ANALYSIS AND DEVELOPMENT OF WALKING ALGORITHM KINEMATIC MODEL FOR 5-DEGREE OF FREEDOM BIPEDAL ROBOT

ANALISIS DAN PENGEMBANGAN MODEL KINEMATIK ALGORITMA BERJALAN UNTUK 5-DERAJAT KEBEBASAN BIPEDAL ROBOT

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Abstract

A design of walking diagram and the calculation of a bipedal robot have been developed. The bipedal robot was designed and constructed with several kinds of servo bracket for the legs, two feet and a hip. Each of the bipedal robot leg was 5-degrees of freedom, three pitches (hip joint, knee joint and ankle joint) and two rolls (hip joint and ankle joint). The walking algorithm of this bipedal robot was based on the triangle formulation of cosine law to get the angle value at each joint. The hip height, height of the swinging leg and the step distance are derived based on linear equation. This paper discussed the kinematic model analysis and the development of the walking diagram of the bipedal robot. Kinematics equations were derived, the joint angles were simulated and coded into Arduino board to be executed to the robot.

Key words: bipedal robot, kinematics model, kinematics analysis, 5-degree of freedom, walking algorithm.

Abstrak

Makalah ini merupakan pengembangan desain untuk algoritma berjalan dan kalkulasi bipedal robot. Dalam hal ini, bipedal robot didesain dan dikonstruksi dengan bagian pinggul, telapak kaki dan beberapa jenis dudukan servo untuk kakinya. Setiap kaki terdiri dari 5-derajat kebebasan, 3 pitch (engsel pinggul, lutut dan engkel) dan dua roll (sendi pinggul dan engkel). Algoritma berjalan untuk nilai sudut tiap engsel dari bipedal robot ini berdasarkan formula cosinus dan sinus dari segitiga. Tinggi hip, tinggi kaki yang diayun dan jarak tempuh melangkah diturunkan berdasarkan persamaan linear. Makalah ini akan mendiskusikan analisis model kinematik dan pengembangan diagram berjalan dari bipedal robot. Persamaan kinematika diturunkan, sudut-sudut joint disimulasikan dan diubah kedalam kode program untuk dieksekusikan pada robot, menggunakan Arduino board.

Kata kunci: bipedal robot, model kinematik, analisis kinematik, 5-derajat kebebasan, algoritma berjalan.

I. INTRODUCTION

Bipedal robot has been developed since many years because of the unique algorithm of human-mimicking walking motion. The development of the bipedal robot has the purpose of approaching the most similar walking algorithm as a human being. The walking algorithm of a human is not limited to one type of walking algorithm but it is vary. *"Bipedalism is a manner of moving on land, where the organism progresses using only its two rear limbs, or legs"* [2]. Bipedal robot means a robot that consists of two feet and since it only has two feet, it is able to move almost freely just like a human being by walking, running or hopping. Bipedal robot has a very complex mathematical calculation in order to find the perfect formula to make the bipedal robot stand still.

"Dany Walker" [3] is another example of a bipedal robot model where each leg has three joints and five degrees of freedom. Each degree of freedom consists of a motor as its actuator, which is servo motor. The material used for the

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bipedal robot is normally aluminum since it is light and strong. Bipedal robot "ARCher 32" [4] uses aluminum for the legs, feet and the hip to avoid the heavy weight because bipedal robot only consists of two legs and it is required to have a high mobility. This bipedal robot has a balancer on its hip part and it helps to maintain the balance of the bipedal robot. The movement of the balancer is only in one axis, left or right, and is moved by a servo motor.

Trajectory planning in bipedal robot [5, 6] is normally consists of starting stride, full stride and ending stride. In order to make the bipedal robot walks, full stride is repeated more than once. In walking motion, either starting, full or ending stride, the bipedal robot always lifts one of its leg before swings it forward, not drag it in order to approach the way of human walks. Trajectory planning of a bipedal robot also consists of two phase, single phase where one leg supports the whole weight of the bipedal robot, and double phase where two legs support the whole weight of the bipedal robot.

Other bipedal robot use Zero Moment Point regulation for the walking control [7-9] and inverted pendulum system for the stabilization of walking [10, 11]. There are also the analysis of both Zero Moment Point gait and Limit-Cycle Walking gait for bipedal robot [12], mechanical energy balance [13] and human's gait pattern analysis [14].

In this paper, the desired walking algorithm of the bipedal robot will be based on the kinematic model. The process of the walking will not form a straight line but a triangle instead. Figure 1 shows the bipedal robot developed at our institution [1]. The equations to obtain the variable values are derived based on the connection of each variable by using a linear equation and the triangle formulation. This paper analyze the movement of the bipedal robot based on derived kinematics equation from 2 dimensional point of view. The result of
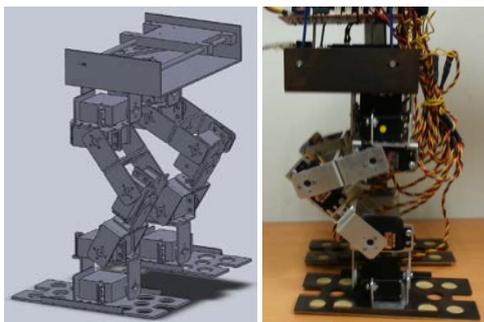

Figure 1. Bipedal Robot [1]: CAD model and the constructed system.

kinematics analysis then is used as parameter within a program to be executed using Arduino board [1, 15]. During the analysis, the roll movement is assumed to be static. The program execution on Arduino board is beyond the discussion of this paper.

II. BIPEDAL ROBOT WALKING DIAGRAM

At our institution, a bipedal robot has been constructed and developed. The bipedal robot height while the leg on a straight condition is 380mm. The bipedal robot torso's width is 160mm. The minimum bipedal robot height on squat condition is 220mm. The graph and the formula discussed in this article are based on our result [1].

There will be three types of motion for the walking diagram of the bipedal robot, starting motion, full motion and ending motion. Starting motion is the beginning of the walking motion of the bipedal robot by lifting one of the leg forward until it touches the ground, then followed by the other leg, which is lagged behind, swings forward until the position of the reference lines are on the same vertical line position. Full motion is the continuation of the walking algorithm for the bipedal robot, where this motion can be repeated as many as required. The sequence will always be the same, by changing the leg that swings forward and lifted at the end of the full motion. The last is ending motion, which to end the motion of the bipedal robot by letting both of the legs stand on the ground where the reference lines are on the same vertical line position at the end of the motion.

A. Starting Motion

Figure 2 is the starting motion diagram, which is also the initial movement of the bipedal robot to take its first step. The bipedal robot will lift the foot and not drag the foot forward in order to approach the human nature in walking. It lifts the foot with a certain height and swings it forward until a certain distance forward achieved then the foot comes back down and touches the ground.

From figure 2, after the red leg reaches a certain distance forward and the foot touches the ground, then the bipedal robot lifts the other leg, which is the black leg with a certain height then it swings the foot forward until the reference line of the black leg reaches the position of the reference line of the red leg. At the end of the starting motion, both of the reference lines will be on the same vertical line position but the black leg's foot is lifted as high as a requested height of swinging leg *h*.
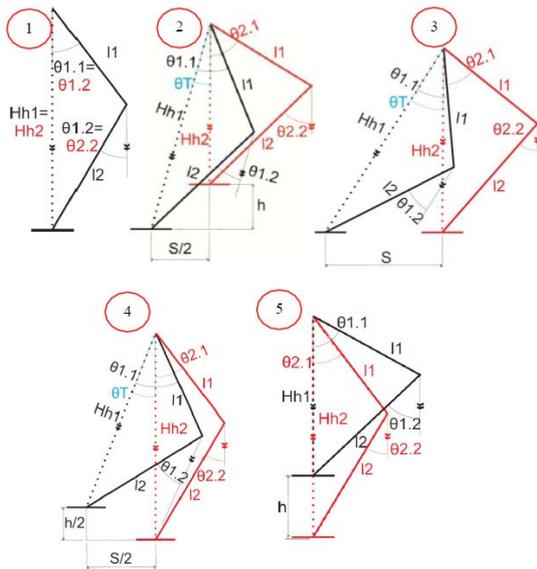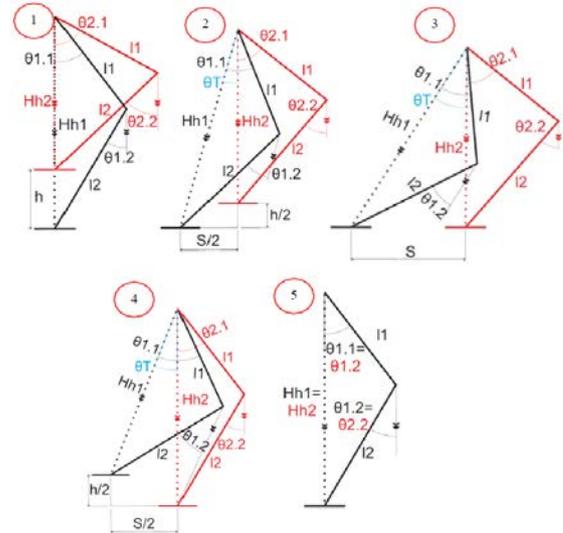
Figure 2. Starting Motion Diagram [1].

As the red leg position leads the black leg and the foot of the red leg touches the ground, there are degree formed between the reference line of the red leg and the black leg because of the difference in position between Hh1 and Hh2.

B. Full Motion

Figure 3 is the full motion diagram for the bipedal robot, which is the next motion after the starting motion. In the starting motion, the leg that is lifted at the end of the motion is the black leg. In the beginning of the full motion (based on the diagram) black leg is lifted (which is from the previous motion) as high as the requested height of swinging leg then it continues to swing forward until requested step distance reached and the foot touches the ground and the angle value
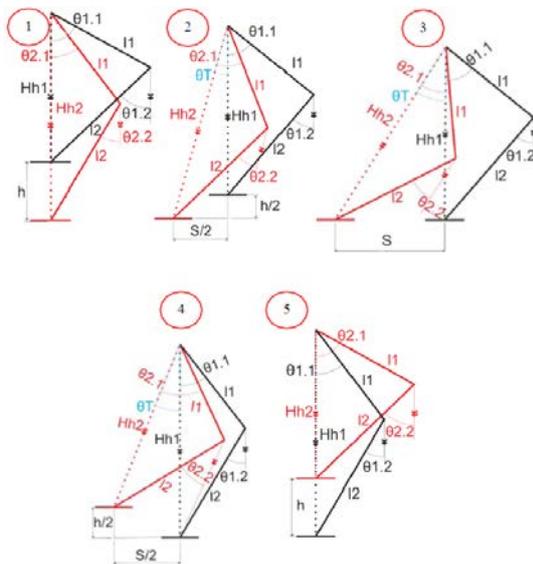

Figure 3. Full Motion Diagram [1].

Figure 4. Ending Motion Diagram [1].

between the reference lines reaches maximum value. Then the red leg will swing forward until both of the reference lines are on the same vertical line position with the red leg lifted as high as the requested height.

This full motion can be repeated as many as requested and the sequence will always be the same but with different leg lifted at the beginning of the motion. After the requested full motion fulfilled, the motion continues to the ending motion.

C. Ending Motion

Figure 4 is the ending motion diagram of the bipedal robot, begins (based on the ending motion diagram) with the red leg lifted as high as the requested height then swings forward until requested step distance, foot touches the ground and the angle value between reference line reaches maximum value. Then the black leg swings forward until it reaches as high as half of the requested height then goes back down. In the end of the ending motion, both of the leg will be in the same position and both legs stand on the ground.

III. EQUATIONS

The main formula use for the bipedal robot is based on the triangle formulation (Figure 5), and described in equation (1) to (4).

$$Hh^2 = l_1^2 + l_2^2 - 2l_1 l_2 \cos \beta \qquad (1)$$

$$l_1^2 = Hh^2 + l_2^2 - 2l_1 l_2 \cos \theta_2 \qquad (2)$$

$$l_2^2 = Hh^2 + l_1^2 - 2l_1 l_2 \cos \theta_1 \qquad (3)$$

$$\frac{l_1}{\sin \theta_2} = \frac{l_2}{\sin \theta_1} = \frac{Hh}{\sin \beta} \qquad (4)$$
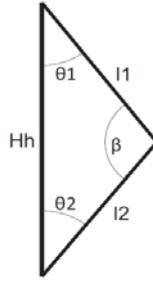
Figure 5. Triangle diagram [1].

A. Angle Value Between Reference Lines

The equation to find the angle value between reference lines is:

$$\theta_T = \tan^{-1}\left(\frac{S_{(t)}}{Hh_{(t)}}\right) \tag{5}$$

where θ_T is the angle value between reference lines.

B. Reference Line Value

The equation to calculate the value of the reference line of black leg and red leg are:

$$Hh_1 = \frac{Hh(t)}{\cos(\theta_T)} \tag{6}$$

$$Hh_1 = \frac{Hh(t)}{\cos(\theta_T)} - \frac{h(t)}{\cos(\theta_T)} \tag{7}$$

$$Hh_1 = (Hh_2)(\cos(\theta_T)) - h(t) \tag{8}$$

$$Hh_1 = Hh(t) \tag{9}$$

$$Hh_2 = (Hh_1)(\cos(\theta_T)) - \frac{h(t)}{2} \tag{10}$$

$$Hh_2 = Hh(t) \tag{11}$$

$$Hh_2 = \frac{Hh(t)}{\cos(\theta_T)} \tag{12}$$

$$Hh_2 = \frac{Hh(t)}{\cos(\theta_T)} - \frac{h(t)}{\cos(\theta_T)} \tag{13}$$

$$Hh_2 = (Hh_1)(\cos(\theta_T)) - h(t) \tag{14}$$

$$Hh_2 = Hh(t) \tag{15}$$

where:
Hh_1 : reference line of the black leg
Hh_2 : reference line of the red leg
$Hh(t)$: reference line value with respect to time.

Eq. 6 is to find the reference line value of the black leg in figure 2 and 4 at time $t = 0$ until time $t = t_f/2$ (number 1 until number 3). Eq. 7 is to find the reference line value of the black leg at the reference line value of the black leg at time $t = t_f /2$ until time $t = t_f$ (number 3 until number 5). For figure 4, eq. 8 is used to find the reference line value of the black leg at time $t = 0$ until time $t =$

$t_f /2$ (number 1 until number 3). Eq. 9 is to find the reference line value of the black leg at $t = t_f/2$ until time $t = t_f$ (number 3 until number 5).

Eq. 10 is to find the reference line value of the red leg in figure 2 at time $t = 0$ until time $t = t_f/2$ (number 1 until number 3), and eq. 11 is to find the reference line value of the red leg at time $t = t_f /2$ until time $t = t_f$ (number 3 until number 5). For figure 3, eq. 12 is to find the reference line value of the red leg in figure 4 at time $t = 0$ until time $t = t_f /2$ (number 1 until number 3), and eq. 13 is to find the reference line value of the red leg at time $t = t_f /2$ until time $t = t_f$ (number 3 until number 5). For figure 4, eq. 14 is to find the reference line value of the red leg at time $t = 0$ until time $t = t_f /2$ (number 1 until number 3), and eq. 15 is to find the reference line value of the red leg at time $t = t_f /2$ until time $t = t_f$ (number 3 until number 5).

C. Angle Value at Hip Joint, Knee Joint and Ankle Joint

The equations for angle value at hip joint for all motions (figure 2, figure 3 and figure 4) are:

$$\theta_{2,1} = -\cos^{-1}\left(\frac{l_{12} + Hh_{22} + l_{22}}{2l_1 Hh_2}\right) \tag{16}$$

$$\theta_{1,1} = \cos^{-1}\left(\frac{l_{12} + Hh_{12} + l_{22}}{2l_1 Hh_1}\right) \tag{17}$$

The equation for angle value at ankle joints are:

$$\theta_{1,3} = -(\theta_{1,2} - \theta_{1,1}) - \theta_T \tag{18}$$

$$\theta_{2,3} = |\theta_{2,2}| + \theta_{2,1} + \theta_T \tag{19}$$

$$\theta_{1,3} = -(\theta_{1,2} - \theta_{1,1}) \tag{20}$$

$$\theta_{2,3} = |\theta_{2,2}| + \theta_{2,1} \tag{21}$$

where:
$\theta_{1,1}$: Angle value at black leg hip joint
$\theta_{1,2}$: Angle value at black leg knee joint
$\theta_{1,3}$: Angle value at black leg ankle joint
$\theta_{2,1}$: Angle value at black leg hip joint
$\theta_{2,2}$: Angle value at black leg knee joint
$\theta_{2,3}$: Angle value at black leg ankle joint

Eq. 18 is used in starting motion and ending motion, with the assumption that the leg that swings first is according to the figures 2 and 4. Eq. 19 is used in full motion for the red leg in figure 3. Eq. 20 is used for the black leg for full motion in figure 3. Eq. 21 is used for the red leg in starting motion and ending motion in figures 3 and 4. These equations can be switched (between the equations that contain the θ_T 1 and the equations that do not contain the θ_T, i.e. between equations 18 and 20 or equations 19 and 21) depend on the position of the red leg and the

black leg in the motions. The equations for angle value at knee joints are:

$$\theta_{1,2} = \cos^{-1}\left(\frac{l_2{}^2 + Hh_1{}^2 + l_1{}^2}{2l_2 Hh_1}\right) + \theta_{1,1} \tag{22}$$

$$\theta_{2,2} = -\left(\cos^{-1}\left(\frac{l_2{}^2 + Hh_2{}^2 + l_1{}^2}{2l_2 Hh_2}\right)\right) + \theta_{2,1} \tag{23}$$

The theta and reference line results of the starting motion, full motion and the ending motion are shown at table 1, table 2, and table 3.

D. Hip Height Equations

Figure 6 is the requested linear graph example of hip height, where the initial time is $t = 0$ and the time final is $t_f = 4$. Basic equation for the linear equation is:

$$\frac{y - y_1}{y_2 - y_1} = \frac{x - x_1}{x_2 - x_1} \tag{24}$$

From figure 6, y equal to Hh and x equal to t. The equation 24 then become:

$$\frac{Hh - Hh_1}{Hh_2 - Hh_1} = \frac{t - t_1}{t_2 - t_1} \tag{25}$$

The equation for time $t = 0$ until time $t = t_f/2$ for hip height is:

$$Hh(t) = \left\{\frac{2t}{t_f}(-h)\right\} + Hh \tag{26}$$

The equation for time $t = t_f/2$ until time $t = t_f$ for hip height is:

$$Hh(t) = \left\{\frac{2t - t_f}{t_f}(h)\right\} + (Hh - h) \tag{27}$$

Table 1.
Theta value and reference line result for starting motion.

ΘT/deg	Hh1/mm	Θ1,1/deg	Θ1,2/deg	Hh2/mm	Θ2,1/deg	Θ2,2/deg	Θ1,3/deg	Θ2,3/deg
0.0	230.0	41.3	71.9	230.0	-41.3	-71.9	-30.6	30.6
2.6	217.7	48.5	85.5	205.0	-60.6	-102.9	-37.0	42.3
5.6	206.0	54.3	96.2	180.0	-79.1	-128.5	-41.9	49.3
8.9	194.8	59.1	104.8	180.0	-79.1	-128.5	-45.7	49.3
12.5	184.4	63.1	111.6	180.0	-79.1	-128.5	-48.4	49.3
8.9	182.2	68.6	117.5	192.5	-69.7	-116.0	-48.9	46.4
5.6	180.9	72.9	122.0	205.0	-60.6	-102.9	-49.2	42.3
2.6	180.2	76.3	125.6	127.5	-51.3	-88.4	-49.3	37.1
0.0	180.0	79.1	128.5	230.0	-41.3	-71.9	-49.3	30.6

Table 2.
Theta value and reference line result for full motion.

ΘT/deg	Hh1/mm	Θ1,1/deg	Θ1,2/deg	Hh2/mm	Θ2,1/deg	Θ2,2/deg	Θ1,3/deg	Θ2,3/deg
0.0	180.0	79.1	128.5	230.0	-41.3	-71.9	-49.3	30.6
2.6	180.0	79.1	128.5	217.7	-48.5	-85.5	-49.3	37.0
5.6	180.0	79.1	128.5	206.0	-54.3	-96.2	-49.3	41.9
8.9	180.0	79.1	128.5	194.8	-59.1	-104.8	-49.3	45.7
12.5	180.0	79.1	128.5	184.4	-63.2	-111.6	-49.3	48.4
8.9	192.5	69.7	116.0	182.2	-68.6	-117.5	-46.4	48.9
5.6	205.0	60.6	102.9	180.9	-72.9	-122.0	-42.3	49.2
2.6	217.5	51.3	88.4	180.2	-76.3	-125.6	-37.1	49.3
0.0	230.0	41.3	71.9	180.0	-79.1	-128.5	-30.6	49.3

Table 3.
Theta value and reference line result for ending motion.

| ΘT/deg	Hh1/mm	Θ1,1/deg	Θ1,2/deg	Hh2/mm	Θ2,1/deg	Θ2,2/deg	Θ1,3/deg	Θ2,3/deg
0.0	230.0	41.3	71.9	180.0	-79.1	-128.5	-30.6	49.3
2.6	217.7	48.5	85.5	180.0	-79.1	-128.5	-37.0	49.3
5.6	206.0	54.3	96.2	180.0	-79.1	-128.5	-41.9	49.3
8.9	194.8	59.1	104.8	180.0	-79.1	-128.5	-45.7	49.3
12.5	184.4	63.2	111.6	180.0	-79.1	-128.5	-48.4	49.3
8.9	194.8	59.1	104.8	192.5	-69.7	-116.0	-45.7	46.4
5.6	206.0	54.3	96.2	205.0	-60.6	-102.9	-41.9	42.3
2.6	217.7	48.5	85.5	217.5	-51.3	-88.4	-37.0	37.1
0.0	230.0	41.3	71.9	230.0	-41.3	-71.9	-30.6	30.6
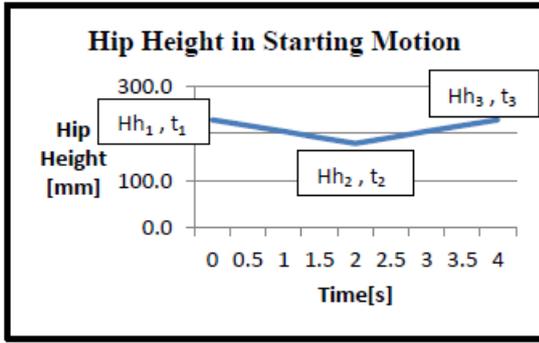
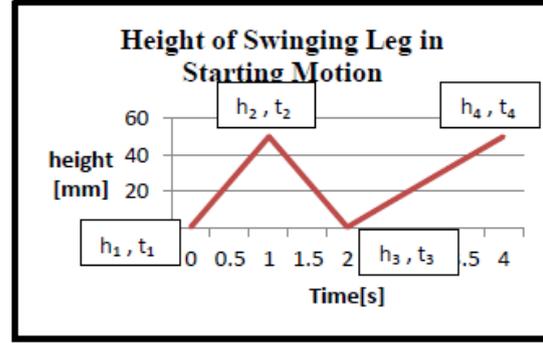Figure 6. Linear graph for Hh (Hip height) [1].

Figure 8. Linear graph for height of the swinging leg [1].

Where
    Hh   : Requested value of hip height
    t   : Time of the motion
    t_f : Time final value
    H   : Requested height of the swinging leg
          value

E. Step Distance Equation

Figure 7 is the linear graph example of step distance where the initial time is $t = 0$ and the time final is $t_f = 4$. The equation for time $t = 0$ until $t = t_f /2$ is:

$$S(t) = \frac{2St}{t_f} \qquad (28)$$

The equation for time $t = t_f/2$ until time $t = t_f$ is :

$$S(t) = \left\{ \frac{(2t - t_f)(-S)}{t_f} \right\} + S \qquad (29)$$

Where
    S(t) : Step distance value with respect to time
    S   : Requested step distance value

F. Height of Swinging Leg Equations

Figure 8 is the linear graph example of height of the swinging leg in starting motion. The equation for time $t = 0$ until time $t = t_f/4$ is:

$$h(t) = \frac{4ht}{t_f} \qquad (30)$$

The equation for time $t = t_f /4$ until time $t = t_f/2$ is:

$$h(t) = \left\{ \left(\frac{4t - 2t_f}{t_f} \right)(-h) \right\} + h \qquad (31)$$

Where h(t) is height of the swinging leg value with respect to time.

The equation for time $t = t_f/2$ until time $t = t_f$ is:

$$h(t) = \left(\frac{2t - t_f}{t_f} \right)(h) \qquad (32)$$

Figure 9 is the linear graph example of height of the swinging leg in full motion. The equation for time $t = 0$ until time $t = t_f/2$ is:

$$h(t) = \left\{ \left(\frac{2t}{t_f} \right)(-h) \right\} + h \qquad (33)$$

The equation for time $t = t_f/2$ until time $t = t_f$ in full motion is the same with equation 32, which is also used for time $t = t_f/2$ until time $t = t_f$ in starting motion.

Figure 10 is the linear graph example of height of the swinging leg in ending motion. The equation for time $t = 0$ until time $t = t_f/2$ is the same with equation 33, which is also used for time time $t = 0$ until time $t = t_f/2$ in full motion.

The equation for $t = t_f/2$ until time $t = 3t_f/4$ is:

$$h(t) = \left\{ \left(\frac{4t - 3t_f}{t_f} \right) \left(\frac{-h}{2} \right) \right\} + \frac{h}{2} \qquad (35)$$
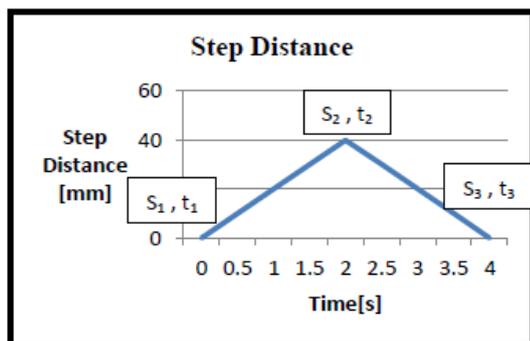

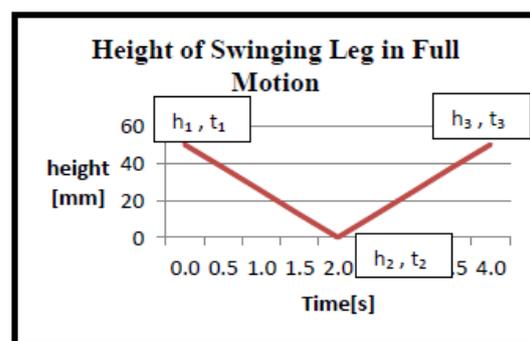Figure 7. Linear graph for S (Step Distance) [1].

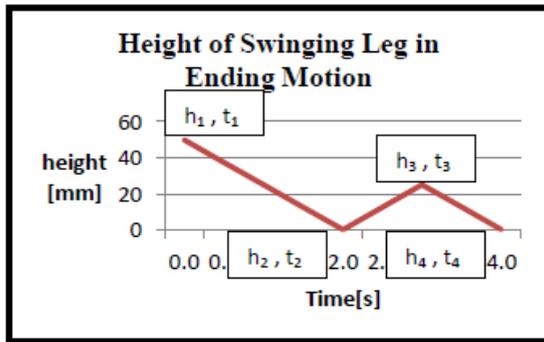Figure 9. Linear graph 2 for height of the swinging leg [1].

Figure 10. Linear graph 3 for height of the swinging leg [1].

IV.   RESULT AND DISCUSSION

Figure 11 is the actual result by using the results of the equations above as the input value for the program in the microcontroller [15]. The bipedal robot is able to move forward, which can be seen that the reference line (red line) forming an angle value with the vertical line (perpendicular to the ground, which is the yellow line).

The motion that is repeated more than once is only the full motion, which resulting the non stop walking motion of the bipedal robot. Take note that the bipedal robot in figure 11 is supported with cable, which tied on the hip part.
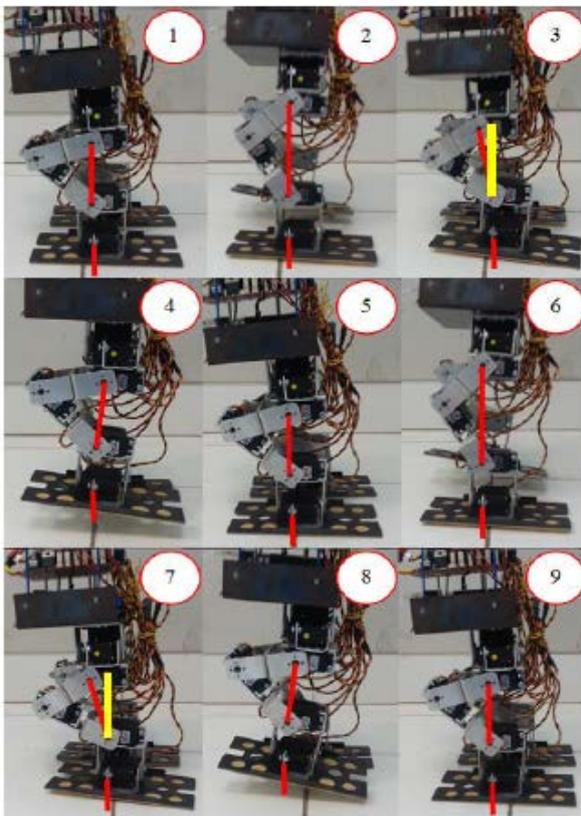

Figure 11. Qualitative Gait result [1].

V. CONCLUDING REMARKS

From the graphical result of the angle value and the change of hip height, height of the swinging leg and step distance value, it is shown that in the beginning of the starting motion and in the end of the starting motion bipedal robot will achieve one step forward. It is also shown in the full motion and the ending motion where from the graphical result, the bipedal robot is able to take steps forward.

The main contribution of this work is the introduction of θ_T where this angle synchronize the left and right leg. The observation of this gait movement is done qualitatively.

The ergonomic of leg design need to be further considered. Since during the qualitative observation, some condition of gait movement need to be further explored.

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