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Efficient mechanical design and limit cycle stability for a humanoid robot: An application of genetic algorithms

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A R T I C L E I N F O

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A B S T R A C T

In this paper the application of Genetic Algorithms is presented to the task of designing a humanoid robot able to exhibit an efficient walking. This task is presented as an optimization problem. The objective function is the so-called Specific Cost of Transportation and the restrictions of the problem are based on the Limit Cycle Walking stability criterion. The mechanical design of the prototype and its walking trajectories are inspired on passive dynamic walkers. A basic genetic algorithm was used to find: the optimized mechanical parameters for design, the walking trajectories and the feedback gains used in the control of the current prototype.

1. Introduction

The present work shows the continuity that our group has given to the design of humanoid robots that began with the development of the prototype *AH1N1* [1]. Now we are focusing our approach on Energy efficiency which is difficult to obtain on humanoid walking robots, we decide to face this task as an optimization problem [2].

According to the Limit Cycle Walking paradigm [3], in order to find more efficient, natural, fast and robust walking motions it is necessary to reduce the artificial constraints added when using other stability criteria usually based on Zero Moment Point [4].

The most generic definition of walking stability, without artificial constraints, is ”to avoid falling”. The use of this definition implies to evaluate all possible walking trajectories and evaluate if the walker falls or not. In order to use this definition in a practical manner we propose the use of Genetic Algorithms by considering the task as an optimization problem.

Since the analysis of Passive Dynamic Walkers [5] follows Limit Cycle Stability we decide to study these machines as a base for the mechanical design of our humanoid robot platform. In Fig. 1 are presented some of the main architectures considered.

The original methodology used to built actuated robots based on passive dynamic walkers [6] consists on the addition of actuation and control systems to the passive version. Since passive walkers move on a downhill slope, the actuators emulate the effect of the gravity on the slope so the actuated mechanism can move on a flat surface. This transition can modify the original mechanical design in such a way that the efficiency of the passive version is mitigated on this transition.

This is the reason why we decided to change the approach by starting with an actuated walker, which uses the principles of passive dynamic walkers and find out which are the parameters that can be optimized to obtain energy efficiency. We study the next different approaches as a point of departure:

Frequency of the system: The oscillatory nature of walking is so evident that is reasonable to attempt to use some of the techniques that show good results on oscillatory systems. One of this methods [7] propose the addition of torsional springs on each joint of the system, the optimal stiffness for each joint is found by using an adjustment law, the idea of this method is to match the natural frequency of the system and the one of the reference trajectory.

Amplitude and frequency of the step: Other method [8] propose to find the optimal amplitude and frequency of the reference trajectory in order to exploit the inherent cyclic characteristics of the system.

Control law: Based on the Optimal Control Theory it is possible to express energy consumption in terms of the feedback control gains [9], however a realistic mathematical walking model is difficult to optimize by using conventional optimization techniques.

The main contribution of this paper is the use of Genetic Algorithms to put together all these partial points of view to define a more general optimization problem where mechanical parameters, walking trajectories and law control can be optimized and by using Limit Cycle Walking stability criterion the solutions are restricted to stable cycles.

In the area of robotics, Genetic Algorithms have already been used in other specific problems such as the design of optimal gaits [10] or to select mechanical parameters and proper morphology [11].

In the remainder of this paper we present our approach on the design of a humanoid robot called *Johnny*. Some of the characteristics of the passive dynamic walkers we used to design our own robot are

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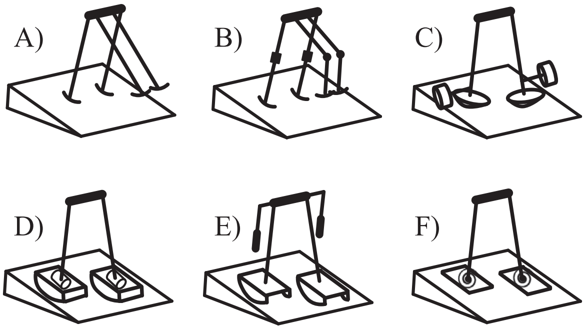

Fig. 1. Passive Dynamic Walkers previously studied.

described in Section 2. The mathematical model of the gait and definition of stability are discussed in Section 3. The gate design and its conversion to joint trajectories is presented in Section 4. The optimization problem, including cost function, restrictions and search space is formulated on Section 5. The characteristics of the Genetic Algorithm selected as optimization method are described in Section 6. The results of the optimization algorithm are presented along with the characteristics of the prototype built in Section 7. We conclude with a summary and future work in Section 8.

2. Passive dynamic walkers

A passive dynamic walker is a two legged machine designed to walk stably. This kind of walker has no actuators neither control systems, the movement of this machine is mainly a phenomena produced by the effect of the gravity on its limbs and the equilibrium between potential and kinetic energy. Passive dynamic walkers exhibit a stable gait when put on downhill slope and proper initial conditions of position and velocity are set.

McGeer began the study of passive dynamic walkers by using a mathematical approach, he built a straight legged prototype with rounded feet, whose movement was restricted to the sagittal plane, which demonstrates stable walking with no control and no actuators, Fig. 1A. This walker uses a mechanism to slightly retract the swing foot to avoid scuffing.

The methodology used to built this first prototype [5] consists in finding proper initial conditions of position and velocity that produce a limit cycle, for a given set of physical parameters of the used gait model, in case that no limit cycle can be found, a new set of physical parameters must be defined in order to continue the search, this can be done by modifying slightly some physical dimension, i.e. the length of the legs, the radius of the feet, mass distribution, etc.

Most of the time, is possible to find more than one set of parameters that produce a stable walking, each one of this possible solutions will produce a corresponding actuated mechanism that requires, in general, a different amount of energy to move on an horizontal surface.

After the original prototype some researchers have studied the addition of other elements:

McGeer [12] designed a second version of his original passive walker by adding knees to the legs (Fig. 1B), he also added a mechanism to lock and release the knees depending if it is the stance or the swing leg. With this addition, the machine was able to exhibit a more human-like movement and avoid scuffing while keeping low actuation.

Coleman and Ruina [13] built a rounded feet walker which allows lateral movement, this walker also have stable bars attached to the legs to increase stability, Fig. 1C. This straight leg walker was able to avoid scuffing without additional mechanisms although it can only move in small steps.

Wisse [14] designed a model with cylindrical feet and articulated ankles, Fig. 1D, showing that coupling Lean and Yaw movements can lead in to stable 3D passive movements above a minimum forward velocity just as bicycles.

Fig. 2. Passive Dynamic Walkers previously developed.

Collins [15] developed a sophisticated prototype that mechanically couples the movement of the legs to balance a torso and moving arms, Fig. 1E, this prototype exhibit a very stable and human-like walking with efficient use of the actuation provided.

Narukawa [16] used springs on the ankles of his flat feet version, Fig. 1F, this addition allows to modify the frequency of the gait in an efficient way, however a bad selection of the springs stiffness can lead in to undesired behaviors as foot oscillations or rebounds at contact.

The previous approaches were studied and compared by simulations and by building our own prototypes, these passive versions can be seen in Fig. 2.

Based on the performance obtained in these passive prototypes it was decided to include the next characteristics on our actuated platform:

- Additional masses on the limbs which form the legs in order to obtain an specific center of mass position.
- Rotational springs on each of the joints which form the legs in order to obtain an specific frequency of the mechanism.
- Flat feet and articulated ankle in order to apply control torques.
- Torso and swings arms to compensate rotational movements.

The mechanical architecture of *Johnny* consist in 22 actuator used as follows: 5 dof for each leg, 2 dof for the chest, 3 dof for each arm, 1 dof for each hand and 2 dof for the neck.

3. Mathematical model

Gait is modeled as an interconnection of continuous stages with discrete events, Fig. 3 shows the five stages of walking used in the model, the final state vector on each stage is used as initial conditions for the next one:

(A) *Swing phase*: When the robot is supported only on one foot, its movement is governed by a system of nonlinear equations, we consider three open kinematic chains whose origin coordinate frame are connected to the foot in the ground (one kinematic chain for each arm and another one for the swing leg).

The mathematical model, during this phase, can be obtained using Euler–Lagrange equation or Newton–Euler formulation, for simplicity we will consider no changes in the walking direction. The complete kinematic chains shown in Fig. 4 has 22 joints however in the mathematical model we will not consider the joints for the head and hands neither the joints used to change walking direction, so the mathematical model considers joints from q_0 to q_{15}.

(B) *Locked knee*: In the case of full passive walkers, knees have mechanical restrictions to avoid hypertension, when the knee is full extended a mechanism blocks its movement and keeps the swing leg straight.

This collision produce a discontinuity on joint's velocity. The