Control of an 8-Legged, 24 DOF, Mechatronic Robot

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Abstract
The objective of this project was to programme an 8-legged robot, each leg being identical and having 3 degrees of freedom each, to move in one dimension, i.e. forward and backwards with varying speeds.

24 servos, model Futaba S9402 for the, "hamstring" and "thigh", and Futaba S9001, for the rotation, were used, 3 per leg, 2 of which for the extension and contraction of the leg and the other for its rotation. Programming involved the use of one Basic Stamp II™ micro-controller chip for each leg. There is also one chip used for timing coordination and radio control purposes.

Future developments of this robot could include 2 dimensional translation and rotational motion.

Acknowledgements
We would like to take this golden opportunity to extend our heart-felt appreciation to the project supervisor, Dr. Francis Malcolm John Nickols, for his invaluable guidance and assistance for the duration of this project.

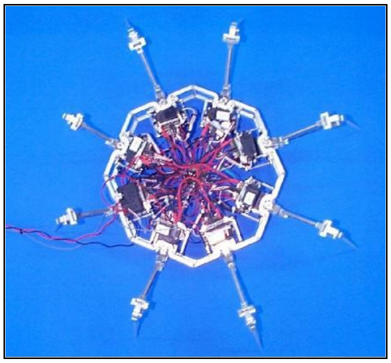
We would also like to thank all the staff of Mechanical and Production Engineering Mechatronic and Control Lab, especially Mdm. Grace Ho for her help in assisting in the assembling of the robot and for the scanning of our materials.

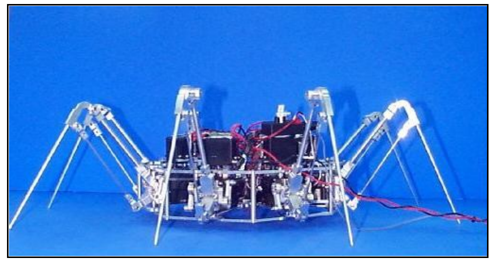
We would also like to thank Assoc. Prof. Michael Lau for teaching to us some of the software programmes in the laboratory.

Introduction
Traversing rough and undulating terrain for probing and reconnaissance require legged robots for the need for added maneuverability, which wheeled vehicles, cannot provide. Being unmanned, these robots eliminate the risks to human life when investigating dangerous environments.

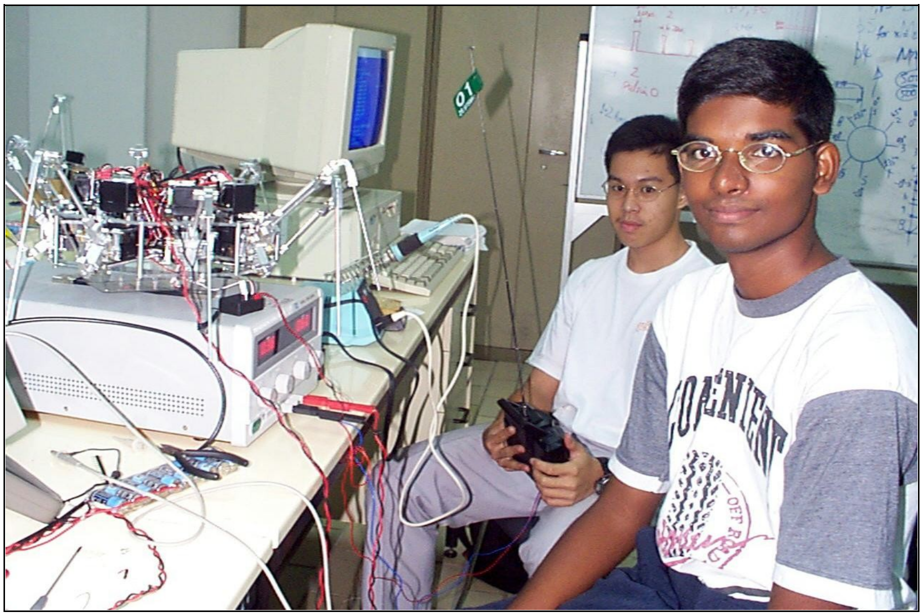
The development of new robots also stimulate thinking and nurture problem solving skills through the investigation of the gait of the robot and how to programme it. The new ideas formulated can be applied to other projects.

Our project deals with one of the numerous types of legged robots. Other such robots include those with 2, 3, 4, etc. legs. Another project under the NTU TERP 1999 is programming a 60-legged, 120 DOF, mechatronic robot. The 8-legged robot, figure 1 was designed with the imitation of the motion of spiders in mind.

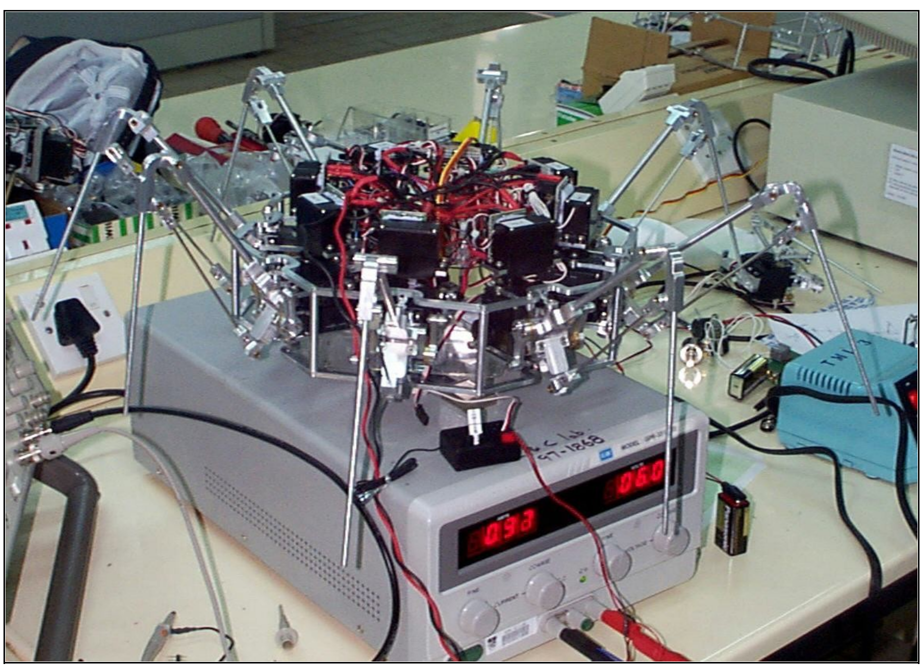




Robot Spider top view and side view



This is us working at the bench



Robot Spider on the bench

Procedure for Programmes

To make the whole robot move, we have to deal with the each leg one at a time, coming up with programmes for each leg, one at a time initially. When we were done with that, we had to coordinate the leg motions such that the gait of the walking in a straight line is achieved. A diagram of the 8 legs attached to the body is shown in figure 2. The legs have been named Leg 0 to 7 clockwise starting from the front.

To make the robot move forward, Leg 0 has to move with 0° heading, Leg 1 with 45° heading, Leg 2 with 90° heading, Leg 3 with -135° heading, Leg 4 with 180° heading, Leg 5 with -45° heading, Leg 6 with -90° heading and Leg 7 with 135° heading. When each of the legs receive their respective programmes, they still need to be in the correct phase for the proper gait. This gait would have 7 of the legs on the ground at all times and only one in the air and each leg would take turns from Leg 0 to 7 to be in the air. This means that the lifting of the legs would be transmitted clockwise around the body. The purpose of this gait is to support the massive structure of the robot.

Note: Original experiments were carried out with what is now defined as 180° heading as 0° heading. Redefinition was to make forward motion in direction of Leg 0.

0° Heading

Firstly, we did some experiments to plot the motion of the foot (end of the leg which touches the ground*) relative to the body (frame of the central structure). This was so as to define the motion in terms of equations. The foot was made to move in one dimension along a line drawn on graph paper. This was done by connecting potentiometers to the controlling circuit and to vary pulse widths of θ_{ham} and θ_{thi} (pulsout values to the "hamstring" servo and the "thigh" servo respectively). Values of θ_{ham} and θ_{thi} were taken for *x*** (displacement from the centre position of the leg motion) between –5.0cm to +5.0cm at intervals of 1.0cm. Results from this experiment were tabulated, Table 1, and plotted in the graph shown in Graph 1. This was also done for straight-line 0° heading 1.5cm above the ground. With the 2 sets of plots, motion on the ground can be charted with the return path through the air. 2 other lines were drawn to determine the ground-to-air and air-to ground transitions for the foot to move from the straight line on the ground to the straight line in the air in the opposite direction and back. The equations in Equation 1 were derived from the linearisation of the graph. We then wrote the programme using these functions of rules and domains. This can be seen in Progamme 1. One error occurred due to the imprecision of the experiment, leading to inaccuracies of the equations; they had to be modified to allow the leg to move more smoothly.

The programme was initially designed such that the time spent in the air was equal to the time spent on the ground (500 steps each), but the latter had to be 7 times slower. So we kept the air travelling duration constant and scaled the steps in the ground stage 7 times up. There are now 4000 steps for the whole cycle, instead of the previous 1000 steps.

The speed of the leg motion can be varied due to the addition of the variable *y* in the step. *y* can be any integer value between 1 and 5 inclusive, so the speed lies between approximately $5.0ms^{-1}$ and $1.1ms^{-1}$.

With the 0° heading motion done, motions for 90°, 45° and 135° headings could be developed. The next one dealt with was the 90° heading motion.

**All ground measurements were taken at lab tabletop height, with the body about 4 cm above the top.*

***x=0 is used as the reference point to all the headings: 0°, 90°, 45°, 135° and their reverses. It is the mid-point of all the displacements of the leg motions on the ground and is kept constant in all measurements.*

90°, 45° and 135° Headings

To get the leg to move in 90° heading, θ_3 (pulsout value to the rotation servo) would now have to be considered. The foot would move parallel to its side of the body with the closest distance to the leg pivot point at x=0. There are 2 known methods to chart out the motion of this motion. Dr Nickols did the experimental and we also attempted it, but found it too tedious and used the theoretical method of determining the motion instead. The experimental technique, also used by Dr Nickols for 45° and 135° headings, involves drawing the path as a line on graph paper, guiding the foot along it and collecting the values of θ_{ham}, θ_{thi} and θ_3 at regular intervals. The method we used involved only measuring the value of θ_3 with the angle the leg makes with 0° heading, from –16.0° to 16.0° at increments of 2.0°. At zero heading, θ_3=722. A graph, Graph 2 was plotted with θ_3 against θ. We then used trigonometry, Diagram 3, where α is 90°, to calculate the necessary value of θ and R for defined integer values of *d* from –5.0cm to 5.0cm, where R=17.8-*x*, the distance of the foot from the axis of pivoting and *d* is the displacement of the foot from *x*=0. A graph is plotted with θ_{ham}, θ_{thi} and θ_3 against *d* and linearized. Equations derived from the graph, Graph 2, were used for the 90° heading programme, Programme 3.

The method for getting 45° heading is very similar to that for getting 90° heading except that α is 45° instead of 90°. With this, the corresponding values of θ_{ham}, θ_{thi}, θ_3 and R are different for values of *d*.

For the 135° heading, it relates to the 45° heading with θ_{ham} and θ_{thi} values being identical, but θ_3 values being reflected about the line θ_3=722, i.e. θ_3 of 135° heading is the reverse of that of 45°.

Reverse Leg Motion (180°, -90°, -45° and -135° Heading)

Reverse motion was quite a simple task to accomplish, as the concept involved is simple and general. We first inverted the step of each for-next loop; i.e. the final value of *x* becomes the initial value and vice versa. This only reverses the motion within each for next loop, but not for the whole cycle. We also had to reverse the sequence of the for next loops by making the first one the last, the second one the second-last, the third one the third-last and so on.

When this was done, each of the eight legs had a programme ready for the forward motion of the robot. Appendix E shows the program for one leg but the the programs for the other legs are not shown due to limited report length restrictions.

Timing

Each leg movement was properly defined, but the gait was not, yet. All the legs would be carrying out their cycles in a disorderly manner; they would not be taking turns one after another in a clockwise direction around the body. Other than that, each pair of programmes was of varying complexities and so the basic stamp would function within different duration and the legs would actually move at varying speeds. This would cause the gait to be disorderly after a while, even if it started off correctly and straight line motion may not even be achieved.

To overcome this problem, another basic stamp II is used as a timing chip. It would make sure the basic stamps of each leg would send out signals at correct timings. This stamp sends out pulses from eight of its pins p0 to p7 each of which connected to different stamps: p0 to the basic stamp of Leg 0, p1 to the basic stamp of Leg 1, etc. Each of these signals comprises a fat pulse 100μs long and 3999 other pulses which are 20μs long. The fat pulse, called the homing pulse, would signal the basic stamp of a particular leg to restart the whole cycle, i.e. the leg return to its original position, while the thinner pulses would signal the activation of each for-next loop. As each leg has to move such that their cycles are $\lambda/8$ out of phase of each other, where λ is the wavelength of each cycle, the signals are identical except for the translation to the right of each consecutive graph. Graph 5 represents this. The basic stamp of Leg 0 would receive its fat pulse first, that of Leg 1 second and so on such that Leg 0 would start moving first and Leg 7 last. The legs would maintain their phase of motion.

Radio Control (Speed variation)

Now the body can move forward, but only at defined speeds. As mentioned earlier, these are represented by integer values of y from 0 to 5. To make it move at different speeds, new programmes had to be downloaded with the new values of y. With radio control, this inconvenience can be eliminated. A radio receiver is connected to the circuit of the robot and would receive signals from a radio transmitter. Only one channel is required as this is only motion in one dimension. The radio receiver sends regular pulses to the timing chip with pulse widths depending on the frequency from the transmitter. We have written a programme such that for certain frequencies received and thus electrical signal produced, the width of the thin pulses is varied as factors of integers between 0 and 5, inclusive.

The programmes for the basic stamps of the legs are further modified by having the stamp to measure the received pulse width from the timing basic stamp and by simple mathematical calculations, translate the information into integer values from 0 to 5. These would be the values of y. With the radio control console, shifting the lever forward would increase the speed of the robot in the forward direction. When the lever is released, there is zero velocity. Reverse motion is disallowed.

Conclusion

Programming the robot has been quite a challenging task, especially the initial measurements to chart out the motion of each leg. Better results can be achieved with more precise measuring techniques and more experiments. Alternatively, a theoretical mathematical approach would be useful, calculating the dimensions of the legs and formulating equations relating them to the foot motion. This would allow programmes of other types of motion to be derived easily from a general rule.

Further developments can be done on the robot by extending the motion to fully one-dimensional with reverse motion and also in two dimensions, with the robot translating forward, backwards and sideways. Rotational motion should also be possible. However, the memory space in the E^3PROM is something to take note of. To keep the programmes small, a unified equation of the total leg motion should be derived, instead of using many linear equations which waste space.

More refinement has to be done on each leg movement, but that would be an extension of the project.

Appendix B — Diagrams

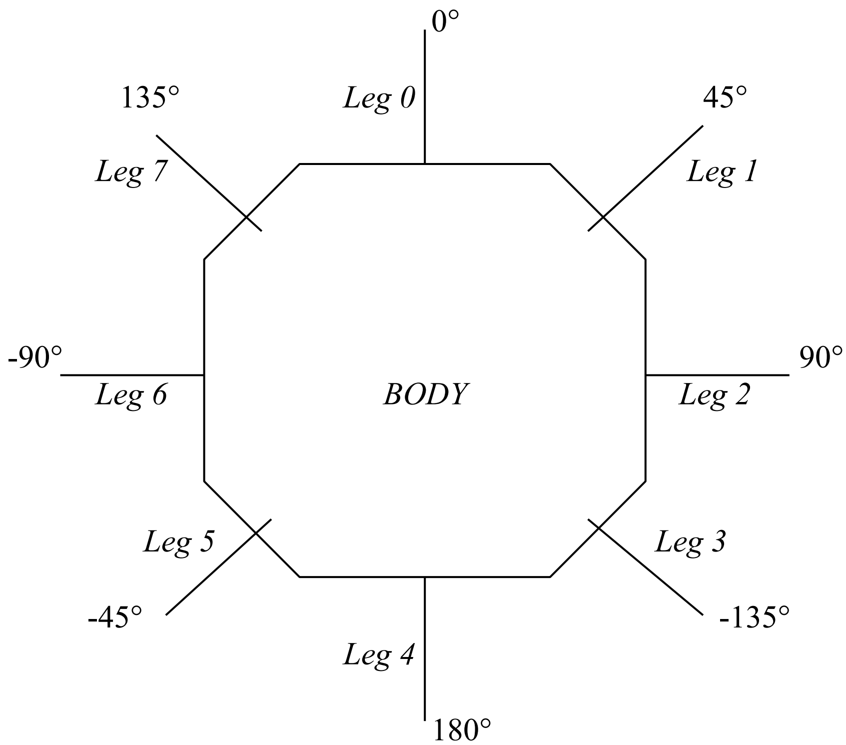


Diagram 1: leg headings for forward motion

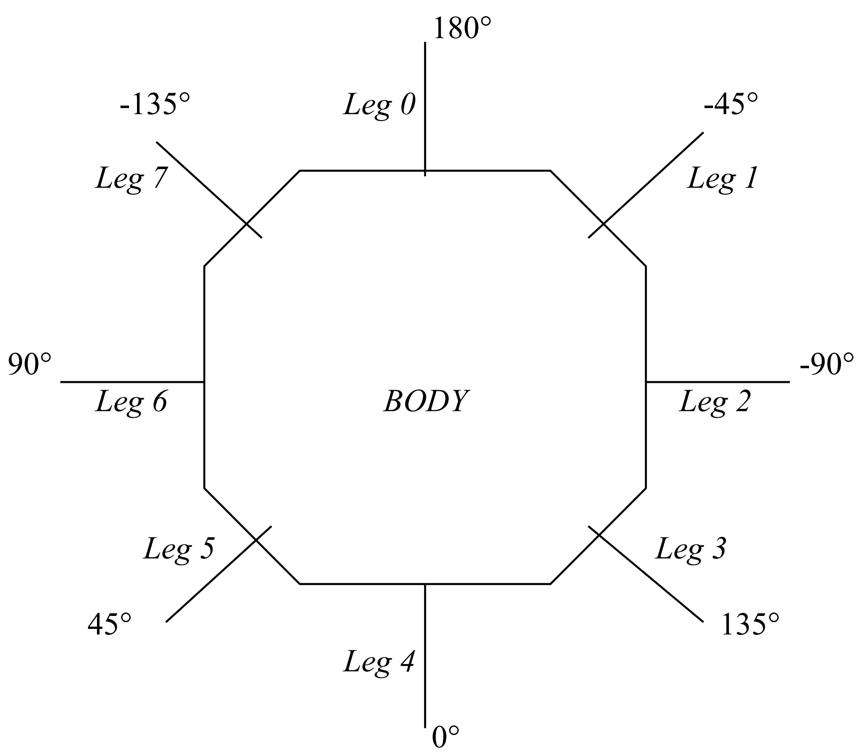


Diagram 2: leg headings for backward motion

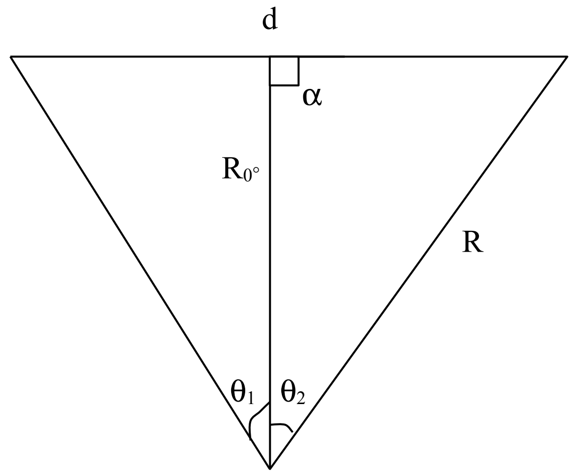


Diagram 3: trigonometric calculation for 90° heading; $\theta_1 \leq 0°$, $\theta_2 \geq 0°$, $R_{0°}$=17.75cm, α=90°

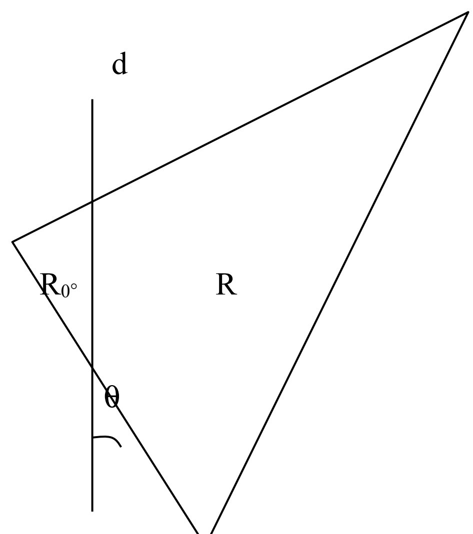


Diagram 4: trigonometric calculation for 45° heading; $R_{0°}$=17.75cm, α=45°

Appendix C—Tables

Ground		Air		
θ_{ham}	θ_{thi}	θ_{ham}	θ_{thi}	*x*/cm
778	716	656	870	0.0
754	698	638	840	1.0
726	682	616	814	2.0
706	662	600	784	3.0
680	640	580	756	4.0
664	628	572	740	4.5
656	614	558	724	5.0
640	598	552	702	5.5
628	586	540	694	6.0
606	552	518	656	7.0
578	514	488	622	8.0
552	472	464	582	9.0
522	418	426	536	10.0

Table 1: motion with 180° heading

θ/°	θ_{rot}
-16.0	930
-14.0	902
-12.0	874
-10.0	850
-8.0	824
-6.0	796
-4.0	770
-2.0	750
0.0	722
2.0	702
4.0	680
6.0	654
8.0	628
10.0	610
12.0	586
14.0	558
16.0	532

Table 2: relation of angular displacement and servo angular displacement

Ground		Air					
θ_{ham}	θ_{thi}	θ_{ham}	θ_{thi}	θ_{rot}	x/cm	R/cm	d/cm
652.5	615.0	552.5	725.0	540.0	4.94	18.44	-5
660.0	622.5	565.0	732.5	575.0	4.70	18.22	-4
665.0	627.5	570.0	737.5	612.5	4.50	18.00	-3
667.5	632.5	572.5	742.5	645.0	4.36	17.86	-2
670.0	637.5	575.0	745.0	682.5	4.28	17.78	-1
607.0	637.5	575.0	745.0	722.0	4.25	17.75	0
670.0	637.5	575.0	745.0	747.5	2.28	17.78	1
667.5	632.5	572.5	742.5	807.5	4.36	17.86	2
665.0	627.5	570.0	737.5	845.0	4.50	18.00	3
660.0	622.5	565.0	732.5	892.5	4.70	18.22	4
652.5	615.0	552.5	725.0	925.0	4.94	18.44	5

Table 3: motion with -90° heading

Ground		Air					
θ_{ham}	θ_{thi}	θ_{ham}	θ_{thi}	θ_{rot}	x/cm	R/cm	d/cm
750.0	696.4	635.5	840.0	560.0	1.1	14.6	-5.0
735.0	684.9	625.0	825.5	597.5	1.7	15.2	-4.0
720.0	673.4	612.5	802.5	635.0	2.3	15.8	-3.0
705.0	661.9	600.0	785.0	662.5	2.9	16.4	-2.0
687.5	648.5	587.5	765.0	690.0	3.6	17.1	-1.0
671.3	633.3	575.0	745.0	722.0	4.3	17.8	0.0
652.5	613.3	560.0	722.5	747.5	5.0	18.5	1.0
635.0	594.7	547.5	702.5	775.0	5.7	19.2	2.0
610.0	580.1	522.5	667.5	800.0	6.7	20.2	3.0
595.0	573.8	505.0	645.0	822.5	7.3	20.8	4.0
575.0	565.4	482.5	615.0	842.5	8.1	21.6	5.0

Table 4: motion with -45° heading

Appendix E—Equations

Graph equations for 180° heading.
Rotation: $b = 722$

Ground:
$0.0cm \leq x_{graph} < 4.0cm$ for $x = 0$ to 4
Hamstring: $a = 1555/2 - 25x$
Thigh: $c = 1435/2 - 115x/6$

$4.0cm \leq x_{graph} < 6.0cm$ for $x = 0$ to 2
Hamstring: $a = 1355/2 - 25x$
Thigh: $c = 640 - 80x/3$

$6.0cm \leq x_{graph} < 10.0cm$ for $x = 0$ to 4
Hamstring: $a = 1255/2 - 25x$
Thigh: $c=1175/2 - 875x/83$

Ground to Air Transition:
$10.0cm \leq x_{graph} < 9.5cm$ for $x = 0$ to $1/2$
Hamstring: $a = 1055/2 - 170x$
Thigh: $c = 865/2 - 255x$

Air:
$9.5cm \leq x_{graph} < 6.0cm$ for $x = 0$ to $7/2$
Hamstring: $a = 885/2 + 55x/2$
Thigh: $c = 560 + 75x/2$

$6.0cm \leq x_{graph} < 0.5cm$ for $x = 1/2$ to 6
Hamstring: $a = 540 + 215x/11$
Thigh: $c = 1585/2 + 1221x/4$

Air to Ground Transition:
$0.5cm \leq x_{graph} < 0.0cm$ for $x = 0$ to $1/2$
Hamstring: $a = 1295/2 +140x$
Thigh: $c = 1715/2 - 125x$

Graph equations for -90° heading.

Ground:
$-5.0cm \leq d < -1.0cm$ for $x = 0$ to 4
Hamstring: $a = 1315/2 + 25x/8$
Rotation: $b = 540 + 5x$
Thigh: $c = 1235/2 - x$

$-1.0cm \leq d < 0.0cm$ for $x = 0$ to 1
Hamstring: $a = 670$
Rotation: $b = 1365/2 + 182x/5$

Thigh: c = 1355/2

0.0cm ≤ *d* < 1.0cm for x = 0 to 1
Hamstring: a = 670
Rotation: b = 722 + 208x/5
Thigh: c=1355/2

1.0cm ≤ *d* < 5.0cm for x = 0 to 4
Hamstring: a = 670 – 25x/8
Rotation: b = 765 + 208x/5
Thigh: c = 1355 – 5x

Ground to Air Transition:
4.5cm ≤ *d* < 5.0cm for x = 0 to 1/2
Hamstring: a = 1525 – 185x
Rotation: b = 930 – 208x/5
Thigh: c = 1235/2 + 225x

Air:
4.5cm ≤ *d* < 1.0cm for x = 0 to 7/2
Hamstring: a = 565 + 20x/7
Rotation: b = 1815/2 – 208x/5
Thigh: c = 730 + 30x/7

1.0cm ≤ *d* < 0.0cm for x = 0 to 1
Hamstring: a = 575
Rotation: b = 1525/2 – 208x/5
Thigh: c = 670

0.0cm ≤ *d* < -1.0cm for x = 0 to 1
Hamstring: a = 575
Rotation: b = 722 – 182x/7
Thigh: c = 670

Air to Ground Transition:
-5.0cm ≤ *d* < -4.5cm for x = 0 to 1/2
Hamstring: a = 565 + 185x
Rotation: b = 1105/2 – 185x/5
Thigh: c = 1465/2 – 232x

Graph Equations for -45° heading

Ground:
-5.0cm ≤ *d* < -3.0cm for x = 0 to 2
Hamstring: a = 750 –15x
Rotation: b = 560 + 145x/4
Thigh: c = 695 – 65x/6

-3.0cm ≤ *d* < -2.0cm for x = 0 to 1
Hamstring: a = 720 – 15x
Rotation: b = 1265/2 + 95x/4

Thigh: c = 2020/3 – 65x/6

-2.0cm ≤ *d* < 0.0cm for x = 0 to 2
Hamstring: a = 705 – 15x
Rotation: b = 2625/4 + 255x/8
Thigh: c = 1355/3 – 15x

0.0cm ≤ *d* < 2.0cm for x = 0 to 2
Hamstring: a = 21345/2 – 39x/2
Rotation: b = 720 + 28x
Thigh: c = 1265/2 – 325x/17

2.0cm ≤ *d* < 3.0cm for x = 0 to 1
Hamstring: a = 1267/2 – 39x/2
Rotation: b = 776 + 28x
Thigh: c = 8753/15 – 32x/3

3.0cm ≤ *d* < 5.0cm for x = 0 to 2
Hamstring: a = 614 – 39x/2
Rotation: b = 800 + 85x/4
Thigh: c = 8753/15 – 32x/3

Ground to Air Transition:
5.0cm ≤ *d* < 4.5cm for x = 0 to 1/2
Hamstring: a = 575 – 170x
Rotation: b = 1685/2 – 85x/4
Thigh: c = 565 + 130x

Air:
4.5cm ≤ *d* < 3.0cm for x = 0 to 3/2
Hamstring: a = 490 + 23x
Rotation: b = 6655/8 – 85x/4
Thigh: c = 630 + 29x

3.0cm ≤ *d* < 2.0cm for x = 0 to 1
Hamstring: a = 525 + 23x
Rotation: b = 1605/2 – 28x
Thigh: c = 1347/2 + 85x/4

2.0cm ≤ *d* < 0.0cm for x = 0 to 2
Hamstring: a = 545 +65x/4
Rotation: b = 1549/2 – 28x
Thigh: c = 1405/2 + 85x/4

0.0cm ≤ *d* < -2.0cm for x = 0 to 2
Hamstring: a = 1155/2 + 65x/4
Rotation: b = 720 – 28x
Thigh: c = 745 + 20x

-2.0cm ≤ *d* < -3.0cm for x = 0 to 1

Hamstring: a = 1205/2 + 5x/4
Rotation: b = 664 – 28x
Thigh: c = 785 + 20x

-3.0cm ≤ d < -4.5cm for x = 0 to 3/2
Hamstring: a = 2415/4 + 5x/4
Rotation: b = 1275/2 – 175x/4
Thigh: c = 805 + 20x

Air to Ground Transition:
-4.5cm ≤ d < -5.0cm for x = 0 to 1/2
Hamstring: a = 1255/2 + 245x
Rotation: b = 4575/8 – 175x/4
Thigh: c = 1665/2 – 265x