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Dynamics and energy recovery of a walking mechanism

Elvedin Kljuno *, Alan Catovic, Marin Petrovic

Mechanical Engineering Faculty, University of Sarajevo, Sarajevo, Bosnia and Herzegovina

A B S T R A C T

Nonlinearity and discontinuity in walking robot dynamics represent a challenge to find adequate control strategies. Walking mechanisms include combined open and closed mechanical chains (loops) consisted of (theoretically) rigid segments. These mechanisms have a relatively high number of degrees of freedom (DOF), which causes that dynamics are represented by complicated differential equations. Complexity is largely expanded if we consider the elasticity of materials within the walking mechanism. Unless we significantly simplify the model of walking mechanism dynamics, model-based controller implementation would require significant computational capacities embedded into the hardware. This paper presents dynamics modeling, controller design, and mechanical energy analysis of a walking robot with elastic strings. The paper shows how to analyze the capability of the walking mechanism with elastic elements to reuse mechanical energy throughout the walking cycle. Energy Recovery Ratio is an efficiency measure that is conceptually adopted from biology. The novelty introduced here is represented by a generalization of the parameter and the analysis to cover non-steady walk with interchanged accelerations and decelerations. The paper shows an analysis of the way biological walkers store and reuse energy cyclically during every step. The walking robot architecture with elastic strings mimics the biological architecture to a certain extent. Based on the kinematic and dynamic analysis of the robot, the mathematical model is formed, which is then used for the controller design implemented in hardware.

1. Introduction

Mechanical work done by actuators in robotic walking mechanisms depends on the control algorithm applied, and the way the robot recovers energy from a step to step. By studying biological walking mechanisms, it has been found that a large portion of kinetic energy gets recovered through a step transition phase of walking cycles (Cavagna et al., 1977; Reilly et al., 2007). A parameter that shows how much potential energy gets accumulated and stored in tendons is the recovery ratio defined as:

$$\text{Recovery ratio} = \frac{K_V + P + K_F - W_{ext}^*}{K_V + P + K_F} \tag{1}$$

where are:

$$K_V = \sum_{i=1}^{n} \frac{1}{2}\left(1 + \text{sign}(\Delta E_{K,V,i})\right)\Delta E_{K,V,i}, \tag{2}$$

$$P = \sum_{i=1}^{n} \frac{1}{2}\left(1 + \text{sign}(\Delta E_{P,i})\right)\Delta E_{P,i}, \tag{3}$$

$$K_F = \sum_{i=1}^{n} \frac{1}{2}\left(1 + \text{sign}(\Delta E_{K,F,i}^*)\right)\Delta E_{K,F,i}^*. \tag{4}$$

Terms in (1), (2)-(4) denote:

- n is the number of increments of a single step,
- $\Delta E_{K,V_i}$ and $\Delta E_{K,F_i}$ are the increments in kinetic energy associated with the vertical motion and forward motion,
- ΔE_{P_i} is the potential energy increment,
- $W_{ext}^* = \sum_{i=1}^{n} \frac{1}{2}\left(1 + \text{sign}(W_{ext,i})\right)W_{ext,i} - \Delta E_{K,F,cycle}$ is the external work reduced by the quantity of the forward motion kinetic energy change over the walking cycle,
- $\Delta E_{K,F,i}^*$ is the forward motion kinetic energy increment reduced by the corresponding kinetic energy portion related to the acceleration, which can be simplified as $\frac{\Delta E_{K,F,cycle}}{n}$ that represents a uniform distribution of the kinetic energy change over the cycle.

A simplified way to compare performances of robotic walking mechanisms is to use an adjusted parameter that is used to compare biological walkers (Cavagna et al., 1977). The cost of transportation is defined as (Cavagna et al., 1977):

$$Cet = (\text{energy consumed})/(\text{Total weight} \times \text{walking distance}), \tag{5}$$

which is a dimensionless quantity that is convenient to compare the efficiency of biological mechanisms. Although the total energy for biological walkers is measured via oxygen consumption, an analog expression can be used for robotic walkers efficiency comparison, as well. The adjustment of the expression in the case of robotic walkers is related to the total energy calculation using the total work done by actuators of the robot on the walked distance.

Since robotic walkers carry independent energy sources (e.g., batteries), it is essential to optimize energy consumption keeping the capacity of actuators sufficient, such that the walker can satisfy the performance requirements regarding accelerations, weight carrying, and ground inclinations.

Minimization of energy consumption results in a reduction of the energy source weight. Further on, the reduction of the energy source weight is directly reflected in a reduction in the actuator capacity needed to operate the robot walker. It can be seen that this relationship represents an optimization loop. Reduction of energy consumption can be made in several ways that can be divided into two groups, reduction by optimization of the control strategy and reduction by optimizing the hardware. A good approach to energy optimization is to accept a biomimetic strategy and try to implement hardware that has counterparts in biological walkers, as well as to implement control algorithms that would cause robotic walkers to move similarly as biological walkers.

Conventional robotic manipulators have actuators mounted directly on joint shafts, which leads to heavy distal segments if the same concept is implemented on robotic walkers. Distal segments of a robotic walker are subjected to high accelerations and, consequently, relatively high inertial forces.

Heavy actuators mounted at distal segments, such as legs and arms, cause relatively high energy expenditure due to periodic accelerations and decelerations of additional mass. Therefore, an architectural change in such a way that segments are actuated via actuators located near the nominal center of mass of the robot would lead to a reduction in energy consumption.

Direct drives with gearbox reductors have two main advantages, the hardware is easier to assemble, and the control algorithm is significantly simpler than in the case of distal actuation, but the main advantage of distal actuation is the reduction in energy consumption. Biological walkers that use an inverted pendulum-like mechanism (Cavagna et al., 1977; Umberger and Martin, 2007; Ruina et al., 2005) are considered energy efficient relatively with respect to the state of the robotic art walkers, using a kind of distal actuators, the muscles, which can be considered as elastic (stretchable) linear actuators.

Elasticity in the actuators (tendons) enables biological walkers to temporarily store and recover energy periodically during every step. The energy of foot-ground collisions and kinetic energy of vertical motion are partially converted into potential energy of tendons. Consequently, energy efficiency and the level of the walk cycle precision and smoothness are among important reasons for mimicking biological walkers. As the fundamental actuator unit, muscle behavior and structure attract special attention to research in robotics. There have been a number of attempts to simulate, design and manufacture artificial muscles in robotics (Kljuno et al., 2012; Vanderborght et al., 2008; Aliev et al., 2009), using several principles such as pneumatics, piezoelectric effect, magnetostriction, metallographic change, etc. Optimization in work done by actuators, as far as the walking robot hardware is concerned, can be achieved using muscle-like actuation, elastic strings attached in a convenient way to the robot's distal segments (e.g., a lower leg and a foot). Another aspect that should be considered regarding efficiency is the controller working principle. One of the main requirements of successful controller design is to obtain information about the robot dynamics, which is contained within the mathematical model of the robot.

2. Walking robot dynamics modeling

2.1. Low DOF modeling

A bipedal walking robot that is able to perform walk along an arbitrary path contains 6 degrees of freedom (DOF) per leg. Dynamics analysis leads to lengthy differential equations (Kljuno, 2012) that are inappropriate for use in controller design. This is one of the most important reasons to simplify dynamics and reduce it to a model with a couple of DOFs. Such a model is a mass-spring-damper model with an active element, shown in Fig. 1. The point mass represents the total mass of the robot lumped to the center of gravity. The spring generally has variable stiffness, such that the model can introduce an active element, similarly to muscles, as well as an energy source through variable stiffness of the spring. The dissipation of energy due to collisions is represented by the dashpot. Finally, the torque is given as a means to involve forward accelerations into the analysis. The figure shows the force acting on the lumped mass, which represents the total reaction force from the ground, acting at the center of pressure CP (which is the zero moment point). For a nonzero torque, the CP is not equivalent to the ground contact point GC.

Stiffness of the single spring represents a combined stiffness of one or more legs, such that the force provided by the virtual spring is approximately

equal to the total force from the ground acting on the real system. For a constant stiffness k and a zero torque at the ground contact, the spring-mass inverted pendulum (Farley et al., 1993) is a passive system and cannot represent a real animal's dynamics closely especially if the animal accelerates/decelerates the walking cycle. In such cases, it is necessary to have an active element in the model, which represents a source of energy used to compensate for the energy lost and to accelerate/decelerate the cycle. This fact justifies the inclusion of the torque at the ground foot contact point.
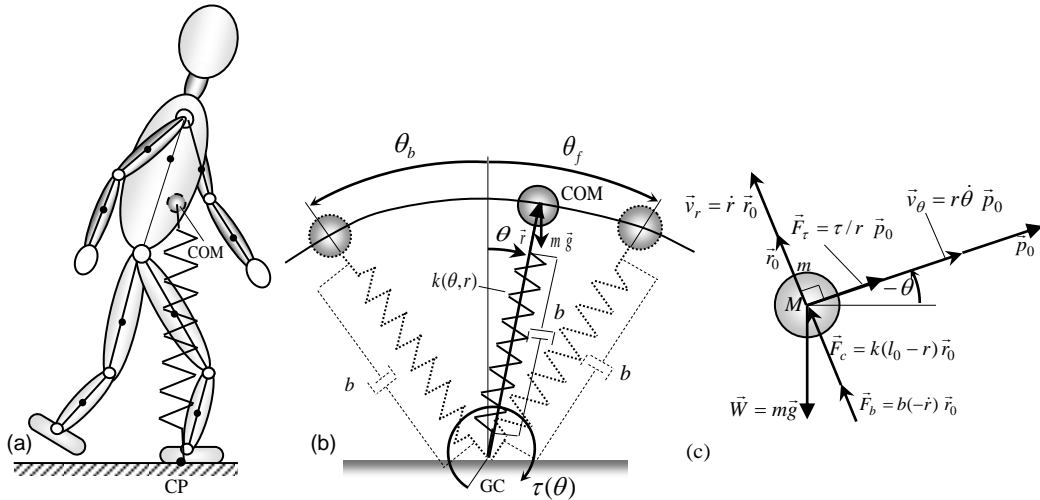

Fig. 1: The mass-spring-damper model as an inverted pendulum indicated on (a) a human body architecture, (b) the mass-spring-damper model and (c) the forces acting on the concentrated mass at the COM

The second reason we included the torque in the model is the fact that the center of pressure CP point is not stationary even during a single support phase, while the ground contact point GC in the model is fixed during a single half-cycle. The equivalent CP in the model can be arbitrarily positioned within a certain area using the contact torque, similarly to the ankle torque in the human body, which can position the CP arbitrarily within the ground-foot contact area. The importance of adding the torque becomes more significant to position the CP for a double (or a multiple support phase in the case of quadrupedals) when the CP location varies within the convex area bounded by the contact area edges of two or more feet, which is a much larger area than just a single foot contact area. The equations of motion for the given model are:

$$\ddot{r} - r\dot{\theta}^2 + g\cos\theta - \frac{k}{m}(l_0 - r) + \frac{b}{m}\dot{r} = 0, \qquad (6)$$

$$r^2\ddot{\theta} + 2r\dot{r}\dot{\theta} - gr\sin(\theta) = \frac{\tau}{m} - \frac{b_\theta}{m}\dot{\theta}. \qquad (7)$$

where, l_0 is the unloaded spring length, b is the dashpot (damper) coefficient, b_θ is the rotational motion dampening coefficient, with other quantities explained earlier.

The model described can be used for motion analysis in the sagittal plane, and the dynamics of motion in the frontal plane should be considered separately. Although the dynamics of the motion in the sagittal and the frontal planes are coupled, the coupling terms can be neglected for the sake of simplicity of equations of motion and for the controller design.

2.2. Full DOF modeling

The dynamics of the walking robot is approximated by the dynamics of the walking robot model. Regularly, walking robots have a relatively high number of joints and, consequently, high DOF. Walking robot models regularly have significantly reduced DOF when compared to DOF of walking robots implemented in hardware. However, to improve the controller performance, a high DOF model needs to be used (Kljuno et al., 2012; Kljuno, 2012). The full biped model architecture consists of 6 DOF per leg (Fig. 2), 3 DOF at the trunk, and 3 DOF per arm.
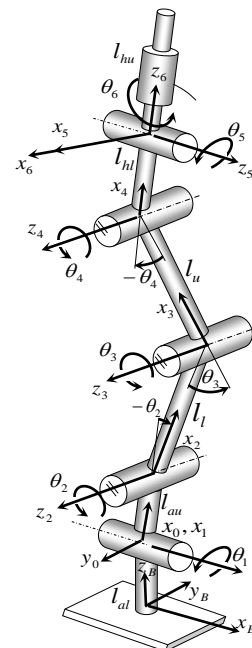

Fig. 2: The 6 DoF leg with coordinate systems assigned

Biological walkers have a physical ball and socket joint at the hip. It is a spherical joint with three DOF. This joint cannot be directly actuated using motors directly attached to joint axes. Robotic ball and socket joints can be implemented in the form of three revolute joints that are apart by additional links. However, the ball and socket joint can be actuated using strings or some sort of special design using dislocated motors (Kljuno et al., 2012). Since the kinematics and dynamics analysis for this robot architecture requires much more space than is allowed for this paper, the mathematical model is not given here, but the analysis can be found in (Kljuno, 2012).
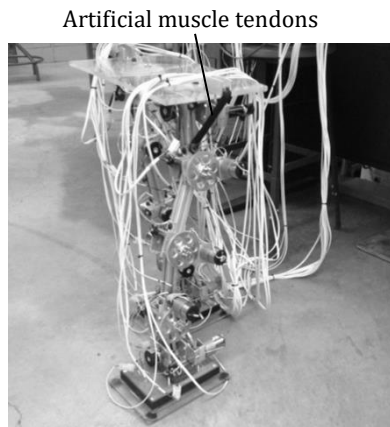
3. Controller Design and Hardware

Since it is difficult to measure precisely energy consumption in biological walkers, it is necessary to design a model and hardware for testing how much energy is reused from a step to the following step. The walking robot hardware and controller architecture are shown in Fig. 3.

Fig. 3: Hardware implementation with artificial "muscle tendons" and the trajectory regulation controller architecture

The controller is consisted of:

a) Nominal joint angles generator,
b) Inverse dynamics for nominal control calculation,
c) Tracking error regulation controller and
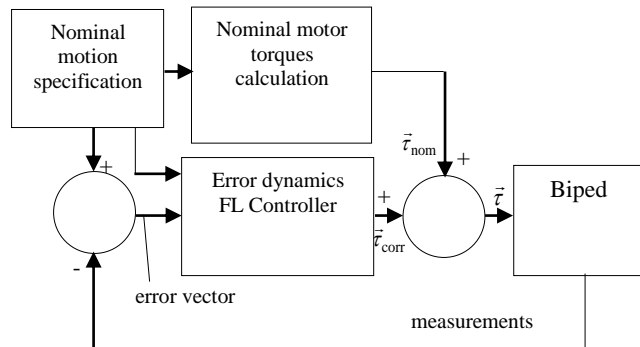d) Measurement system.

The nominal motion specification block generates the joint trajectories that provide a balanced walk. The information about the nominal joint angles at every time-step is sent to the error dynamics controller and the nominal torques generator. The nominal torques are generated based on the inverse dynamics mathematical model. Since the mathematical model of the robot is not an exact description of the dynamic behavior, there are errors in the resulting motion. The amount of the resulting motion deviation from the desired motion is calculated based on the measurements of the joint's angles, which is used by the error dynamics controller to generate the correction torques. The controller showed capabilities of the error reduction and closed following the given nominal trajectories (Kljuno, 2012).

The controller generates the control signal based on the dynamics represented by a model internally in the controller. Nominal functions of torques and forces are predicted using the dynamics model of the bipedal mechanism. After an error is registered by measuring the angles by encoders, the control signal is corrected. These corrected signals are sent to power electronics units (amplifiers), and a corresponding electric current is passed through dc motors generating corresponding motor torques.

Details about the controller and the hardware implementation are given in Kljuno's (2012) study.

4. Energy recovery ratio

Recovery ratio, as explained in the introduction, is one of the essential indicators of walking mechanism efficiency. The mechanical energy of the walking mechanism consists of kinetic and potential energy. In an ideal case of passive walk without losses, the total mechanical energy remains constant. A portion of mechanical energy is lost at every step, mainly due to collisions and internal friction.

Like biological walkers, walking robots need to compensate for the portion of mechanical energy through actuators' activity. Fig. 4 shows the total kinetic and the total potential energy for an accelerating walk and for a decelerating walk.

Using the walking mechanism model, the recovery ratio was predicted for two major groups of walkers: (a) "small" animals (approximately m<5kg) and (b) "larger" animals (m≥5 kg). The model can be applied to robotic walkers that have capabilities to store potential energy, recover it, and convert into kinetic energy at every step, using a kind of elastic tendons. Fig. 5 shows the recovery ratio dependence on an average acceleration over the walking cycle plotted for different walking speeds.

5. Results analysis

The interesting parametric relationship can be obtained by comparing the recovery ratio plots for small (a) and larger (b) walkers. The small walker

recovery ratio is not as much dependent on the acceleration magnitude as the recovery ratio of larger walkers. Although the small walker's recovery ratio is generally lower for the chosen speeds ranges, it is noticeable that the gradient with respect to the acceleration magnitude is significantly higher in absolute value in the case of larger walkers ($tan(\phi_L) > tan(\phi_S)$).
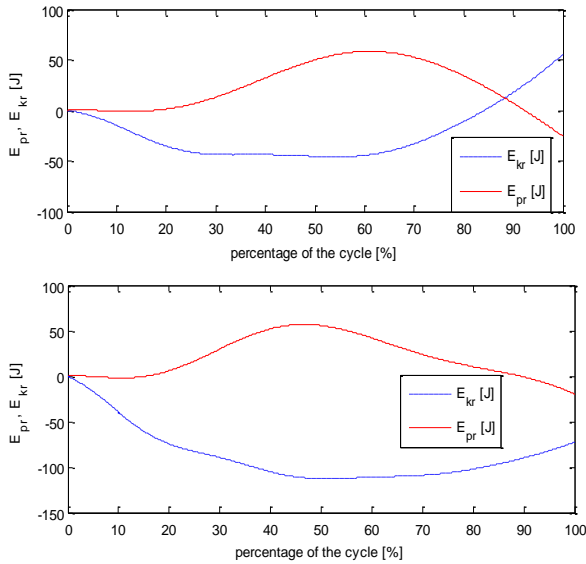

Fig. 4: Relative potential and kinetic energy for an accelerating (above) and a decelerating (down) walking cycle (m=80 kg, v_{in}=1.5 m/s, $a_{aver} = \pm0.71$m/s^2)

By accelerating their bodies, larger walkers suffer significantly more than small walkers. The converted potential energy contribution to kinetic energy decreases significantly, and animals need to generate the energy to cover the deficit from the external energy sources (muscles).

Since it is difficult to obtain experimental results on the recovery ratio for small animals accelerating at a particular magnitude, the model results have particular importance and can be used to make some conclusions/explanations about small animals' behavior that usually perform an accelerating walk/run much more often than larger animals do.

6. Conclusion

The analysis showed that simplified models of walking dynamics could predict how much energy can be recovered by accumulating the energy of collisions into potential energy and recovering the accumulated energy and reusing it cyclically. Using the model and the recovery ratio, as a measure for the walking efficiency, it was shown that larger walkers suffer a higher percentage of energy loss due to accelerations and decelerations. Using tendons, the recovery ratio can be improved on robotic walkers, and the controller can be implemented in such a way that it uses the dynamics model and improves the recovery ratio via the cyclic energy reuse.
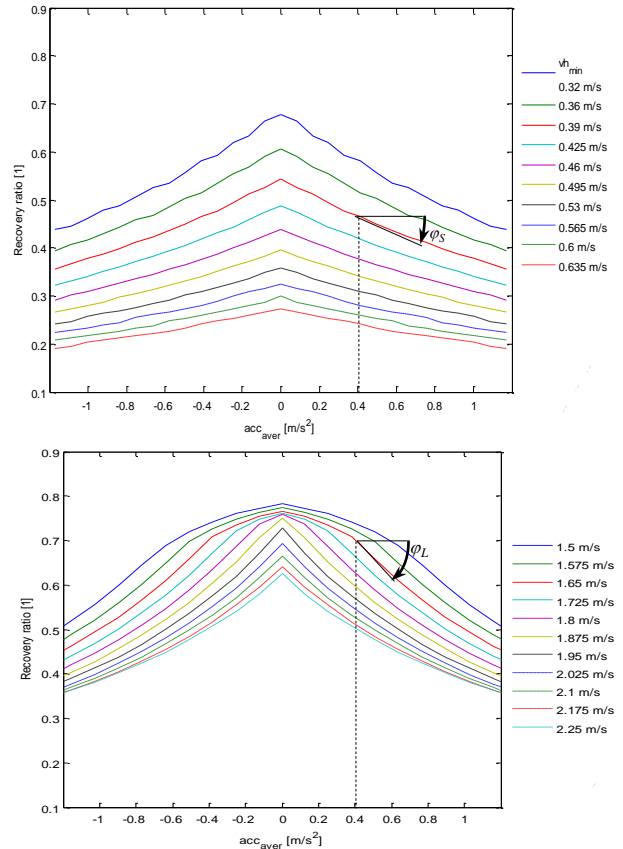

Fig. 5: Recovery ratio functions of the average acceleration/deceleration within the range [-1.2, 1.2] m/s^2 for different walking speeds: (above) small animals (0.5 kg), (down) large animals (30 kg)

Compliance with ethical standards

Conflict of interest

The authors declare that they have no conflict of interest.

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