A Mechatronic Analysis and Synthesis of Human Walking Gait

Luis I. Lugo-Villeda*, Antonio Frisoli, Oscar O. Sandoval González, and Massimo Bergamasco
Perceptual Robotics - PERCRO
Scuola Superiore Sant’Anna
Pisa, Italy, Via Martiri della Libertà 33,56127,
Email: {l.lugovilleda,a.frisoli,o.sandovalgonzalez}@sssup.it

Vicente Parra-Vega
Robotics and Advanced Manufacturing Division,
Research Center for Advanced Studies Saltillo Campus
CINVESTAV Carretera Saltillo-Monterrey Km 1.5 - CP 25000
- Ramos Arizpe, Coahuila, Mexico
Email: vparra@cinvestav.mx

Abstract—Human walking gait (HWG) involves concurrently complex aspects of control, signal conditioning and processing, motion capture and biomechanical analysis as well as biomedical instrumentation and robot control. To merge some of these concepts into a unique framework, in this paper, a computational mechatronics scheme is proposed for the analysis and synthesis of HWG based on a seven-link sagittal rigid dynamical biped robot in closed-loop with an advanced force/position/velocity model-free position-force controller. Desired trajectories come from real human motion data: Lower-limbs walking gaits kinematic patterns are captured with a human motion Vicon ® tracker system, including landing point, and impact (ground reaction) forces are obtained from femur/tibial muscles via EMG. A criteria is established to map such signals into a 7 DoF workspace of the dynamical biped robot. Fast dynamical tracking is achieved under real HWG patterns, which provides greater insight into the design and control process of humanoid robotic biped locomotion.

I. INTRODUCTION

Biped locomotion constitutes a complex interdisciplinary problem, which has attracted lot of attention over the last two decades in several research areas, such as robotics, mechatronics, biomechanics, neurosciences, bioelectronics, applied nonlinear control and virtual reality, which have contributed with basic understanding on this subject. There is a vast literature on those research areas, which covers several fundamental aspects, unfortunately disconnected from one to the other. The intrinsic nature of biped locomotion tightly couples human walking gait patters to biped robots, however few studies offer dynamical closed-loop analysis of real HWG patters into robotic biped locomotion. Since biped robot locomotion basically aims to mimic biped humanoid walking, it is desirable to further understand the closed-loop behavior of dynamical biped robots while tracking real HWG patters, including ground reaction forces (GRF). In this paper, it is argued that a mechatronic scheme provides further insight and tools to merge several concepts and ideas in a synergetic scheme so as to yield some ideas previously proposed for one area but not well understood for another area. In particular, in this paper it is argued that a mechatronics approach allows to introduce human natural locomotion analysis into a dynamic setting to produce an advanced human-like walking gait for biped robots, useful for better understanding and design of biped robots. To this end, a 7 DoF constrained dynamical sagittal robot is considered to track real HWG trajectories. Vicon® kinematic signals are mapped properly from 3D space into the 2D sagittal plane to produce admissible desired position and velocities trajectories, while EMG magnitude and its time activation analysis provides desired GRF for each limb. HWG and EMG input data fit into sagittal seven-link biped dynamical robot model as desired position and force trajectories to render accurately a realistic AWG1 in a highly nonlinear constrained dynamics of seven-link sagittal biped robot. To successfully track these signals, a very fast tracking position/force controller is proposed, which provides very good transient response. Furthermore, to guarantee tracking in the time axis too, not only in the spatial coordinates, a time-base generator is introduced to guarantee exact tracking in time and space domains. This controller accounts explicitly for all dynamic internal and external forces, as well as mechanical impedance of the swing leg when touching the ground, those reproducing dynamically the desired trajectories to make walking realistically the biped robot model.

A. Organization

The general concept of applied computational mechatronics to the sagittal biped robot is given in Section II. Section III shows the nonlinear dynamical equations of the sagittal biped robot which is used as test bed. EMG analysis and procedure for getting amplitude of exerted force and time activation are given in Section IV. The synchronized VICON® data and the EMG-based measurements are presented in Section V. Fast and robust force/position controller with time finite convergence is given in Section VI, including simulations in Section VII. Finally conclusions are presented into last Section VIII.

This work is partially supported by Skills-IP project and Scuola Superiore Sant’Anna. *Main author acknowledges support from CONACyT Mexico the research grant No. 165889.

1 Artificial Walking Gait.
II. COMPUTATIONAL MECHATRONICS-BASED SCHEME

A. Background

Dynamic and passive biped walking concepts are well understood nowadays to reproduce biped locomotion on simple robots in the sagittal plane, subject to rather stringent assumptions, there exists some fundamental papers on analysis and modeling of biped locomotion in 2D and 3D spaces see for instance [16], [6], among others. However, Despite new technology on sensors, motors and processing units, and a better understanding on analysis, synthesis and design of biped robots, human-based walking locomotion or humanoid biped systems remains elusive. Because, basically, the robot control research community focus mainly on modeling and control issues of biped trajectories, not necessarily modeled after HWG trajectories, while human walking locomotion patterns are studied more by the computers science, bioengineering and neuroscience research communities, mainly in virtual reality or open loop applications, [17], [11].

In some cases, the biped robot is modeled after Ordinary Differential Equations, it means that the applied classic formulation of Euler-Lagrange can be viewed as a nonlinear energy balance equations, which contains high nonlinear couplings and inertial/gyroscopic interactions among joints and links, even environmental normal and tangent forces has been modeled via ODE formulation, [20]. For ODE models, even linear conventional controllers or nonlinear controllers can be implemented to guarantee stable walking, as well as control of impact dynamics at leg interchange times [7], [15]. However, when there exists unilateral constraints, in this case foot on the floor, Differential Algebraic Equations are more suitable to model the energy balance, according to the variational principle of Euler Lagrange constrained dynamics. In this paper, we focus on DAE model and control of humanoid biped locomotion using real human biped locomotion trajectories, which are extracted using HWG, for position/velocities, and EMG, for contact force. It is modeled the human lower-part, which includes reaction external forces, coriolis effects, inertia parameters, discontinuous phases switching, on the assumption of frictionless contact (there is not slipping).

B. Computational Mechatronics Scheme

Since human locomotion is a quite complex process in 3D, we surmise that accurate data for the 2D sagittal model is by applying the synergetic integration of several disciplines, within the mechatronics paradigm, rather than working on it using isolated knowledge from one research area. The main problem concerned with it, is to decompose the problem properly to apply a computational-based mechatronics scheme, as shown by Figure 1. To this end, the analysis for human walking locomotion is worked out as a complex constrained DAE model (Differential-Algebraic-Equation), [14], of seven-link biped robot in either non-free or free motion depending on walking-phase gait. Afterwards, due the commuting of gait phases and the EMG amplitude as well as activation time, it is required a fast and robust controller to guarantee simultaneous tracking on force as well as position, with negligible transient. The stability of AWG and its behavior of all involved elements depend on each factor of the proposed scheme of figure 1. In order to analyze and fit the HWG and EMG-based force measurements onto computational seven-link sagittal biped robot, applied computational mechatronics scheme is shown in figure 2.

Fig. 1. Computational Mechatronics Scheme

Fig. 2. General mechatronics scheme including the human-data as input

As we can see, the input of the DAE equation through the nonlinear controller are the tri-dimensional HWG data \( q_d \in \mathbb{R}^7 \) recorded by the Vicon® system. The EMG raw signals come from the electrodes located at triceps surae and hamstring in order to measure the EMG activity, thereafter those signals are processed to determine the exerted force and its time activation. Information processing blocks compute the continuous tracking desired force \( \lambda_d \in \mathbb{R} \), with \( \lambda_d \in \mathbb{C}^1 \), and the numerical derivative of articular coordinates \( q_d \in \mathbb{R}^7 \), to produce the desired velocity profile. The DAE system must
track precisely $q_d \in \mathbb{R}^7$, $\lambda_d \in \mathbb{R}$, with $\lambda_d \in \mathbb{C}^1$, and $\dot{q}_d \in \mathbb{R}^7$ to reproduce HWG.

III. DYNAMIC MODEL OF PLANAR BIPED ROBOT

Consider a planar fully actuated seven rigid link biped robot walking, interconnected by massless revolute joints, in the 2-dimensional vertical space, as shown in Fig. 3.

Similar to [3], single-support-phase (SSP) is assumed to yield three main elements: stance leg, swing leg and rigid pelvis, interconnected at pelvis coordinates $X_h \in \mathbb{R}^2$. Both legs are composed by three rigid links, that is foot, tibia and femur, whose physical parameters are mass, center of gravity and length. According to Lagrange modeling formalism for human walking motion analysis. Therefore, the acquisition of different parameters like force level, fatigue, time activation and position of the muscles represent a useful tool to carry out different analysis. The EMG acquisition hardware used to find out the effort and forces consists of electrodes, preamplifiers, filters, amplifiers with bias adjustment and 16 bits A/D converter at 4Khz. Normally, when a muscle is contracted during HWG, the electrode picks up EMG signal, afterwards, a contact line while the GRF point is translating from the heel to its toe. In this case, we can assume that the contact line, which occurs in the frontal view, in turns is a contact point in the sagittal view. Thus, the general equation of the constraint describes the following holonomic constraint,

$$\phi(x, y, z) \triangleq \varphi(q) = 0$$

where $\varphi(q) \in \mathbb{R}$, and $\varphi(q) \in \mathbb{C}^2$. Differentiating (2), we obtain the following,

$$J_\varphi(q)\dot{q} = 0 \rightarrow J_\varphi(q)\dot{q} + J_\varphi(q)\dot{q} = 0$$

Notice that the dot product of vectors $J_\varphi(q)$ and $\dot{q}$ is zero, so they belong to orthogonal complements each other. Further physical interpretation of (3) suggests that the velocity vector arises onto the tangent space at the contact point to the surface $\varphi(q) = Ax + Bx + Cz - D \triangleq 0$, and therefore $J_\varphi(q)$ maps onto the normal subspace at the contact point. This fact is very useful to design energetically stable force controllers for robot manipulators, and it is known as the Orthogonalization Principle [1]. In our case, we will propose a force controller to achieve tracking of GRF. On the another hand, the stance leg heel $X_f \in \mathbb{R}$ moves on $x-axes$, from the heel, passing to zero moment point (ZMP) [9], [18], [8], arriving to foot rotation indicator (FRI) [5]. In this way, there arise a kinematically stable walking, see Figure 4.

IV. LOWER-LIMBS EMG-BASED COMPUTED FORCE

Bio-signals provide information about the behavior of the human body when is performing a certain action. Unquestionably, the muscles give the most valuable data regarding to human walking motion analysis. Therefore, the acquisition of different parameters like force level, fatigue, time activation and position of the muscles represent a useful tool to carry out different analysis. The EMG acquisition hardware used to find out the effort and forces consists of electrodes, preamplifiers, filters, amplifiers with bias adjustment and 16 bits A/D converter at 4Khz. Normally, when a muscle is contracted during HWG, the electrode picks up EMG signal, afterwards, the preamplifier amplifies at TTL voltage levels and filters the signals in order to prevent electrical interference and sensitivity to noise. Finally, the A/D converter converts signals into digital form. The bipolar surface electrodes Ag/AgCl (models DS02, DS03, DS04, DS26 and GS27), from Biomedical© company has been used.
A. Muscle Activity Detection and Noise Reduction by Using Wavelets

The estimation of on-off timing of human skeletal muscles has an important role in the walking analysis, which is typically carried out with EMG, however EMG signals are subject to noise, then it is essential to apply special methodologies for the correct extraction of the muscle activity detection information. There are different techniques referred to as "single-threshold methods," [19], which are based on the comparison of the rectified raw signals and an amplitude threshold whose value depends on the mean power of the background noise. Another method is known as "double threshold method," [2], based on noise level and time of activation.

In [10], it is performed a three level of decomposition using a db3 wavelet decomposition, at level 3, that is for level 1 to 3 it is selected a threshold and applied a soft thresholding to the detailed coefficients. In our case, it is performed a wavelet reconstruction using the original approximation coefficients of level 3 and the modified detailed coefficients of levels from 1 to 3. The de-noised signal is rectified in order to envelope it experienced by the swing leg when it is landing represents the desired force to be tracked by a fast and robust position/force controller of the biped robot.

V. DATA ACQUISITION FROM VICON® SYSTEM AND EMG-BASED FORCE ANALYSIS

An experiment interfacing the Vicon® System and the EMG signals is performed for the walking analysis. The aim was to obtain the response and activation of 4 muscles of the legs in the precise time and position along the movement. The electrodes are located in the Hamstring, Quadriceps, Triceps Surae and Tibialis. To obtain correlated results, position in the space of the legs (acquired by the Vicon® System) and the EMG signals are synchronized, see figure 7. Figure 8 shows the response of the four muscles during a walking cycle, wherein Wavelets de-noising methodologies are applied to reduce noise level of the signals. It is assumed that the force experienced by the swing leg when it is landing represents the desired force to be tracked by a fast and robust position/force controller of the biped robot.

VI. DYNAMIC PD SLIDING FORCE/POSITION FOR STABLE WALKING

Now, for carrying out the tracking of the HWG-EMG data, we consider the sliding PD controller [13], it is given in original coordinates as,

\[
\tau = -K_d S + \frac{J_T^2}{||J_T^2, J_p||} \left\{ -\lambda_d + \eta F_F + \gamma_2 \tanh(S_{q_F}) \right\}
+ \eta_2 \int_0^t \text{sgn}(S_{q_F})(\zeta) d\zeta
\]  

(4)
where position and velocity errors are given by $\Delta_q = q - q_d$ and $\dot{\Delta}_q = \dot{q} - \dot{q}_d$, respectively, with $\Delta_F = \int_{t_0}^{t} (\lambda - \lambda_d)(\xi) d\xi$ as the force tracking error. Positive feedback gains are defined as $\eta, \gamma_1, \gamma_2 \in \mathbb{R}^{2d} \in \mathbb{C}^2$ and $\lambda_d(t) \in \mathbb{C}^2$ are the desired references for position and force respectively, $sgn(\cdot)$ represents the signum function of the its vector argument. The orthogonal manifold sliding surface of position/force $S$ is defined as,

$$S = Q(q)S_{vp} - \beta \frac{J^T}{|J^T|}S_{vF}$$

where each attractive stable manifold of the extended orthogonal position and force $S_{vp}$ and $S_{vF}$ are written as follows

$$S_{vp} = S_{qF} + \int_{t_0}^{t} sgn(S_{qF})(\xi) d\xi$$

$$S_{vF} = S_{qF} + \int_{t_0}^{t} sgn(S_{qF})(\xi) d\xi$$

where

$$S_{qF} = S_p - S_{dp}, S_p = \Delta_q + \alpha(t)\Delta_q$$

$$S_{dp} = S_p(t_0)e^{-\rho(\tau-t_0)}$$

$$S_{qF} = S_F - S_{dp}, S_F = \Delta_F$$

$$S_{dp} = S_F(t_0)e^{-\eta(\tau-t_0)}$$

with $\rho_0, \eta$ as positive constant values.

**Proof.** It is based on Lyapunov stability analysis to prove that all closed-loop signals are bounded, then Variable Structure Control arguments are used to prove the existence of sliding modes for position/velocity and force tracking errors simultaneously, thus exponential tracking is achieved, with robust performance, because second order sliding modes are verified. The proof depends strongly on the properties of analysis of (1), such as $\left|H(q)\right| \geq \lambda_{Min}(H(q)) > 0, \left|H(q)\right| \leq \lambda_{Max}(H(q)) < \infty, \left|C(q)\right| \leq \beta_2 \left|q\right|, \left|G(q)\right| \leq \beta_3 < \infty, \left|B_0\right| \leq \beta_4 > 0, A_1 = I_{n_1}, \left|D\right| \leq \beta_5 < \infty$ where $\lambda_{Max}(E) \leq \beta_5 < \infty, \lambda_{Min}(E) \geq \beta_1 > 0$ are the maximum a minimum eigenvalues of $E \in \mathbb{R}^{n \times n}$.

**Remark 6.1.** The controller given in (4) is very fast and robust against perturbations and slow sample rate, it is capable to track the desired trajectory and conserves the same properties and response onto the two invariant manifolds of force and position previously defined. Whatever arbitrary desired trajectories or real ones, this controller exhibits robustness and fast response without relying on a given Euler Lagrange model, which is particularly important for biped robots, because usually the resulting final walking robots are so complex that the exact dynamical model is not available, for this reason it is important to use model-free passivity-based controllers.

**Remark 6.2.** It is necessary to choose adequate feedback gains to achieve fast convergence of each sliding surface, $\eta, \gamma_1, \gamma_2, \beta, \alpha_0 \in \mathbb{R}$, while satisfying the geometrical constraint $\varphi(q) = 0$. It is important then that desired trajectories be smooth, which needs to be verified for real data at each walking cycle.

Finally, walking gait requires a fast controller with high bandwidth, normally the dynamic response of (1) depends on the desired trajectory, thus to enhance its performance, finite time convergence (FTC) is desirable, it means that in the phase-portrait, feedback gain $\alpha(t)$ is time-dependent to reach finite time convergence independently of the sliding condition$^4$.

### A. Time Base Generator $\xi(t)$ to Control Exactly the Landing and Departure Time of Swing and Stance Leg

The previous result, although it enforces exponential convergence (a much better and faster convergence regime than asymptotic one), cannot guarantee the desired landing nor departure time of swing and stance leg, compromising the full scheme, because the biped robot will walk as long as it follows precisely in time and space the HWG patterns. To achieve this, consider a time base generator (TBG) given in [12]. Let (a(t) be such that $S_p = \Delta_q + \alpha(t)\Delta_q = 0, S_p \to 0$ as $t \to 0$, it is possible if we solve the following first order homogenous time equation,

$$\dot{z} + \alpha(t)z = 0 \Rightarrow \dot{z} = -\alpha(t)z,$$

where

$$\alpha(t) = \alpha_0 \frac{\dot{\xi}}{(1 - \xi)}$$

with $\alpha_0 = 1 + \epsilon, 0 < \epsilon \ll 1$ and $0 < \delta < 1$. The TBG $\xi(t) \in \mathbb{R}^2$ goes smoothly from initial point $\xi(t_0) = 0$ to $\xi(t_b) = 1$ with $t_b$ as time base and $t_0 > 0$. Thus, $\xi(t_0) = \dot{\xi}(t_b)$, under this conditions the solution of (12) is,

$$z(t) = z(t_0)(1 - \xi + \delta)^{1+\epsilon}$$

Finally, notice that $t_b$ is independent of any initial condition and hence

$$\xi(t_b) = 1 \rightarrow z(t_b) = z(t_0)\delta^{1+\epsilon} > 0$$

With the feedback gain $\alpha(t)$ it is possible to enforce fast convergence of each sliding surface at any desired time base $t_b$, where this time means the cycle of each gait, the time when a swing leg becomes the stance leg and viceversa. In this way, we can handle properly the commuting of dynamics and controllers, avoiding the numerical and dynamical problems introduced because of commuting.

### VII. Numerical Simulations

We take into account a seven-link biped robot whose physical parameters are approximately computed by using anthropometric data of a real human, such that these parameters are going to be implemented on the DAE system. Applying the sliding PD controller previously defined with a period gait cycle of 8 sec we use the VICON®-EMG data as desired position/force profiles. Considering the total mass of a 80 Kg, next figures 9-10 show the actual AWG as well as the GFR in one leg at the commuting process: swing leg and stance leg. Notice that when the swing leg lands to the holonomic constraint and passes from initial contact point to FRI, the

$^4$If we are using human walking patterns, it is possible to know precisely the time base of the FTC algorithm.
interacting force starts increasing up to 113% of the total weight during the stance leg phase, the normal average landing transition force of a human is among 110-120 percent of its total weight.

VIII. Conclusions

The contribution of this paper is three fold: First, based on a constrained full nonlinear biped DAE seven-link biped robot model, a model-free decentralized controller is proposed, which guarantees robustness and finite time convergence in position as well as in velocity, with exponential tracking of force trajectories. This controller ensures fast and robust tracking of desired stable walking gait patters, coming from reconditioned real data of human walking gait. A time-based generator is introduced to enforce precise, in time and space, tracking of position and force trajectories. Secondly, a computational mechatronics platform merges seemingly signals usually analyzed in different and independent domains. Thirdly, EMG and VICON® signals are synthesized to produce 2D human walking gait (HWG) patters, which can be used as desired patterns for force/position control of biped robots. The complete result is a realistic simulator thanks to introduced mechatronics philosophy, which handle even transitions based on a complete procedure for stabilizing constrained systems.

References