An Evolutionary Approach to Passive Dynamic Walking
Alife Project Coursework

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Abstract

Research has been done regarding the correct mechanical parameters (such as mass or lengths) of nonsingular passive dynamic walkers (PDW) using nonlinear dynamics theory, simple physical experiments and simple analytic approaches. By using evolutionary techniques I have found values for the mechanical parameters of a 2D passive dynamic walker with knees similar to the one studied by Ruina, Garcia, Coleman [9][3][7] and McGeer[4][5]. It appears to have an stable periodic gait. A genetic algorithm encoding for the physical properties of each of the Passive Dynamic Walker parts and the initial leg separation was used fro this purpose, rating mainly on distance travelled and on a small average displacement of the hip.

1 Introduction

Tad McGeer [4] demonstrated that a 2D legged mechanism can exhibit stable human like walking without a control unit and where the only source of power comes from gravity. Having stable walking without a power supply or a control unit suggests that the physical properties of the device are highly important and have to be taken into consideration for the design of robots and prosthetics.

Correct mechanical parameters of the walker can contribute to a more efficient stable walking.

There is still much to be understood about walking and finding an efficient model of a passive dynamic walker can help us study walking as a natural process. A good way to learn about human and robot walking may be to learn more about passive dynamic walking.

Garcia, Ruina, Coleman and Chatterjee found a efficient mass distribution criteria [7] for 2D passive dynamic walker with knees so that it could walk efficiently in very small slopes. They use the recipe suggested by McGeer [3] involving nonlinear dynamics to find stable periodic gaits. Here I have succeeded in the same task with an evolutionary approach.

2 Model

The Passive Dynamic Walker consists of 3D rigid bodies in a 3D world. Each of the legs is transparent to the other which means it can only collide with the ground. Both legs are identical and consist of 2 (3D) boxes and a sphere. Each of the leg elements has different mass which is uniformly distributed.

The sphere and one of the boxes form one body (shank) which is attached by a massless hinge (knee) to the other box (thigh)(see figure 1). There is a knee stop to prevent extensions of more than πrad. The axis of rotation of the knees as well as the hip is the x axis in the body's frame of reference.[1].

The 2 legs are attached by another massless hinge (hip) which has the same axis of rotation as that described in the caption of figure 1 and whose anchor is in the middle of the upper face of each of the thighs.

The 2 masses (sphere and box) added together[2] allows a whole variety of possible positions for the center of mass.

The mass distributions allowed by this model include the efficient mass distribution criteria[3] found by Garcia, Ruina, Coleman and Chatterjee([9],[3]).

To simplify the simulation the force of gravity is decomposed in 2 components, one in the y direction, and one in the $-z$ direction, which is absolutely equivalent as having the walker on an inclined plane. This force of gravity in the y direction can be exchanged for a source of power of any nature. It could be interpreted as power supplied by muscles or a motor. Here is taken to be a constant force to reduce arbitrariness.

The ground has infinite friction and the collisions of the walker with the ground are plastic (which means no bounce and no slip).

3 Simulation

The simulations were carried out using the Open Dynamics Engine library provided by Russel Smith[1], which has proven to be an excellent simulation tool for modelling articulated rigid bodies dynamics.

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[1] This means that if the bodies have any rotation outside the $y-z$ plane this axis would change

[2] The space the 2 geometries share has a mass equivalent to the sum of the respective masses.

[3] Efficient mass distribution implies collinearity of nominal contact point, center of mass and hip joint with the ground normal vector, and also the shank center of mass has to be on a vertical line through the knee

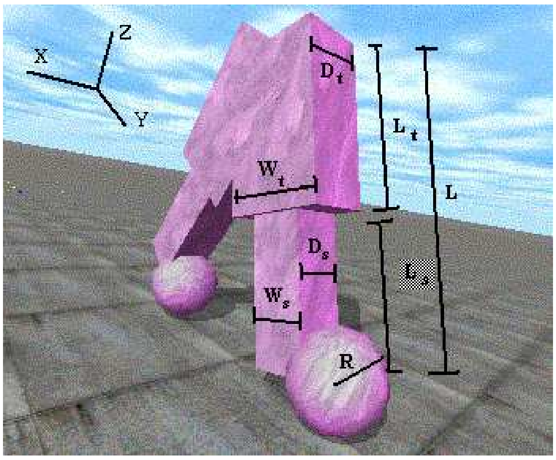

Figure 1: The shank is modelled so that the border of the sphere is exactly placed halfway inside the box, and the normal vector of the sphere surface is parallel to the lower face of the box. The knee anchor is exactly in the middle of the upper border of the shank box and the middle of the lower border of the thigh box.

Even though the simulation was done in a 3D world, no constraints were made to restrain rotations of the bodies in the $(y - z)$ plane. Computational error was not observed. Walkers didn't seem to leave the plane $(x = 0)$ unless they had already fallen down and were bouncing on the ground[4]

4 Initial Condition

The initial condition of the PDW determines how successfully it's going to walk or even if it is going to walk at all. In nonlinear dynamical systems language the passive dynamic walker is a system whose initial condition has to be on the basin of attraction of a periodic gait attractor. All individuals start with straight legs and feet touching the floor and a certain leg separation.

One of the genes in the genotype encoded for the angle θ that the back leg (or the first leg that swings) makes with the z axis (see figure 1), which is absolutely equivalent to encoding for the initial leg separation.

Encoding for the initial configuration means that not only the individuals with the appropriate mass distributions but also the ones that have a good starting condition would succeed.

It was important to find the angle ϕ that the front leg makes with the same

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[4] The walker was observed for 300 walking steps without showing any signs of instability in any way.

axis. Both angles satisfy the equation

$$L \cos\theta - R \sin\theta = L \cos\phi + R \cos\theta \tag{1}$$

This equation was solved numerically using binary search.

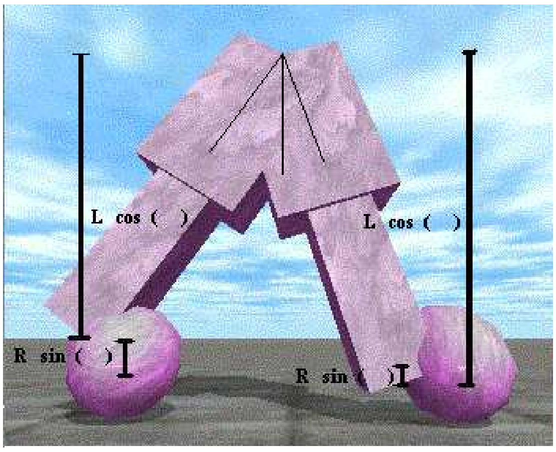

Figure 2: This figure shown the relationship used in equation 1 to describe the initial configuration of the angles the legs make with the z axis.

5 Genetic Algorithm

The GA uses tournament selection. Pick 2 individuals to compete against each other, the winner has an 80% chance of being one of the parents. Repeat this to pick the other parent. There is 30% chance of having multiple crossover between the 2 parents. If crossover doesn't take place both parents pass to the next generation. There is a 10% chance that each of the genes mutates with a mutation rate of 10%.

5.1 Genotype

The genotype had 11 genes which encoded for:

- Radius of the sphere, this value could vary between 0.1 - 0.4. I restricted the range this value could have to speed up evolution and to avoid balls[5]. It can't be too small either so that the shank box doesn't collide with the ground.
- Density of the sphere, range 1 - 10.

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[5] A ball is a phenotype with big, massive spheres, and small shanks and thighs. They usually leave the $x = 0$ plane because of the nature of the collisions with the ground.

- Density of the shank box, range 1 - 10.
- Density of the thigh box. range 1 - 10.
- Depth of Shank box D_s (x axis), range 0.05 - 0.4.
- Width of Shank box W_s (y axis), range 0.15 - 0.6.
- Height of Shank Box L_s (z axis), range 0.25 - 1.
- Depth of Thigh box D_t (x axis),range 0.05 - 0.4.
- Width of Thigh box W_t (y axis), range 0.15 - 0.6.
- Height of Thigh Box L_t (z axis), range 0.25 - 1.
- θ, initial position angle. Range 0 - 0.3. (figure 2)[6]

For simulation purposes Lengths should not be more than 1.

Encoding for the density and volume (3 lengths for each box and radius for the sphere) gives a whole range of masses and moments of inertia which determines the rotation of the bodies. I decided to include the depth of the bodies as a gene although this gene doesn't affect explicitly the rotations in the $(y - z)$ plane. The effect of this gene is a smoother fitness landscape.

I had to restrict the range of each of the genes so at to avoid evolving balls and to increase the speed of evolution. Starting from a closer point in my search space would make the search much faster but there is a chance that I would miss some of the solutions. Genes have a low limit and an upper limit range mostly to keep the the Passive dynamic walker within a certain range of values and avoid growing.

5.2 Fitness Function

The fitness function should evaluate distance travelled but also needs to evaluate stability so as to make sure the individual was walking instead of rolling or jumping. The fitness function had the form

$$F = \alpha(\Delta Y) - \beta|\Delta Z|_{max} - \gamma < \bar{\Delta Z} > -\mu(\Delta X) \tag{2}$$

Where ΔY and ΔX are the displacement of the hip at the end of the simulation in the y and x directions respectively. $|\Delta Z|_{max}$ is the maximum displacement of the hip in the z direction during the simulation and $< \bar{\Delta Z} >$ the average displacement. Parameters α, β, γ and μ where adjusted according to the simulation time.

When evaluating only on distance travelled there was a tendency to evolve balls that rolled very fast and hoped when the hip touched the floor. To avoid

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[6] By looking closely at the results I realize that this range is to too small, the angle θ should be allowed to increase much more. Even though a solution was successfully found.

balls the other terms in the fitness function where included and the radius of the sphere was restricted (see section 5.1).

The hip height average should be constant. This criteria alone evolved individuals that just stood still. A combination between distance and constant hip height is necessary. Evaluating for the average displacement of the hip in the z direction gave preference to those phenotype that remained standing for a long time. This is the most important term in the fitness function and was the only criteria used for optimizing the PDW obtained.

The term $\mu(\Delta X)$ was introduce to penalize those phenotype that leave the $x = 0$ plane and was only necessary in the first few runs of the GA. It showed to be unnecessary since there was no further displacement in the x direction.

The term $|\Delta Z|_{max}$ was included to avoid jumpers[7] and explosions[8]. Also if the height of the hip went over a certain limit the simulation was stopped because it was obviously not walking.

5.3 Simulation Time

At the beginning long simulation times were useless since most individuals fall down very quickly and some of them roll and land forward. I took the approach of aiming to evolve stable individuals that covered a positive distance and whose hip remained at the same height most of the time.

At first the simulation time was approximately the time taken to complete one step. Once the average population was successfully completing one step, the simulation time was increased to that of 2 steps and parameter γ was made stricter.

Next the simulation time was increased about 5 times also having a stricter fitness function for the variation of the hip position.

6 Final Step

Once a passive dynamic walker able to complete 9 steps was obtained, I took a population of 20 individuals with exactly the same genome, and evolved this population, mutating 20 % of the population. Each of the mutated individuals had 10% of its genes mutated 10% of their value. Tournament selection was used and winners had a 30% chance of multiple crossover. Distance was not evaluated any more because of the increase this would have on simulation time. The only criteria used to stabilize the gait was the average hip displacement being as low as possible.

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[7] A jumpers is a phenotype that fall hard and bounce forward, they usually covered more distance than the ones which where really trying to walk.

[8] Explosions are simulation errors that happen every once in a while. They are the result of a restauration force used by ODE to correct bodies going through the floor or knees stretching more than they are allowed.

7 Results

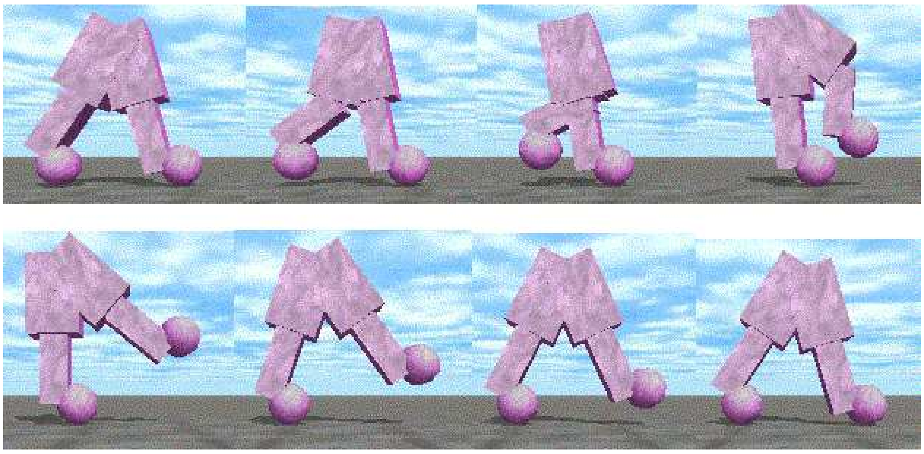

Figure 3: Figure showing one complete step, you can see the knee-strike and the heel-strike. Both legs are on the ground at the same time for just one instant, then one of the legs becomes a swing leg while the other is the stance leg.

Numerical values for the densities and volumes of a PDW who walks stably down a slope of $\gamma = 0.2974$ were obtained (see table 1).

A small transient (about 3 steps) is observed before the PDW enters a periodic gait orbit. By increasing the range that the initial angle θ has the transient should become smaller.

8 Future Work

I still have to check if these results satisfy the efficient mass distribution criteria, and if not (which is the most probable case) tune it and compare the effect of tuning on its efficiency. Evaluating for efficiency on the GA could be a way of tuning the PDW to make the mass distribution more efficient.

There is much to do still in the area of passive dynamic walking. It is not very difficult to adjust this model to 3D since the simulation environment is already implemented. For this purpose the passive dynamic walker would have four identical legs instead of 2, to make it stable in 3D. ODE allows more real simulations. This includes realistic hinges, more real collisions, finite friction, noise, air drag, non-absolute flat surfaces and many other 'realistic' phenomena.

Since an Evolutionary approach has shown to be successfully, parameters can be found for a certain number of slopes, including near zero slopes.

Gene	Value
Radius	0.2363
Density of the sphere	1.4690
Density of the shank box	3.8367
Density of the thigh box.	8.3445
Depth of Shank box D_s (x axis)	0.2822
Width of Shank box W_s (y axis)	0.3013
Height of Shank Box L_s (z axis)	0.7601
Depth of Thigh box D_t (x axis)	0.3472
Width of Thigh box W_t (y axis)	0.5718
Height of Thigh Box L_t (z axis)	0.8598
θ	0.3000

Table 1: Mechanical parameters of the stable PDW obtained for a slope $\gamma = 0.2974$. Gravity had a magnitude of 0.5099 in whatever units the other parameters are.

9 Conclusion

Research has been done to find the mechanical parameters for an efficient passive dynamic walker using nonlinear dynamics tools. The results obtained here suggest than an evolutionary approach is a possible solution to the problem of finding the right mechanical parameters that a passive dynamic walker should have in order to become efficient, and to have a stable periodic gait.

It is important to have approaches other than nonlinear dynamics theory since more realistic models can result in very high dimensional problems difficult to analyze.

References

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