Harmonic Gait under Primitive DOF for Biped Robot

(Harmonically Communicated Movement)

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Abstract. Here argues about an effective and an energy less-consuming walking for a humanoid type of robot. There are many humanoid types of robots in the world that can walk, run, dance, and get up, etc. Those are mostly used and enjoyed in the field of entertainment for kids' pleasures. For any other usages, humanoid types of robots are not practical enough in a daily life usage or in factory usages or in any others. Because the robotics movements are not smooth enough and not effective enough for doing things in them, that is to say, the stable biped walking and the energy optimization biped walking (series of those walking figures) could not meet the necessary conditions for the expected usages or for other purposes. So here introduces a new idea of humanoid type of harmonic gait, which makes a robot move more effectively and an energy less-consuming walking.

Keywords: harmonic gait, less-consuming walking.

1 Humanoid Type of Robotic Basic Movement

As we know well, the basic idea of biped locomotion method with two legs is traced back to the original thought of the Zero Moment Point (ZMP), which is the point or the aria between the biped feet and the contact surface of a ground or of a floor. And that ZMP usually becomes a rectangle or a polygon as the area of the stability. As the contact forces are due to gravitation and inertia of the walking body, the ZMD in a rectangle or polygon can also be defined as the point of the surface where the moment of the resultant gravitation and inertia forces becomes zero. This phenomenon of the walking mechanisms can also be true to be said for very complex biped waling creatures like a human and others.

2 Problems in Biped Locomotion Method

2.1 Problems of Biped Locomotion

It is said that a jogging robot including a walking robot consumes many times as much energy as its jogging by human, which shows us that there is much waste movements and futile activities with it, that is to say, the locomotion mechanism is not smooth enough or effective enough in a sense of the walking movements. When we can pick up a couple of reasons why it comes as it is so as shown below.

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1. Two-legged movement of human is not deeply studied in a sense of effective, smooth, and a low energy consumption method for a biped type of robotics. It seemed that a focus of the whole studies was only on how to get various kinds of walking types mechanisms or figures by a biped locomotion that were able to be applied to a biped robot walking.
2. It is true to say that we are under the atmosphere of the gravity, so that the living creatures in this world should be very good at using the gravity in walking movements effectively, smoothly, and with low energy consumption. So it would have been better to learn more about effective and smooth movements out of human or other biped walking creatures in a sense of gravity.

2.2 Human Walking in General

When we walk on a road in flat, we feel that we can walk as much longer as we want. And it is, in fact, true to say that we can walk for a several hours or more continuously. It may come to a conclusion for this reason that we move legs within a minimum amount of energy consumption by resting some part of muscles of legs or by releasing some part of muscles of legs or by taking a low energy consumption leg movement method. But when we want to go fast or run fast, it can continue going fast only for a couple of minutes for an ordinal person (not for an athlete). The reason why is that we use legs (muscles) only for going or running fast, which is equivalent to making always keep forcing legs moving back and forth without resting or releasing muscles at all or even against smooth and a low energy consumption mechanisms for going or running. This method is a very tiresome and energy consuming futile moving method even though it is able to go faster or to run faster, so that usually an ordinal person cannot go or run with this way for long.

So from these arguments, we can say that it might be possible to extract some of more important facts about the smooth and effective moving methods out of human gait if we closely look at our movements with two legs from other aspects.

2.3 Legs Movements in Dancing and the Seamless Low Energy Consumption Gait Mechanisms

We have now various kinds of dancing by from old to young and by from snob to shabby and from traditional to brand new. Some of those have got quite histories and others do not. Here is just putting a focus on the social dancing for its movements of walking and walking mechanisms of legs.

The social dancing is now a popular dancing in the world and it is centered in England. And lots of techniques for dancing have been developed for several kinds of social dancing. And the social dancing in general has got two categories, one is “Modern” and another is “Latin”. If we talk about Modern of Blues, there are some interesting walking techniques behind. Basically it consists of back and forth walking movements. And those movements are smooth enough to go forward and to go backward seamlessly with a couple stuck and with a couple simultaneous moving (walking).

Here shows the basic walking mechanisms from an aspect of the social dancing in a sense of seamless and low energy consumption manners. And those are as follows.

1. Releasing the muscles of one leg to stand by this one leg, which is immediately and closely linked with the forward or backward movements, is for starting a movement.
2. And then by using the ankle joint and the knee joint of the leg to make both of them bending gradually, the whole body goes forward or backward as the whole body sinking down by those bending, which can be done theoretically with a minimum energy consumption by transformation from the potential energy to the kinetic energy of the whole body forward movement.
3. And then, make the another leg release in order to get it beside the bending leg of the ankle and the knee without using any muscles, which is again no energy consumption involved theoretically just like a pendulum movement that goes back to the gravity stable position and that swings over further to forward.
4. And then the another leg (the released leg that went forward) is now ready for standing upright by pushing a bit onto the floor, which can make the whole body go further and can make the whole body stand upright onto the released leg at a floor.
5. And this movement is connected to the following forward or backward movement of the whole body, and further.
6. By giving these movements of the two legs one after another, the whole upper body (torso) is always stabilized upright onto the one leg or onto another leg one after another.
7. And the repetition of this walking pattern comes up for in a series of seamless and low energy consumption gait (manner of walking).

3 Ideas of Harmonic Gait

3.1 Waling Method in General

It is classically said that a biped locomotion can be done by having the Zero Moment Point (ZMP) at the point of the contact place of floor or ground or road or at any others. As the related contact point of forces are the gravitation and an inertia of the whole waling body, the ZMP can also be expressed as the point of the contact place of floor or ground or road or at any others where the moment of the assembled inertias for each part of the body (the total sum of the inertias of the moments vectors) and gravity forces for the whole body comes to zero.

As explained in the section 2.3, the whole upper body (torso) can be always stabilized upright onto the one leg or onto another leg one after another under the situations explained. As the result of it, we are able to define a biped robot as shown in Figure 1 with 8 dof as the most primitive case of possible walking mechanisms. And so, in general, it can be defined and expressed as follows.

q1, q2: displacement of a hip joint in XY coordinate plane.
q3, q4, q5, q6: rotation angle of hip, knee, ankle, and toe joint for a right lower limb.
q7, q8,q9, q10: rotation angle of hip, knee, ankle, and toe joint for left lower limb.
In this case, the coordinate dimensions can be defined as follows.

Rhip = $(q1, q2)^T$; hip joint,
R3 = $\{q1+r3\cos(q3), q1+r3\sin(q3)\}^T$; right thigh,
…
R10.

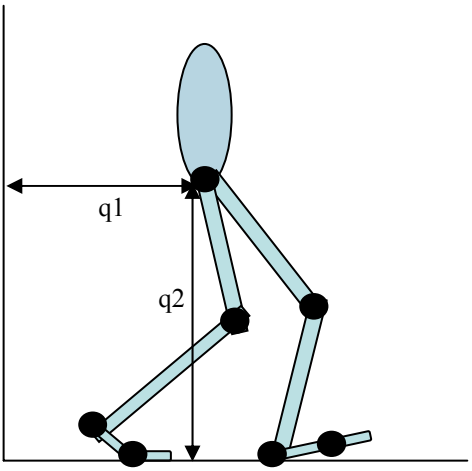

Fig. 1. Example of Biped Robot of Gait

And there should be the ranges of joints' angles for each joint. Those can be defined within limitations of those angles as they should be, like from the minimum possible bending angles to the maximum possible bending angles for each joint. So those are to be defined by the natures that we want to put on a robot.
And the velocity vector of each segment can be defined as follows.

Dot(**R3**) = {dot(q1) –r3dot(q3)sin(q3), dot(q2)+r3dot(q3)cos(q3)},
…..,
Dot(**R10**).

And the kinetic energy can be defined as follows.

K = f{q1, q2, q3, …, q10, dot(q1), dot(q2), dot(q3), …, dot(q10)}
= 1/2{dot(**q**)^T**M**(**q**)dot(**q**)}.

And the potential energy can be defined as follows.

P = f{q1, q2, q3, …, q10}.

And so, Lagrange equation can be simply defined in the conservative forces of system as follow.

L = (**K** – **P**).

3.2 Theory of Harmonic Gait

Here argues about a theoretical walking method that minimizes a cost function in energy consumption by using the idea of Harmonic Gait.

When we think about a walking method within a minimum energy consumption pattern, we will know that it will be the minimum when we can use wisely the gravity and inertia of each object without wasting extra energy for keeping balancing, etc. as we know well. For doing these, we can have the following conditions by the knowledge of dancing techniques that are shown and argued partly in the previous section.

[Necessary and Enough Conditions for Harmonic Gait]

1. The whole body should be calm and smooth and seamless without irrelevant movement for walking.
2. The usage of gravity means that the whole body goes forward or backward by transforming a potential energy into a kinetic energy by sinking the whole body or by transforming a kinetic energy into a potential energy by raising the whole body upward for conservative forces.
3. An inertia can be used for going forward or backward seamless movement of the whole body by releasing some part of the body freely. That is to say, by using the ankle joints and the knee joints of one leg to make both of them bending gradually, the whole body goes forward or backward by those pair of bending as it is without wasting any extra energy consumption with sinking the whole body down too. And also by releasing a leg situated backward freely like a pendulum, its energy can be transformed into the body of forward movement just like a pendulum swinging coming-back and going further forward.
4. The biped walking should be smoothed by interchange the legs one after another, that is to say, the gravity centre should be changed smoothly from onto Left foot to onto Right foot or vice versa within a seamless swing.
5. A cooperative two robots movements need a harmonic behaviours of stabilized, synchronized, and seamless movements. And so, the continuously calm and stable and smooth torso onto one leg or onto another leg deadly uprighted should be the necessary behaviours for a cooperative two robot movement.

So we can have the following theory by using the above sorts of the knowledge.

[Theory of Harmonic Gait]

The initialisation of walking energy (**Lsink**) can be given by sinking the whole body, that is to say, a potential energy is transformed into a kinetic energy by bending the ankle and the knee as releasing the whole legs' muscles.

The potential energy (**P**) is defined by the following equation with sinking (**Psink**).

P = (Pinitail – Psink)

And the kinetic energy (**K**) is defined by the following equation with sinking (**Ksink**).

K = Ksink

And the energy loss (**E**) by the system is defined by the following equation with loss (**Eloss**) in movement.

E = Eloss

And put the above equations into the following Lagrangian equation, we have

L = (K – P) – E
L = {Ksink – (Pinitial – Psink)} – Elossdown
= Ksink – Pinitial + Psink - Elossdown
= Lsink

So the above equation also says that the potential energy by the action of sinking (**Lsink**) will be transformed into Kinetic Energy of Walking (**Ksink**) in the five conditions mentioned above. That is to say, ideally we can have the following energy transformation.

Lsink → Ksink, that is to say, ideally, **Lsink = Ksink**.

And the effectiveness (**EFsink**) in walking with sinking will be defined by the following equation.

$$\mathbf{EFsink} = \frac{\mathbf{Lsink}}{\mathbf{Ksink} - \mathbf{Pinitial} + \mathbf{Psink}}$$

And also, we can say that this action of Walking can be transformed into **P**(**Pup**: going upward and back to the initial original state) again smoothly if this transformation can be done without any loses in the five conditions as mentioned above.

Krise → Pup

That is to say, ideally we can have the following transformation.

L = (K – P) – Eloss
L = {Krise – (Psink - Pup)} – Elossup
= Krise – Psink + Pup – Elossup
= Lup

And the effectiveness (**EFup**) in walking with up will be defined by the following equation.

$$\mathbf{EFup} = \frac{\mathbf{Lup}}{\mathbf{Krise} - \mathbf{Psink} + \mathbf{Pup}}$$

And in this case, we have **Krise = Pup**. And so, the above Lagrangian equation will be;

L = –Psink + Pup – Krise – Elossup
= –(Psink – Pup) – (Krise + Elossup)
= K – P.

And the above equation shows that "the movement comes back to the original situation". These kinds of movements and transformations can be done if and only if the "Necessary & Enough Conditions" as mentioned in this section above are satisfied. And these series of movements with transformations will be able to be circulated and repeated for good within the minimum energy consumption condition.

These transformations, the gravitation centers' changes, up and down movements displacements, and the robotics generalized movements and generalized movements figures are illustrated in Figure 2 below.

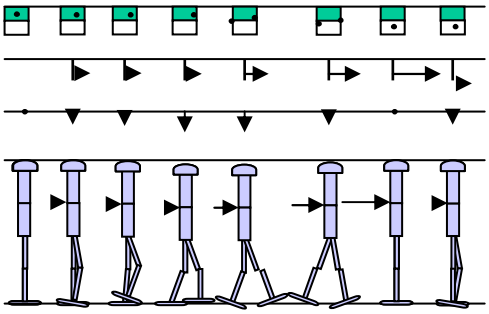

Fig. 2. Robotic Generalized Movements

[Contents of Figure 2]
First row shows the gravity center changes in ZMP.
Second row shows the body movement displacement on the horizontal axis.
Third row shows the body upward and downward movement displacement.
Fourth row shows the generalized legs movements figures and the gravity center position movements.
[END]

So, this theory proves "the method of walking patterns and figures with a low energy consumption mechanisms by using Harmonic Gait Method".

Here shows an example by using the theory shown in the above. The Figures 3 and 4 show the general initial conditions for the dynamics and the concrete values for the upward (Wvup) and the downward (Wvdown) forces in the case of 176 height robot (h), the gravity (G), the moment of inertia (M), and the lean angle of the body (theta; θ). And **Eloss** will be less than 40% ideally.

By using the above dynamics values for the biped robot, the movements histories are shown by the equations below.

The time to go downward; Td

$$Td = \text{square root } [2(176*\sin\theta - h)/G]$$

The distance to move forward by bending the knee, Df, in the time Td.

$$Df = (1/2)*Fb * (Td)^2$$

The distance to move downward by bending the knee, Dd, in the time Td.

$$Dd = (1/2) * Fvd * (Td)^2$$

The results of the movements by using the theory is summarized at Figure 2 above.

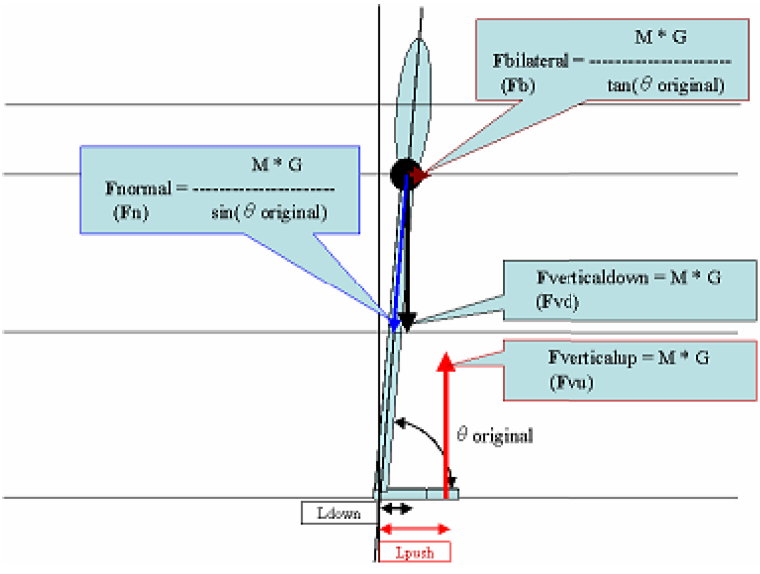

Fig. 3. Initial Dynamics for Gait

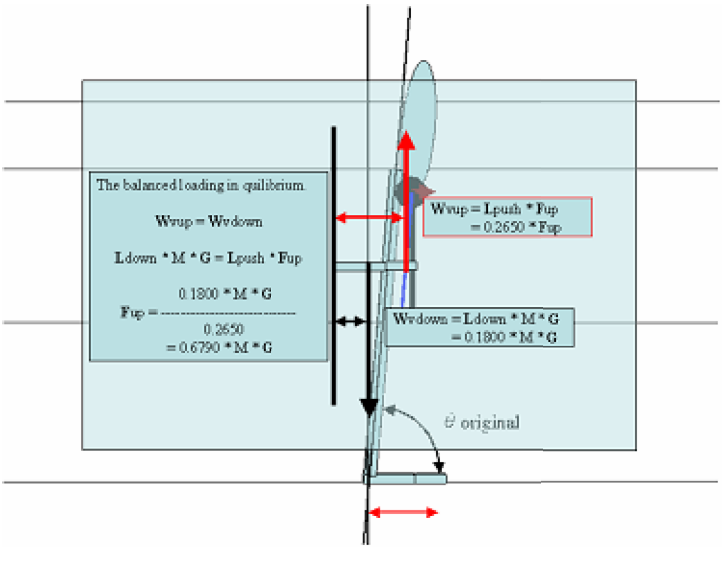

Fig. 4. Initial Dynamics for the Elements of Values of Gait

3.3 Theory of Continuous Body onto Method and Harmonic Walking

The important matter for a biped robot to walk in a low energy performance is not to have extra irrelevant movements; that is to say, the whole body should be stable and calm but flexible in dynamic movement as having been studied in the above. In order

to have this situation, we can say the following things from the knowledge of the social dancing.

1. The whole upper body (torso) is always upright onto the one leg or onto another leg one after another, which makes a biped robot allow being stable, calm, and dynamic in movement. So the torso is just stable without redundant movements and the legs only shall move as they are wanted to be. In this condition, we can consider and generalize a robot figure as shown in the equations below. That is to say, the upper body can be thought as a simple unique figure without the hands nor the neck nor the head just like an accumulated unity mass, and it is illustrated as shown in Figure 5 below.
2. The above condition makes allow two biped robots walk always with simultaneous and identical movements with a stable and calm "A" and "B" (torsos) as shown in Figure 6. And the walking figures are under the low energy consumption method by using Gravity and Inertia. And those can move harmoniously closely side by side or they may have a thing between them for bringing to.
3. The two robots will be able to do cooperative work under the above condition because the two robots can be with upright body, which can allow two bodies closely side by side as shown in Figure 6. And because two torsos are stable and calm but very flexible in bilateral movements, it makes possible for the two robots work together cooperatively and harmoniously for bringing a good or for doing harmonious working, etc.

Robot ="The whole parts of the biped robot"="Head + Upper Body + Hands + Legs"
= "Torso + Legs" = "Torso" + "Legs" = "Object A" + "Object B"
= "A" + "B".

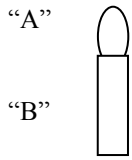

Fig. 5.

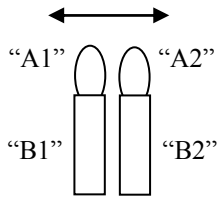

Fig. 6.

4 Conclusion

Through the examinations and discussions in this paper, the following results have been given;

1. Basic idea of harmonic Gait Walking has been shown,
2. The generalized walking mechanisms of the biped robot and the theory for a low energy consumption (more than 30% less respectfully) for a biped robot has been introduced,
3. By using the theory of harmonic Gait Walking, it has been shown that a cooperative movement of a couple is possible to perform for a harmonic works to bring a thing together.

Aknowledgements. First of all, I am truly indebted to my professional dancing instructors, Ms. S. Yamamoto and Ms. M. Yamashita who showed and taught me about the detailed dancing movements & mechanisms and those logical aspects of explanations through a year or so. And also I would like to thank Professor M. Sasaki at Gifu University for having given me basic and general robotics dynamics information.

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