CHAPTER 4 - RESULTS AND DISCUSSIONS

4.1. Experiment Introduction

There are three sets of gait parameters which have been tested. Details of the parameters values are enlisted on Table 4.3 (first parameters set), Table 4.6 (second parameters set) and Table 4.9 (third parameters set).

The process of attempting the implementation of each set of parameters started with the gait model performance testing (Section 4.3.1 for the first parameters set, Section 4.4.1 for the second parameters set, and Section 4.5.1 for the third parameters set). *GaitSimulator* program was run for the purpose of predicting the state of the legs during the motion of the actual quadruped robot. The gait was then approximated by means of taking certain setpoints. *GaitSetpoint* program calculated both the angular position and angular velocity setpoints. The obtained data was analysed to determine whether the gait defined by the respective parameters set is applicable for the quadruped robot (Section 4.3.2 for the first parameters set, Section 4.4.2 for the second parameters set, and Section 4.5.2 for the third parameters set). The valid array of setpoints was embedded to the motor controller afterwards (Section 4.6).

The leg parameters (*LF1*, *LF2*, *LF3*, *LH1*, *LH2*, and *LH3*) are the length of the leg segments of the quadruped leg. *LF1*, *LF2*, and *LF3* respectively represent the length of the first, second, and third segment of the front limbs in millimeters, while *LH1*, *LH2*, and *LH3* correspond to the length of the first, second, and third segment of the hind limbs, also in millimeters. These parameters were adjusted to match the actual quadruped robot.

The angle profile parameters conclude the parameters related to the forming of sinusoidal profile of the hip and knee joint angle profile. *Tswing* and *Tstance* symbolize the periods of swing phase and stance phase on one gait cycle in seconds. The other angle profile parameters are the minimum and maximum angular position of the hip joint (*Hip min* and *Hip max*), the minimum and maximum angular position of the knee joint (*Knee min* and *Knee max*), and the stance phase oscillation amplitude of the knee joint (*A knee st*). Their units may be in degrees or in radians. Hip and knee joint angle parameters were determined intuitively by considering the minimum and maximum angular position which can utilize the position control feature of the servo motors.

Simulation parameters are related to discrete time calculation. The number of stick figures per cycle displayed on the result window is determined under *figures per cycle*, while the number of cycle to be repeated is input under *number of cycle*. The phase differences of the legs are represented as fraction of one cycle period. *Phase Differences FL*, *FR*, *HL*, and *HR* are the phase offsets of the front-left leg, front-right leg, hind-left leg and hind-right leg.

4.2. Result of Motor Test

The following motor test served as a preliminary test in case of implementing the speed control approach. The main purpose of the test was to relate the required value of PWM duty cycle to the desired angular velocity and the input voltage obtained from the voltage source. The input voltage and PWM duty cycle were being the independent variables, while the measured angular velocity was being the dependent variable.

Table 4.1. Angular Velocity Measurement Result

ω (deg/ms)	Vs (V)	7	7.5	9	10.5	12
	Vin (V)	6.19	6.69	8.19	9.69	11.19
p						
-1023		-285.2	-308.2	-377.9	-439.42	-492.3
-768		-212.333	-227.375	-286.1	-339.567	-390.1
-512		-131.2	-146.75	-184.65	-222.6	-256.675
-256		-55.95	-62.26	-81.15	-102	-118.15
0		0	0	0	0	0
256		55.25	65.4	80.45	100.1	118.8
512		130.5333	144.3333	184.4333	224.2	254.1667
768		208.5	224.333	283.0667	336.4333	385.8167
1023		283.4	309.7667	375.0667	444.8	506.8625

The motor test experiment data is presented on Table 4.1. The resulting angular velocity ω was measured in variety of input voltage Vin and PWM duty cycle value p. The variable Vs denotes the output voltage of the variable power supply, measured on the output voltage terminal of the power supply, On the other hand, the variable Vin symbolizes the input voltage of the servo, measured on the input voltage terminal of the servo. There was a voltage drop of around 0.81 V.

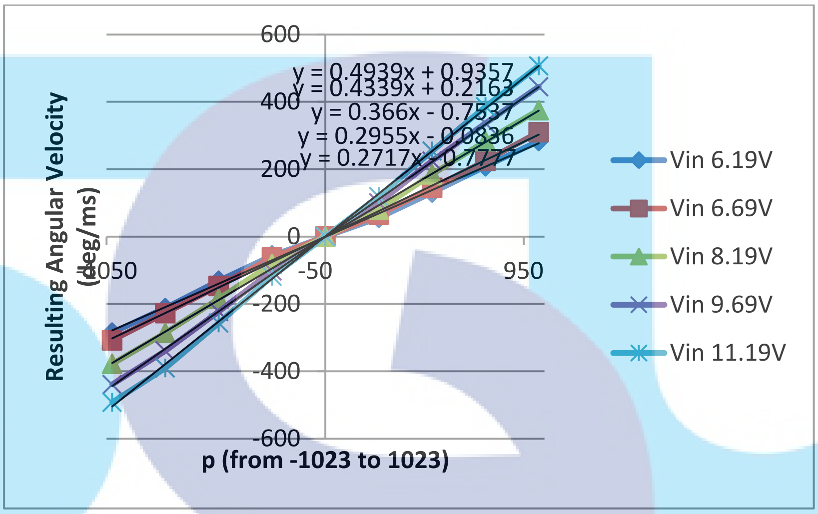

Figure 4.1. Angular Velocity as a Function of PWM Duty Cycle Value at Different Input Voltage

Figure 4.1 shows the relationship of the resulting angular velocity and the PWM duty cycle value. The resulting angular velocity as a function of PWM duty cycle is very similar to a linear equation, and its y-intercept is really close to zero. Therefore, the resulting angular velocity may be defined mathematically:

$$\omega = mp \quad \text{Eq. (4.1)}$$

where ω = the resulting angular velocity (deg/ms)

m = the slope of angular velocity with respect to PWM duty cycle value (deg/ms)

p = PWM duty cycle value (from -1023 to 1023)

In addition, the slope m itself, as shown by Table 4.2, was rising with increasing input voltage. The values on Table 4.2 were obtained from the regression lines shown on Figure 4.1.

Table 4.2. Slope *m* as a Function of Input Voltage – Tabular Representation

Vin (V)	m (deg/ms)
6.19	0.2717
6.69	0.2955
8.19	0.366
9.69	0.4339
11.19	0.4939

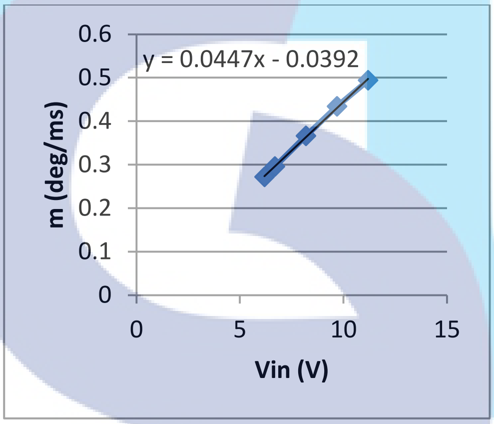

Figure 4.2. Slope *m* as a Function of Input Voltage – Graphical Representation

The relationship between the slope and the input voltage is depicted on Figure 4.2. According to the linear regression line displayed on the figure, the equation of the slope as a function of input voltage is:

$$m = 0.0447 \frac{deg}{V\,ms} V_{in} - 0.0392 \frac{deg}{ms} \quad \text{Eq. (4.2)}$$

Combining Equation 4.1 and 4.2:

$$\omega = mp$$

$$\omega = \left(0.0447 \frac{deg}{V\,ms} V_{in} - 0.0392 \frac{deg}{ms}\right) p$$

Finally, the equation of required PWM value duty cycle p as the function of input voltage V_{in} and desired angular velocity ω is stated as Equation 4.3:

$$p = \frac{\omega}{0.0447\frac{deg}{V\,ms}V_{in} - 0.0392\frac{deg}{ms}} \quad \text{Eq. (4.3)}$$

4.3. First Gait Parameters Set – Walking Gait

Table 4.3 enlists the first set of gait parameters to be tested.

Table 4.3. First Gait Parameters Set: Walking Gait

Leg Parameters					
Front Limbs			Hind Limbs		
LF1 (mm)	LF2 (mm)	LF3 (mm)	LH1 (mm)	LH2 (mm)	LH3 (mm)
56	76	70	76	74	49
Angle Profile Parameters					
Tswing (s)	0.5				
Tstance (s)	1.5				
Hip					
min (degrees)			max (degrees)		
15			45		
Knee					
min (degrees)		max (degrees)		A knee st (degrees)	
60		90		6	
Simulation Parameters					
Segmentation					
figures per cycle			number of cycle		
20			1		
Phase Differences					
FL	FR	HL	HR	Gait	
0	0.5	0.75	0.25	walking	

The length of the front leg segments was 56, 76, and 70 mm for the hip-knee segment, knee-ankle segment, and ankle-toe segment; while the length of the hind leg segments were 76, 74, and 49 mm for the hip-knee segment, knee-ankle segment, and ankle-toe segment. The swing and stance periods were set to be 0.5 and 1.5 seconds respectively. The hip joint angle oscillated from its lowest point at 15 degrees to its highest point at 45 degrees. The knee joint angle ranged from 60 degrees to 90 degrees, with 6 degrees of oscillation amplitude during the stance phase of a particular leg. The graphical representation was defined to show a single period cycle with 20 stick figures of leg state per cycle. There was a quarter period of phase differences among the legs which sequence was configured as quadrupedal walking gait.

4.3.1. Result of Gait Model Performance Testing of the 1st Parameters Set

Figure 4.3 displays the result window of the *GaitSimulator* program as an effect of applying the first set of gait parameters, which represents the walking gait.

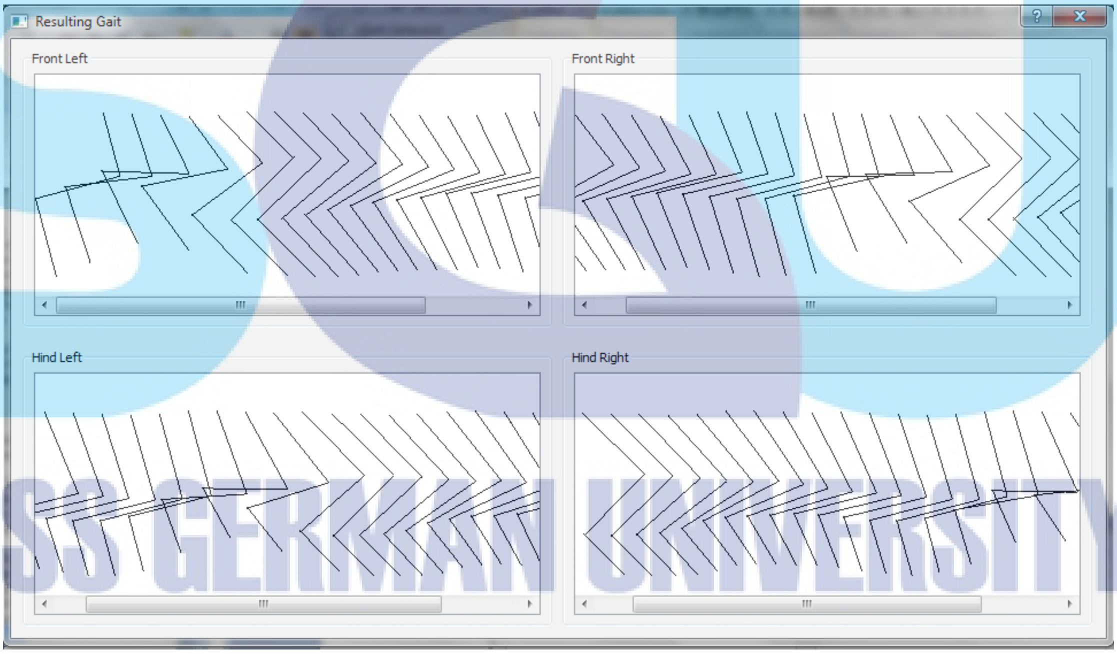

Figure 4.3. Leg Motion Prediction Result, 1st Parameters Set

As visualized on Figure 4.3, the top-left area depicting the motion of the front-left leg shows that the leg retracted its knee while swinging itself forward, leaving the ground surface (toe-off). During this motion the hip joint angle profile increased from its minimum point, whereas the knee joint angle decreased from its maximum value. After the knee was fully retracted, the knee joint angle was at its narrowest state. This concluded the first-half of the swing phase of the front-left leg.

During the second-half of swing phase, the hip joint angle kept increasing that the leg continued its swinging process. However, the knee joint angle started to widen back to the maximum point, which is its natural state. The whole process caused the extension of the leg. The swing phase of the leg ended with touch-down of the toe of the leg. On this state, both of the hip and knee joint angle were at their peak.

After touch-down, the leg started to swing backward and retracted its knee. The hip joint angle gradually went down. The knee joint angle narrowed again, but not as much as it did during swing phase. At certain point the knee joint angle stopped decreasing and broadened instead. When the hip joint angle reached its minimum position and the knee joint angle had gone back to its maximum position, the stance phase of the leg was completed, and the leg was ready to start another cycle.

The movement sequences of the other legs were very much the same. The difference was that the occurrence of the sequence was shifted by the phase offsets. The front-left leg served as the reference, since the phase offset of the front-left leg was 0 for the first set of gait parameters. Phase offset indicates that the leg in particular has its start point ahead of the reference leg by certain fraction of cycle period. The hind-right leg was ahead of the front-left leg by a quarter of cycle period. The front-right leg was ahead of the hind-right leg also by a quarter of cycle period, and the hind-left leg was ahead of the front-right leg by another quarter of cycle period.

4.3.2. Result of Gait Approximation Performance Testing of the 1st Parameters Set

In addition to the gait parameters set on Table 4.3, the time segmentation period was determined at 0.125 second, which value was also input to the *Tdiff* parameter on the user interface of *GaitSetpont* program. The text file in which the program stored its calculation result contains values including the calculated time setpoints in seconds, hip joint angular position setpoints in degrees, knee joint angular position setpoints in degrees, cam joint angular position setpoints in degrees, hip joint angular velocity setpoints in degrees per second, and cam joint angular velocity setpoints in degrees per second.

On this particular discussion of gait approximation, the intended meaning of this test was to examine the possibility of applying the proposed gait parameters set onto the actual quadruped robot platform. The main consideration was the capability of the servo motors used as the actuators of the hip and knee joint. However, the knee joint is not directly manipulated by the servo, but connected through a cam and pulley system instead. It is the cam which is directly mounted on the servo. For this reason, primary attention was given to the angular position and velocity of the hip and cam joints. Meanwhile, the competence of the servo motors is measured by its ability to reach certain angular position at certain time, or technically in providing the required angular velocity to achieve such goal.

Table 4.4. Hip Motor Setpoints Calculation Result, 1st Parameters Sets

Time Setpoint (seconds)	Angular Position Setpoint (degrees)	Delta of Angular Position Setpoints (degrees)	Average Changing Rate of Angular Position Setpoint (degrees / second)	Angular Velocity Setpoint (degrees / second)
0.000	14.9	-	-	0.0
0.125	19.3	4.4	35.6	71.2
0.250	30.1	10.7	85.9	100.6
0.375	40.8	10.7	85.9	71.2
0.500	45.3	4.4	35.6	0.0
0.625	44.7	-0.5	-4.1	-8.3
0.750	43.2	-1.5	-12.1	-16.0
0.875	40.8	-2.4	-19.3	-22.6
1.000	37.7	-3.1	-25.2	-27.7
1.125	34.0	-3.7	-29.3	-30.9
1.250	30.1	-3.9	-31.4	-32.0
1.375	26.2	-3.9	-31.4	-30.9
1.500	22.5	-3.7	-29.3	-27.7
1.625	19.3	-3.1	-25.2	-22.6
1.750	16.9	-2.4	-19.3	-16.0
1.875	15.4	-1.5	-12.1	-8.3
2.000	14.9	-0.5	-4.1	0.0

Table 4.4 and 4.5 contain the calculation result of the motor setpoints due to the first gait parameters set. The first, second, and fifth columns (Time Setpoint, Angular Position Setpoint, and Angular Velocity Setpoint) had their values directly taken from

the raw data output of the *GaitSetpoint* program. The values on the third column (Delta of Angular Position Setpoints) are the differences between the angular position of a particular time setpoint and that of the previous time setpoint. The fourth column (Average Changing Rate of Angular Position Setpoint) is calculated by dividing the values on the third column with the time segmentation period (0.125 second). This resulted on average changing rate of angle displacement of the hip joint. It is to be differed with the fifth column, in which the angular velocities are intended for approximating the sinusoidal profile of joint angle position as a set of quadratic equations. In the mean time, the average changing rate of angular position would approximate the sinusoidal profile of joint angle position as a set of linear equations.

Gait approximation through position control, as narrated on Section 3.5.1, utilizes the position control mode of HerkuleX servo, using the angular position setpoints (the second column). Thus, examining the motor capability was done by consulting the values on the fourth column. The biggest absolute value of average angular position changing rate indicates the required achievable rotation speed of the motor actuating the joint for implementing gait approximation through position control. The maximum absolute value on the fourth column of Table 4.4 is 85.9 degrees per second. Compared to the maximum rotation speed of HerkuleX servo of 360 degrees per second at 7.4 V, the servo is capable of actuating the hip motor based on the gait defined by the first parameters set.

On the other hand, gait approximation through speed control, explained on Section 3.5.2, exploits the speed control mode of HerkuleX servo using the angular velocity setpoints (the fifth column). The motor capability in actuating the joint by means of speed control was checked by investigating the maximum absolute value of angular velocity on the fifth column. The angular velocity value of 100.6 degrees per second is also lower than the maximum rotation speed of the HerkuleX servo at its rated voltage, thus speed control is also applicable on actuating the hip motor based on the gait defined by the first parameters set.

Examination of the motor capability in manipulating the cam joint to perform the gait based on the first parameters set follows the same way, but referring to the data on Table 4.5, which shows the cam motor setpoints calculation result due to the first set of gait parameters. The required rotation speed for applying position control is 311.1 degrees per second, while for applying speed control the rotation speed of 675.4 degrees per second is necessary. Judged against the HerkuleX maximum rotation speed of 360 degrees per second, the cam joint actuation based on the first set of gait parameters is possible through position control, but not through speed control.

Table 4.5. Cam Motor Setpoints Calculation Result, 1st Parameters Set

Time Setpoint (seconds)	Angular Position Setpoint (degrees)	Delta of Angular Position Setpoints (degrees)	Average Changing Rate of Angular Position Setpoint (degrees / second)	Angular Velocity Setpoint (degrees / second)
0.000	0.0	-	-	0.0
0.125	35.5	35.5	284.4	568.8
0.250	74.4	38.9	311.1	53.3
0.375	35.5	-3.3	-26.7	-675.4
0.500	0.0	-35.5	-284.4	106.6
0.625	2.3	37.8	302.5	-70.5
0.750	8.5	6.3	50.1	170.8
0.875	17.3	11.0	88.3	-30.3
1.000	26.3	9.0	72.1	174.5
1.125	33.1	24.0	192.3	-66.7
1.250	35.5	2.5	20.0	106.6
1.375	33.1	30.6	244.5	-146.6
1.500	26.3	-6.7	-53.9	38.7
1.625	17.3	24.0	192.3	-182.9
1.750	8.5	-8.8	-70.2	42.5
1.875	2.3	11.0	88.3	-142.8
2.000	0.0	-2.3	-18.1	106.6

4.4. Second Gait Parameters Set – Trotting Gait

The second set of gait parameters is enlisted on Table 4.6. The length of the front leg segments was 56, 76, and 70 mm for the hip-knee segment, knee-ankle segment, and ankle-toe segment; while the length of the hind leg segments were 76, 74, and 49 mm for the hip-knee segment, knee-ankle segment, and ankle-toe segment. The swing and stance periods were set to be 0.5 and 1 second respectively. The other angle profile parameters were maintained to be the same as the angle profile parameters of the first parameter set. The minimum position of the hip joint angle was at 15 degrees, while the maximum position was at 45 degrees. The knee joint angle fell and rose on the values inbetween 60 and 90 degrees during the swing phase of a particular leg, but the profile only dipped with 6 degrees of oscillation amplitude during the stance phase. A single period cycle with 20 stick figures of leg state per cycle would form the graphical representation. A half period of phase differences existed between the different diagonal pair of legs which sequence was configured as quadrupedal trotting gait.

Table 4.6. Second Gait Parameters Set: Trotting Gait

Leg Parameters					
Front Limbs			**Hind Limbs**		
LF1 (mm)	**LF2 (mm)**	**LF3 (mm)**	**LH1 (mm)**	**LH2 (mm)**	**LH3 (mm)**
56	76	70	76	74	49
Angle Profile Parameters					
Tswing (s)	0.5				
Tstance (s)	1				
Hip					
min (degrees)			**max (degrees)**		
15			45		
Knee					
min (degrees)		**max (degrees)**		**A knee st (degrees)**	
60		90		6	
Simulation Parameters					
Segmentation					
figures per cycle			**number of cycle**		
20			1		
Phase Differences					
FL	**FR**	**HL**	**HR**	**Gait**	
0	0.5	0.5	0	trotting	

4.4.1. Result of Gait Model Performance Testing of the 2nd Parameters Set

The narration on Section 4.3.1 concerning the reference sequence of leg movement in one cycle period is also valid for the second set of gait parameters. Compared to the first set of gait parameters, which stance period was 1 second, the 0.5 second stance period of the second gait parameters set resulted on the increasing and decreasing of joint angle being more rapid during the stance phase.

The second set of gait parameters represented the trotting gait. Each two legs were paired so that they were on the same phase. The legs were paired diagonally, that is, the front-left leg was coupled with the hind-right leg, while the front-right leg was coupled with the hind-left leg. The front-left and hind-right legs were the reference, while the other pair was more advance by half cycle period. Figure 4.4 thus illustrates the motion of the legs on performing the trotting gait.

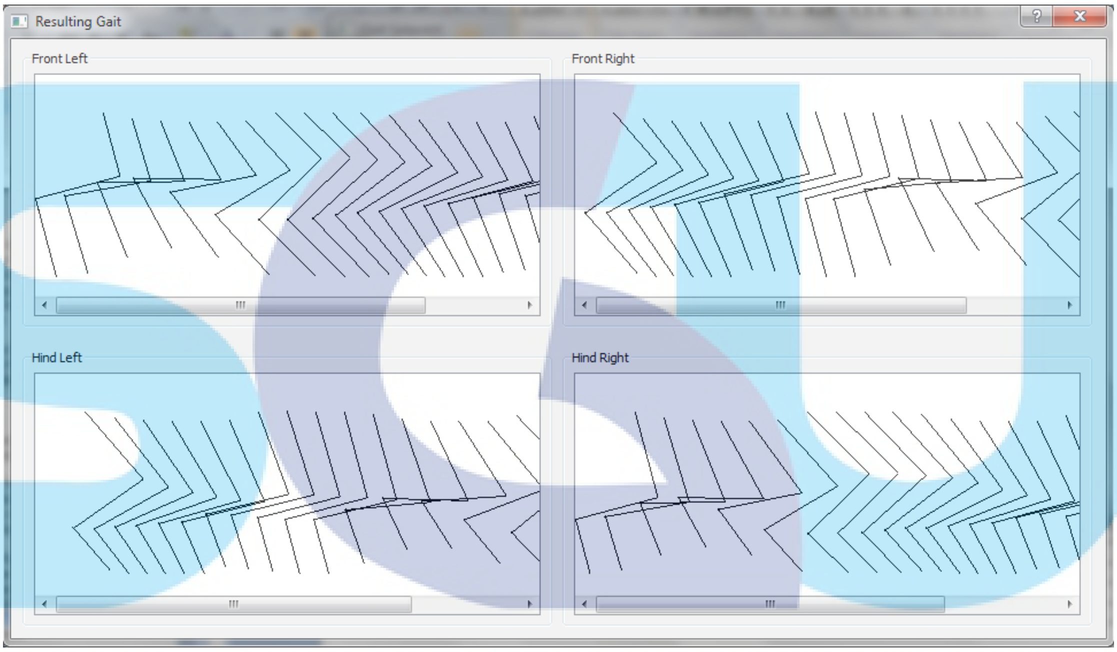

Figure 4.4. Leg Motion Prediction Result, 2nd Parameters Set

4.4.2. Result of Gait Approximation Performance Testing of the 2nd Parameters Set

Similarly to the first set of gait parameters, the time segmentation period was determined at 0.125 second. The value was input to the *Tdiff* parameter on the user interface of *GaitSetpont* program. The gait approximation analysis method accounted on Section 4.3.1 towards the first set of gait parameters was also performed on the second set as well. The rotation speed limit was 360 degrees per second, corresponds to the maximum allowable rotation speed of HerkuleX servo at rated voltage of 7.4 V.

The calculation result of the hip motor setpoints based on the second gait parameters set is presented on Table 4.7. The maximum absolute value of hip joint angular position average changing rate on Table 4.7 is 85.9 degrees per second. Compared to the maximum rotation speed of HerkuleX servo of 360 degrees per second at 7.4 V, the servo is capable of actuating the hip motor based on the gait defined by the second parameters set. Meanwhile, the angular velocity value of 100.6 degrees per second is also lower than the maximum rotation speed of the HerkuleX servo at its rated voltage, thus speed control is also applicable on actuating the hip motor based on the gait defined by the second parameters set.

Table 4.7. Hip Motor Setpoints Calculation Result, 2nd Parameters Set

Time Setpoint (seconds)	Angular Position Setpoint (degrees)	Delta of Angular Position Setpoints (degrees)	Average Changing Rate of Angular Position Setpoint (degrees / second)	Angular Velocity Setpoint (degrees / second)
0.000	14.9	-	-	0.0
0.125	19.3	4.4	35.6	71.2
0.250	30.1	10.7	85.9	100.6
0.375	40.8	10.7	85.9	71.2
0.500	45.3	4.4	35.6	0.0
0.625	44.1	-1.2	-9.2	-18.5
0.750	40.8	-3.3	-26.3	-34.2
0.875	35.9	-4.9	-39.4	-44.6
1.000	30.1	-5.8	-46.5	-48.3
1.125	24.3	-5.8	-46.5	-44.6
1.250	19.3	-4.9	-39.4	-34.2
1.375	16.1	-3.3	-26.3	-18.5
1.500	14.9	-1.2	-9.2	0.0

Table 4.8 shows the cam motor setpoints calculation result due to the second set of gait parameters. The required rotation speed for applying position control is 311.1 degrees per second, while for applying speed control the rotation speed of 675.4 degrees per second is necessary. Judged against the HerkuleX maximum rotation speed of 360 degrees per second, the cam joint actuation based on the second set of gait parameters is possible through position control, but not through speed control.

Table 4.8. Cam Motor Setpoints Calculation Result, 2nd Parameters Set

Time Setpoint (seconds)	Angular Position Setpoint (degrees)	Delta of Angular Position Setpoints (degrees)	Average Changing Rate of Angular Position Setpoint (degrees / second)	Angular Velocity Setpoint (degrees / second)
0.000	0.0	-	-	0.0
0.125	35.5	35.5	284.4	568.8
0.250	74.4	38.9	311.1	53.3
0.375	35.5	-38.9	-311.1	-675.4
0.500	0.0	-35.5	-284.4	106.6
0.625	5.0	5.0	39.7	-27.2
0.750	17.3	12.3	98.7	224.6
0.875	30.1	12.8	102.5	-19.6
1.000	35.5	5.4	43.5	106.6
1.125	30.1	-5.4	-43.5	-193.6
1.250	17.3	-12.8	-102.5	-11.4
1.375	5.0	-12.3	-98.7	-186.0
1.500	0.0	-5.0	-39.7	106.6

4.5. Third Gait Parameters Set – Bounding Gait

The length of the front leg segments was 56, 76, and 70 mm for the hip-knee segment, knee-ankle segment, and ankle-toe segment; while the length of the hind leg segments were 76, 74, and 49 mm for the hip-knee segment, knee-ankle segment, and ankle-toe segment. The swing and stance periods were set to be 0.5 and 0.25 second respectively. Consistent to the first and second set of gait parameters, the other angle profile parameters were identical to the angle profile parameters of the prequelling parameter sets. The minimum hip joint angle was 15 degrees, while the maximum position was 45 degrees. The knee joint angle varied inbetween 60 and 90 degrees during the swing phase, and the oscillation amplitude during the stance phase was 6 degrees. The graphical illustration of the gait would be formed of a single period cycle with 20 stick figures of leg state per cycle. A half period of phase differences existed between the different parallel pair of legs which sequence was configured as quadrupedal bounding gait. The members of the third set of gait parameters are recited on Table 4.9.

Table 4.9. Third Gait Parameters Set: Bounding Gait

Leg Parameters					
Front Limbs			**Hind Limbs**		
LF1 (mm)	**LF2 (mm)**	**LF3 (mm)**	**LH1 (mm)**	**LH2 (mm)**	**LH3 (mm)**
56	76	70	76	74	49
Angle Profile Parameters					
Tswing (s)	0.5				
Tstance (s)	0.25				
Hip					
min (degrees)			**max (degrees)**		
15			45		
Knee					
min (degrees)		**max (degrees)**		**A knee st (degrees)**	
60		90		6	
Simulation Parameters					
Segmentation					
figures per cycle			**number of cycle**		
20			1		
Phase Differences					
FL	**FR**	**HL**	**HR**	**Gait**	
0	0	0.5	0.5	bounding	

4.5.1. Result of Gait Model Performance Testing of the 3rd Parameters Set

The third set of gait parameters followed the basic sequence of leg motion in one cycle period, as accounted on Section 4.3.1 and also adhered by the second as well as the first set of gait parameters. The stance period of 0.25 second gave even more rapid changing of hip and knee joint angle than that of the first and second gait parameters set during the stance phase.

Alike the second parameters set, there were also two pairs of legs, each consisted of two legs. However, instead of diagonally paired, the legs are parallelly-paired. The front-left and front-right legs were coupled together, while the hind-left and hind-right legs made up the other pair of legs. The two pairs differed by half cycle period of phase offset, forming the bounding gait.

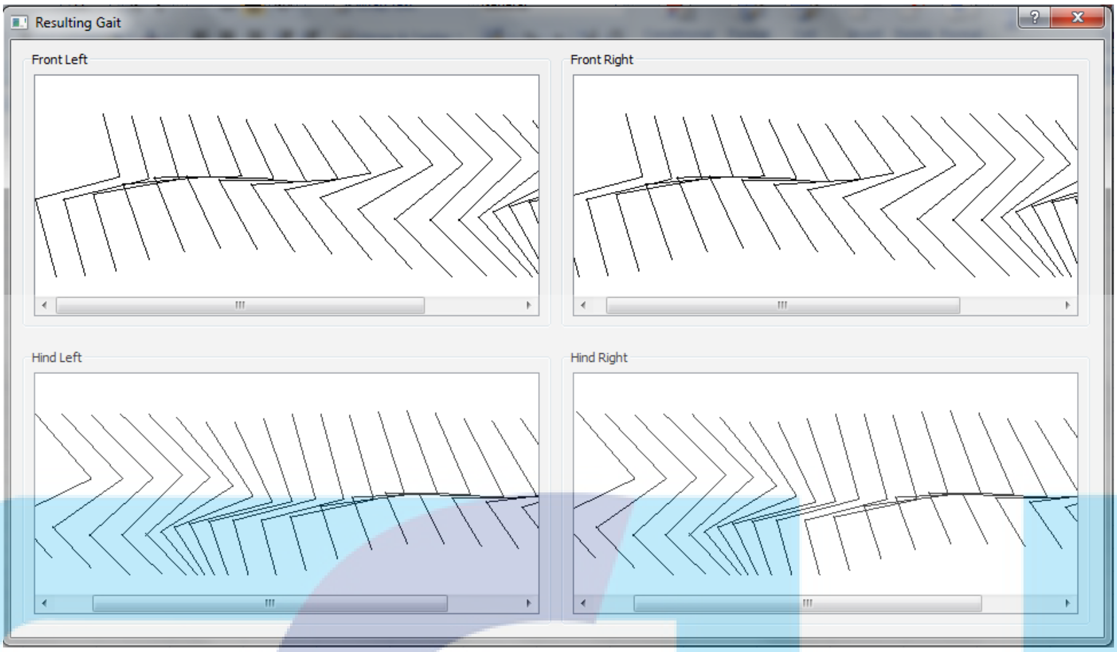

Figure 4.5. Leg Motion Prediction Result, 3rd Parameters Set

4.5.2. Result of Gait Approximation Performance Testing of the 3rd Parameters Set

The hip motor setpoints calculation result due to the third parameters set is displayed on Table 4.10.

Table 4.10. Hip Motor Setpoints Calculation Result, 3rd Parameters Set

Time Setpoint (seconds)	Angular Position Setpoint (degrees)	Delta of Angular Position Setpoints (degrees)	Average Changing Rate of Angular Position Setpoint (degrees / second)	Angular Velocity Setpoint (degrees / second)
0.000	14.9	-	-	0.0
0.125	19.3	4.4	35.6	71.2
0.250	30.1	10.7	85.9	100.6
0.375	40.8	10.7	85.9	71.2
0.500	45.3	4.4	35.6	0.0
0.625	30.1	-15.2	-121.5	-242.9
0.750	14.9	-15.2	-121.5	0.0

Consistent to the value of time segmentation period applied on the first and second set of gait parameters, the value was maintained at 0.125 second for the third set of gait parameters. Actuation of the hip motor through both position and speed control is possible, since the maximum magnitude of the hip angular position average changing rate is 121.5 degrees per second, and that of the hip angular velocity is 242.9 degrees per second. Both of these values are under the 360 degrees per second rotation speed limit.

Table 4.11. Cam Motor Setpoints Calculation Result, 3rd Parameters Set

Time Setpoint (seconds)	Angular Position Setpoint (degrees)	Delta of Angular Position Setpoints (degrees)	Average Changing Rate of Angular Position Setpoint (degrees / second)	Angular Velocity Setpoint (degrees / second)
0.000	0.0	-	-	0.0
0.125	35.5	35.5	284.4	568.8
0.250	74.4	38.9	311.1	53.3
0.375	35.5	-38.9	-311.1	-675.4
0.500	0.0	-35.5	-284.4	106.6
0.625	35.5	35.5	284.4	462.2
0.750	0.0	-35.5	-284.4	-1031.0

Table 4.11 contains the calculation result data of the cam motor setpoints for the third set of gait parameters. The critical magnitudes of the cam joint angular position changing rate and angular velocity are 311.1 degrees per second and 1031 degrees per second respectively. While the gait approximation through position control is applicable compared to the 360 degrees per second rotation speed limit, the gait approximation through speed control is proved to be too demanding.

4.6. Summary of Gait Approximation Performance

Gait approximation is approximating both the hip and knee joint angle by determining certain setpoints. The time segmentation period for the three sets of gait parameters is defined to be 0.125 second. For ensuring the implementation of position control mode of the motor controller, the values on the column “Average Changing Rate of Angular

Position Setpoint (degrees / second)" were considered, whether there were values exceeding the maximum speed of the motor or not. For ensuring the implementation of speed control mode of the motor controller, the values on the column "Angular Velocity Setpoint (degrees / second)" were consulted. Similarly to the position control mode, there should be no value bigger than the maximum speed of the motor.

The rated maximum speed of the HerkuleX servo with input voltage of 7.4V is 360 degrees per second. Therefore, position control mode may be used for generating gait with the first, second, and third parameters sets on the actual quadruped robot. However, speed control mode seems not applicable for any of the three gait parameters set, since some of angular velocity setpoints of the cam motor setpoints on the three parameters set exceed the 360 degrees per second limit.

Table 4.12. Comparison of Gait Approximation Result

Set	Rotation Speed Limit (deg/s)	Maximum Magnitude of Angular Position Changing Rate (deg/s)	Maximum Magnitude of Angular Velocity (deg/s)	Conclusion
1	360	Hip: 85.9 Cam: 311.1	Hip: 100.6 Cam: 675.4	Position control is possible, speed control is not possible
2	360	Hip: 85.9 Cam: 311.1	Hip: 100.6 Cam: 675.4	Position control is possible, speed control is not possible
3	360	Hip: 121.5 Cam: 311.1	Hip: 242.9 Cam: 1031	Position control is possible, speed control is not possible

4.7. Result of Gait Implementation Performance Testing

Due to the result of gait approximation performance test, as concluded on Table 4.12, only position control mode of the motor controller is tested. The first set of gait parameters is implemented on the quadruped robot.

When the quadrupedal robot performed the gait, the body of the robot tended to tilt to the left due to the difference of force magnitude exerted by the linear spring for countering the load on each leg. However, when the lower part of the robot is slightly supported while it is moving like shown in Figure 4.6, the robot is able to move forward, but the tip of the leg frequently grazed the rubbery surface. Another problem lied on the pulley system. The string used for retracting the leg was often loose, while ideally the tension of the string was meant to be kept at most of the time.

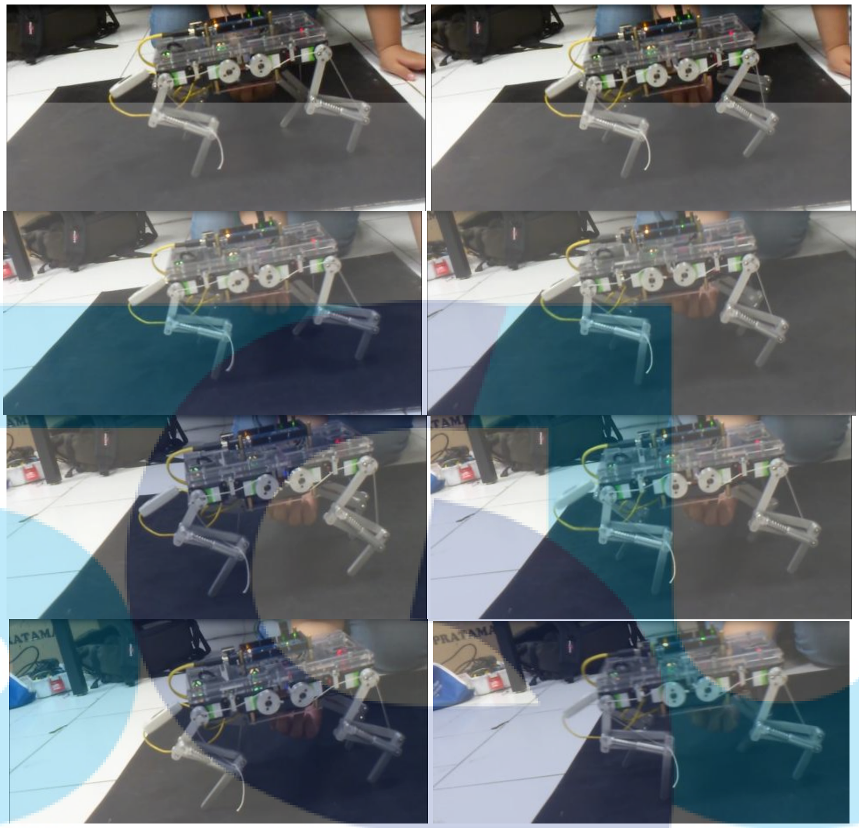

Figure 4.6. Implementation of the 1st Set of Gait Parameters

However, after replacing the springs (so that the spring length is equal for each leg instead of longer at the back or at the front), the robot was able to move forward without any additional support.