Journal of Trends in the Development of Machinery and Associated Technology
Vol. 19, No. 1, 2015, ISSN 2303-4009 (online), p.p. 185-188

MECHANICAL ENERGY ANALYSIS AND CONTROLS OF A WALKING ROBOT

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ABSTRACT
Although walking robots are still at the stage of an experiment and initial development, they have prospective applications in a daily life and numerous special applications, such as search and rescue, military, police and surveillance applications.

In such applications when they have to carry their own weight and a source of energy, it becomes essential to reduce the energy consumption. On the one hand, the energy density of the on-board energy source has limitations, such that relative large mass of battery is required to provide the robot with sufficient energy to carry on a task or a mission. Consequently, one of the heaviest subsystems is the independent energy source. Therefore, large portion of energy consumed by the walker is associated with carrying its own energy source. On the other hand, not only the weight is necessary to be minimized, but also the mass need to be allocated properly across the robot architecture.

While the first design requirement is directly related to energy consumed by the robot during each cycle, the second one is related to energy and the robot controller performance. These are the two main design requirements that are addressed in this work for a bipedal robot.

Keywords: Walking robot, bipedal, dynamics, mechanical energy.

1. INTRODUCTION
Several engineering areas, mechanical engineering, biomechanics, electrical engineering, applied mathematics, control theory, sensor technology, all are being applied on and further researched in the area of a walking robot. Making an energy efficient walking robot is still a challenging task.

Some of the most advanced walking robots [1,2] use relatively enormous amount of energy per distance walked, when compared to the energy consumption of biological walkers [3,4,5]. Energy efficiency of biological and robotic walkers can be compared using the parameter cost of transportation [5]. The parameter is defined as C_{et} =(energy for walk)/(weight×distance walked). It is a dimensionless quantity that is convenient to compare efficiency of biological mechanisms. Although the parameter is primarily for biological walkers, it can be adjusted for robotic walkers.

The general requirement for a walking robot is minimization of energy consumption due to the fact that batteries or fuel with a generator represent the largest mass on the walking robot and the major part of the energy is consumed by walking robots to carry their own weight. One of the main reasons that biological walkers have significantly higher efficiency comparing to the robotic counterparts lies in the mechanism, the architecture of the walker. The fact is that the efficiency can be improved by analyzing biological walking mechanisms and designing the robot walking mechanism in such a way that it includes similarities to biological walkers, the efficiency can be significantly improved, although the control gets more complicated [6]. Although modern control theory has achieved remarkable results in engineering, it is still underdeveloped for walking robots regarding the relatively pure efficiency. The more the passivity of the mechanism is used, the more efficiency is achieved [6,7]. Precondition for a good control algorithm is to understand the dynamics of the walking mechanism.

2. KINEMATICS AND DYNAMICS ANALYSIS OF THE WALKING ROBOT

The biped model architecture that is considered here is shown in Figure 1. It is consisted of 6 degrees of freedom (DOF), per leg. That means that a leg can move in 6 different ways. In other words, the position and orientation, the pose of the leg depends on six independent variables, which are the angles.

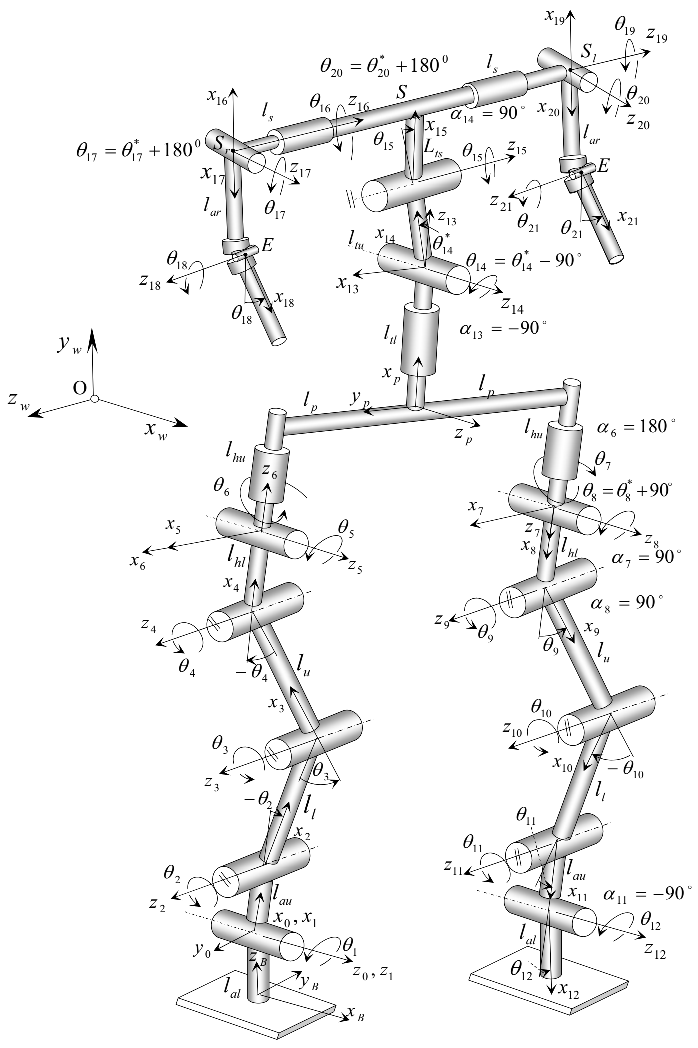


Figure 1. Bipedal Walking Robot Architecture

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, but it is implemented in the form of three revolute joints that are apart by additional links, as shown in Figure 1. The knee is a single revolute DOF, although the real knee has a limited additional DOF, but the range is negligible, such that it is approximated by a single revolute joint. Similarly, the ankle joint is a two DOF joint that allow rotation about the lateral axis and about the antero-posterior axis. The trunk section has three DOF, with 2-DOF shoulders and 1-DOF elbows. However, the dynamics analysis in this paper will consider the architecture with 2x6 DOF for legs and the trunk as a single rigid body, i.e. with no DOF within the trunk. Since the kinematics and dynamics analysis for this robot architecture requires much more space than is allowed for this paper, only final results will be given here.
The matrix equation of the walking robot dynamics is

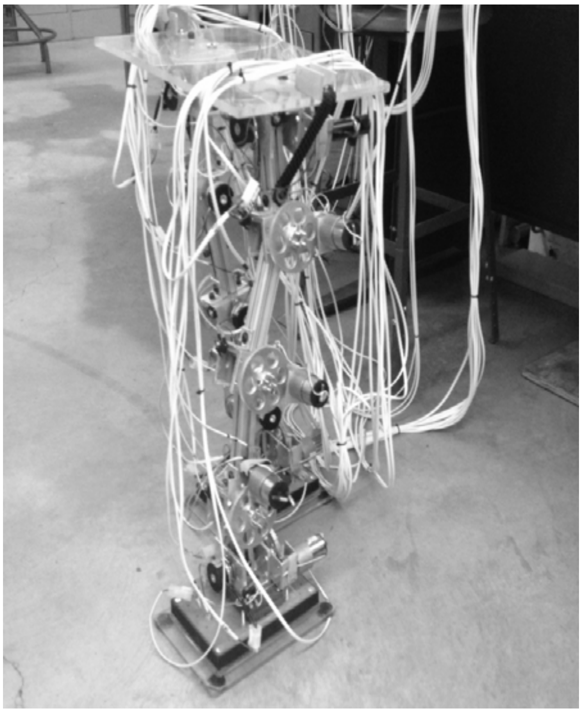
$$\left[\mathrm{M}(\vec{\theta}(t))\right]\ddot{\vec{\theta}}(t)+\left[\mathrm{C}(\vec{\theta}(t),\dot{\vec{\theta}}(t))\right]\dot{\vec{\theta}}(t)+\left[\mathrm{P}(\vec{\theta}(t))\right]=\vec{\tau}(t), \qquad ...(1)$$

where $\vec{\theta}(t)$, $\dot{\vec{\theta}}(t)$ and $\ddot{\vec{\theta}}(t)$ are the joint angle, velocity and acceleration vectors, respectively, $\left[\mathrm{M}(\vec{\theta}(t))\right]$ is the inertial properties matrix; $\left[\mathrm{C}(\vec{\theta}(t),\dot{\vec{\theta}}(t))\right]$ is the angular speed coupling matrix, $\left[\mathrm{P}(\vec{\theta}(t))\right]$ is the vector that includes the gravity terms, and $\vec{\tau}(t)$ is the vector of actuator torques acting at the joints. The product $\left[\mathrm{C}(\vec{\theta}(t),\dot{\vec{\theta}}(t))\right]\dot{\vec{\theta}}(t)$ represents all combined products of the joints angular speed, which consists of the Coriolis and relative normal accelerations (for the full model, see [6]).

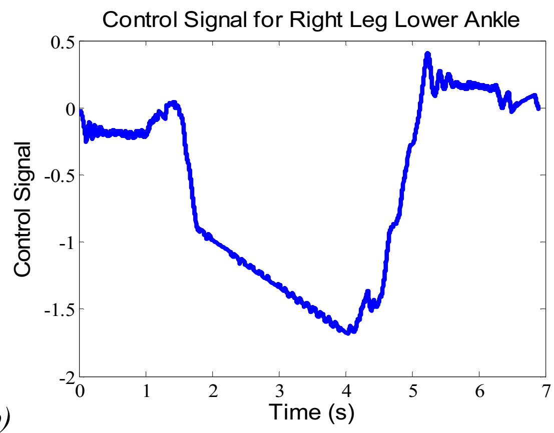
3. HARDWARE IMPLEMENTATION AND TESTINGS

In the frame of the previous work [6], a bipedal walking robot has been designed and implemented in the hardware, as shown in the Figure 2. This is one of the series of the hardware versions that has been developed associated to the research described in [6]. Analysis that will be shown here is associated to the biped model shown in the figure, regarding the architecture and degrees of the freedom of motion.

a)



b)



c)

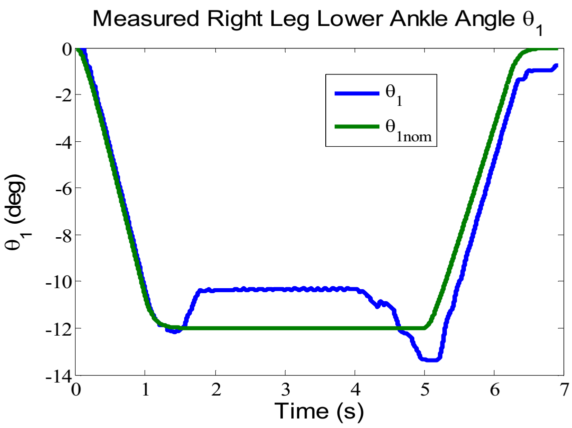


Figure 2. Walking robot hardware implementation: a) walking robot, b) measured control signals, c) measured ankle angle vs. nominal angle

The control system is based on an internal dynamics model of the biped. Nominal torques are predicted by the model and then the control signal is corrected via measurements using encoders directly attached to the joints. Control signals are measured on a signal conditioning board, just before the set of amplifiers. Realized angle is compared to the nominal angle for the ankle, as shown in Figure 2.

4. MECHANICAL ENERGY

Mechanical energy can be calculated numerically using the dynamics model (1). However, "negative" mechanical work does not mean that the energy is returned to the energy source (batteries), dc motors always consume energy; they do not return energy to the source. Electrical motors consume energy even in the case of static pose of the robot, when they generate holding torques. Total work over a single step was calculated using simulation of the dynamics, given by (1). The mechanical energy is shown in Figure 3, where it is compared to mechanical energy in a case of an alternative actuation and mass distribution described in [6]. The energy is significantly higher than required energy for biological walkers, since the total mass of the robot is approximately 10.2 kg, but the energy consumed is of the order of an adult human.

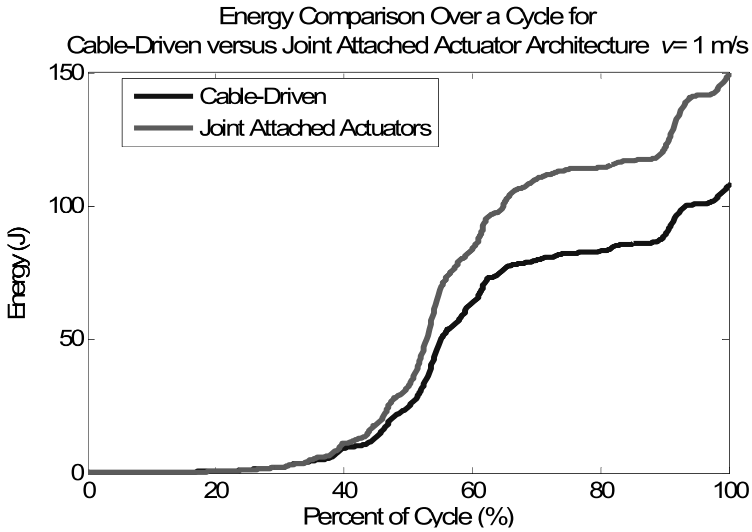


Figure 3. Mechanical work done by biped actuators

The mechanical work can be also directly calculated via measurement electric currents through dc motors using moment constants of electric motors.

5. CONCLUSION

The analysis showed that mechanical work done by robotic walkers is significantly higher than mechanical energy consumed by biological walkers with similar weight. One of the most convenient parameters for biological walking mechanisms efficiency comparison is the "cost of transportation", which can be adjusted and used for robotic walkers, as well. By appropriate design of the walking mechanism and mass allocation over the architecture, the energy consumption can be reduced.

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