114.
- [32] S. Adhikari, "Damping models for structural vibration," in *Ph.D. dissertation*, Cambridge University, UK, 2000.
- [33] A. H. Hansen, D. S. Childress, S. C. Miff, S. A. Gard, and K. P. Mesplay, "The human ankle during walking: implications for design of biomimetic ankle prostheses," in *Journal of Biomechanics*, vol. 37, no. 10, 2004, pp. 1467-1474.



Barkan Ugurlu (S'08-M'10) received his Ph.D. degree in Electrical and Computer Engineering from Yokohama National University, Japan, in March 2010, with the MEXT scholarship granted by Japan, Ministry of Education, Culture, Sports and Technology. From May 2010 to March 2013, he was a Postdoctoral Researcher, respectively at the Istituto Italiano di Tecnologia, Genova, Italy, and Toyota Technological Institute, Nagoya, Japan. At present, he holds a Research Scientist position at Computational Neuroscience Laboratories of Advanced

Telecommunications Research Institute International (ATR), Kyoto, Japan. He was nominated for a Best Paper award at IROS 2009. His research interests are biological sensorimotor control and motor recovery, active orthoses and exoskeletons, robot-aided rehabilitation, humanoid/quadruped locomotion control and multibody dynamics, force and compliance control.



Jody A. Saglia (S'09-M'10) received his Ph.D. degree in Mechanical Engineering from King's College London, UK, in 2010. Since 2007, he has been a researcher at the Istituto Italiano di Tecnologia, Genova, Italy, working on the design and control of rehabilitation robots for lower limbs. His research interests include rehabilitation robotics, mechatronic design, actuation systems and human-robot interaction. He is also particularly interested in all aspects of the transfer of robotic technologies to the market. He received the Professional Engineering Publishing

Award from the Journal of Systems and Control Engineering in 2009.



Nikos G. Tsagarakis (S'98-M'01) received his Ph.D. in Robotics, from the University of Salford, UK, in 2000. Upon receiving his Ph.D., he was a Research Fellow and then a Senior Research Fellow in the Centre for Robotics and Automation at the University of Salford, UK, where he worked on haptic systems, wearable exoskeletons, rehabilitation robots and humanoids robots. Since 2005, he has been holding a Senior Researcher position at the Istituto Italiano di Tecnologia, Genova, Italy, with the overall responsibility of Humanoid design & Human Centered Mechatronics development. His research interests are humanoid robots, mechanism design, compliant and variable impedance actuators, human-centered/friendly mechatronics (intrinsically soft robotic arm/leg systems and wearable robotics for power augmentation), haptic systems, force and tactile sensing. He is the author/co-author of over 150 papers in research journals and at international conferences, and he has 6 patents. He has received the 2009 Professional Engineering Publishing Award from the Journal of Systems and Control Engineering and prizes for Best Paper at ICAR (2003). He was also a finalist for Best Entertainment Robots and Systems - 20th Anniversary Award at IROS 2007 and finalist for the Best Manipulation Paper at ICRA 2012 and Best Paper at Humanoids 2012. Since 2013, he is also serving as a Visiting Professor at the Centre for Robotics Research (CORE), Department of Informatics, Kings College University, London, UK.



Stephen Morfe (M'13) received a masters degree in Mechanical Engineering with Mechatronics from the University of Newcastle-upon-Tyne, UK, in 2005. After his degree, he worked at the Shadow Robot Company designing humanoid robotic hands. Following this, he spent several years in a UK startup company developing medical robots to assist with neurosurgery, orthopaedic surgery and laparoscopy. From 2010 to 2013, he was a Research Technologist at the Istituto Italiano di Tecnologia, Genova, Italy, where he designed the child-sized compliant humanoid robot, COMAN. He also developed a novel robotic joint actuator with large and adjustable energy storage capacity for high-power, high-efficiency locomotion. He is currently a Research Engineer at SRI International, where he is developing high-performance, high-efficiency humanoids and low-cost robotic arms. His professional interests include humanoid/legged robots, novel high-efficiency and high-performance robotic actuation, sensor design, dextrous hand design and medical robotics.



Darwin G. Caldwell (S'89-M'92) received his Ph.D. in Robotics from the University of Hull, UK, in 1990. From 1989 to 2006, he was at the University of Salford, UK, as a Lecturer (1989-96), Senior Lecturer (1996-97), Reader (1997-99) and finally Professor of Advanced Robotics in the Centre for Robotics and Automation (1999-2006). Currently, Prof. Caldwell is a Director at the Istituto Italiano di Tecnologia, in Genova, Italy, and a Honorary Professor at the Universities of Sheffield, Manchester, Bangor, King's College London, UK, and in

Tianjin University, China. His research interests include innovative actuators, humanoid and quadrupedal robotics and locomotion (iCub, HyQ and CoMan), haptics, exoskeletons, dexterous manipulators, medical robotics. He is the author or co-author of over 400 academic papers, 15 patents and has received awards from several international journals and conferences. He is an associate editor for the IEEE Trans. on Mechatronics and on the editorial board of the International Journal of Social Robotics and Industrial Robot.