CHAPTER VI

EXPERIMENTS AND DISCUSSIONS

Wheel-ground contact angle estimation and kinematics modeling derived in Chapter 4 and control schematic derived in Chapter 5 was implemented on the six-wheel robot test bed. The experiment divided into 3 sections. First, the experiment was set up to measure motion error. Second, the traction control system was verified by simulation on Visual Nastran 4D. And the robot test bed was tested on various types of terrain in the last experiment.

6.1 Motion Error

The experiments was set up to measure error in various motions, such as, linear motion (forward - backward), turning around a point, rotation in place, at various speeds. The motion error is finding out by compare the actual position and the desired position set by command.

6.1.1 Error in linear motion

The robot is commanded to move in straight line 3 times in 2.5 meters, with various speed, 5, 10 and 15 cm/s. The average positions are being plotted compare to the desire position.

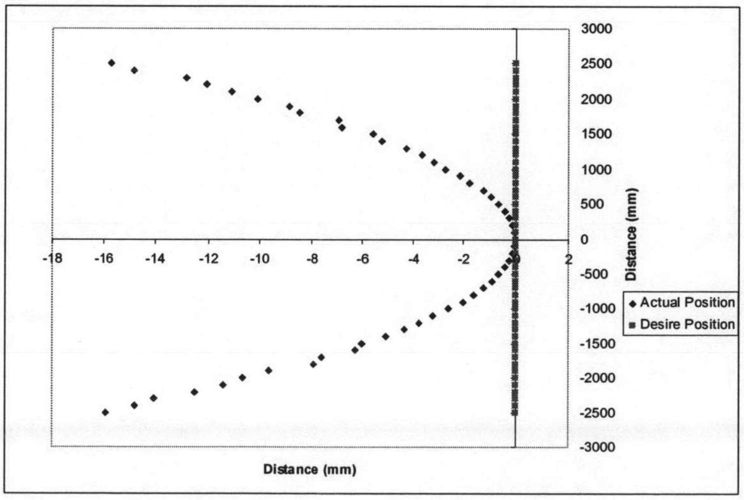

Figure 6.1: Position when move in linear motion with speed 5 cm/s

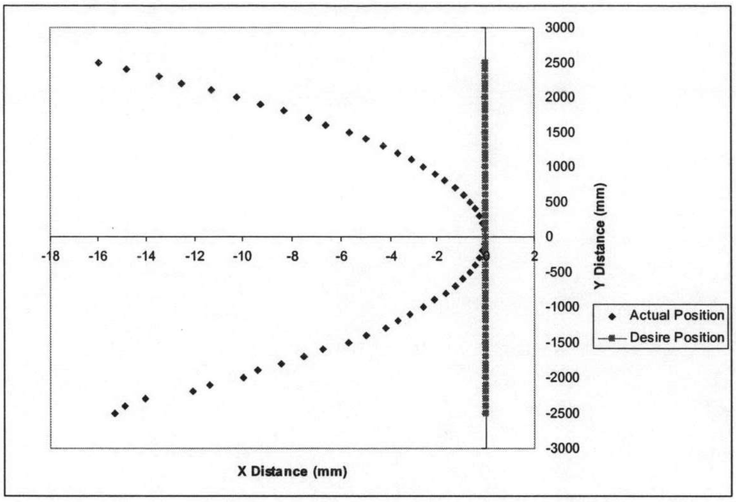

Figure 6.2: Position when move in linear motion with speed 10 cm/s

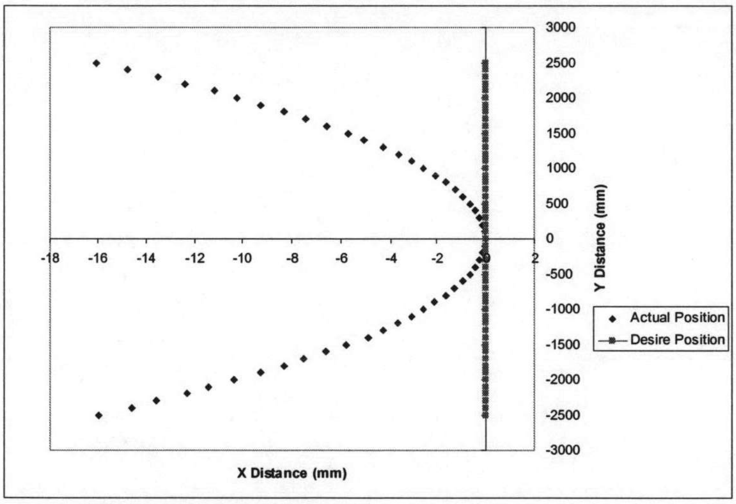

Figure 6.3: Position when move in linear motion with speed 15 cm/s

In linear motion, the robot tends to deviate to the left side in both directions (forward - backward). The error is slightly increased when using high speed. The error is about 16 mm at 2.5 m distance.

The error may be the result from many reasons such as:

1) Error in calibration of the steerable wheels.

2) Structure of the Rocker-Bogie suspension is not rigid enough to withstand the driving force. Due to it acts as a cantilever beam with long span; there will be undesired movement in sideway.

3) Error in measurement system.

6.1.2 Error when turning around a point.

The robot is commanded to turn around a point to the left and right side, with various speed, 5, 10 and 15 cm/s. Using 100 and 200 cm radius of curvature.

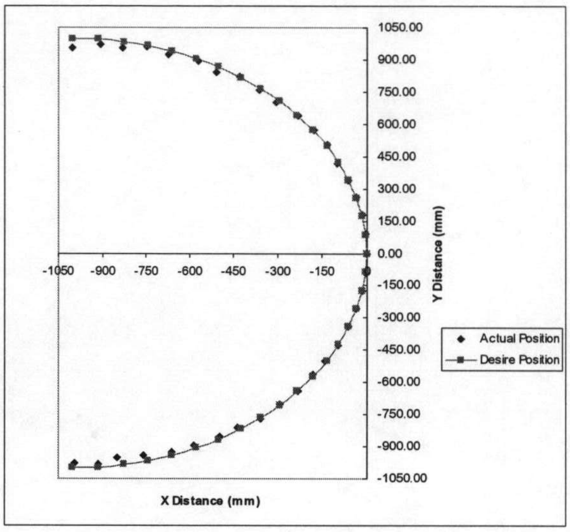

Figure 6.4: Position when turn around a point to the left with 100 cm radius of curvature with speed 5 cm/s

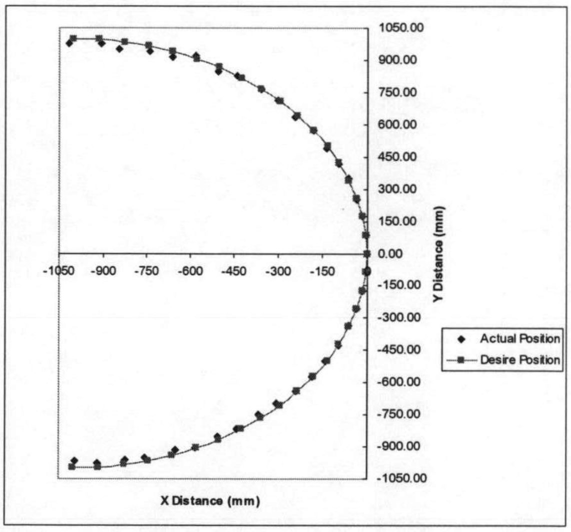

Figure 6.5: Position when turn around a point to the left with 100 cm radius of curvature with speed 10 cm/s

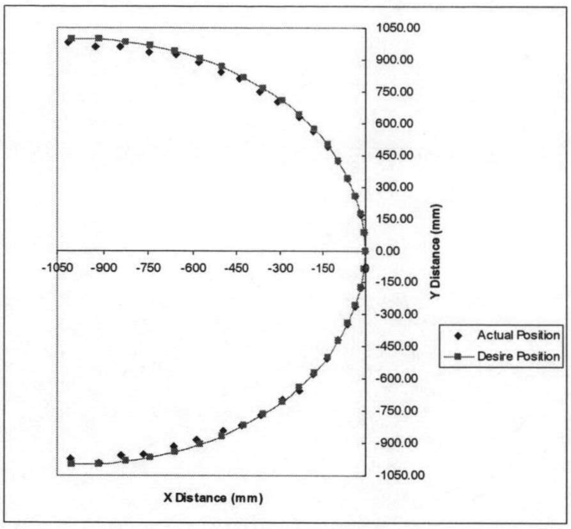

Figure 6.6: Position when turn around a point to the left with 100 cm radius of curvature with speed 15 cm/s

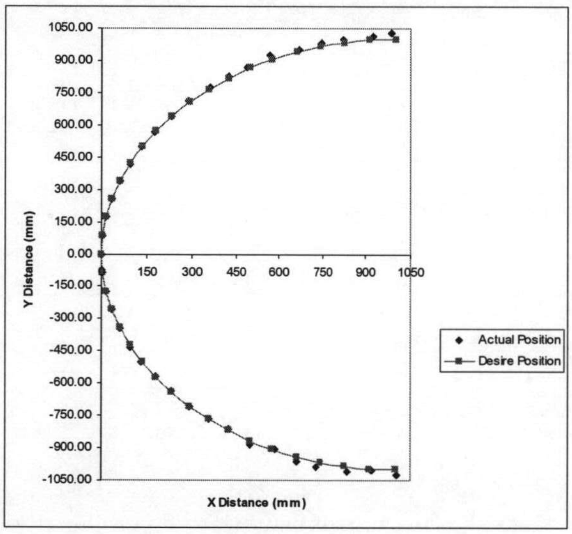

Figure 6.7: Position when turn around a point to the right with 100 cm radius of curvature with speed 5 cm/s

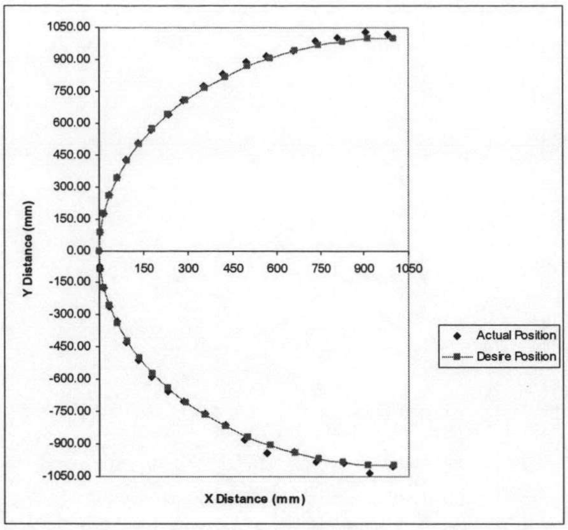

Figure 6.8: Position when turn around a point to the right with 100 cm radius of curvature with speed 10 cm/s

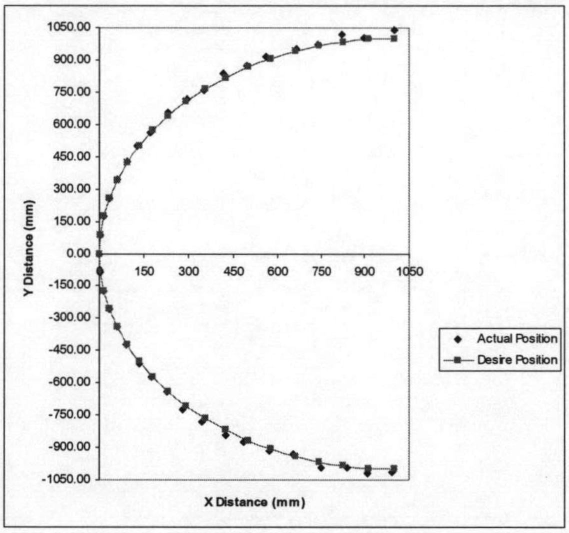

Figure 6.9: Position when turn around a point to the right with 100 cm radius of curvature with speed 15 cm/s

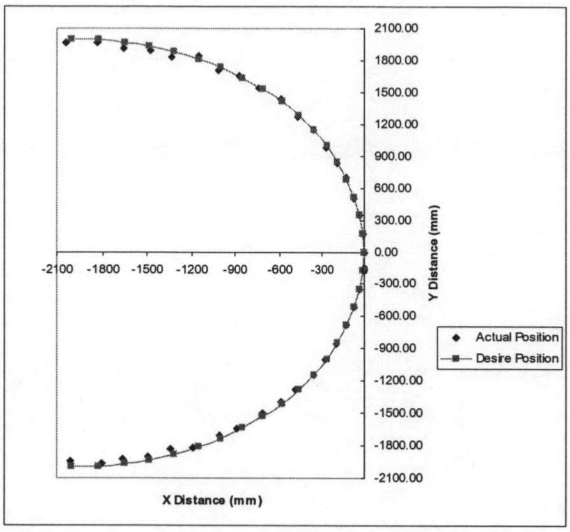

Figure 6.10: Position when turn around a point to the left with 200 cm radius of curvature with speed 5 cm/s

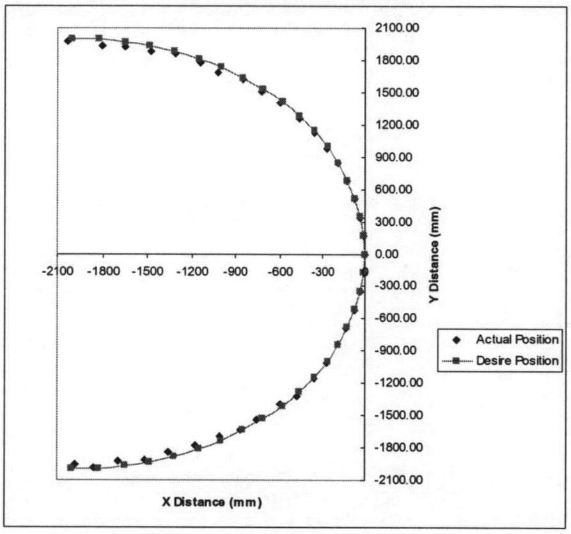

Figure 6.11: Position when turn around a point to the left with 200 cm radius of curvature with speed 10 cm/s

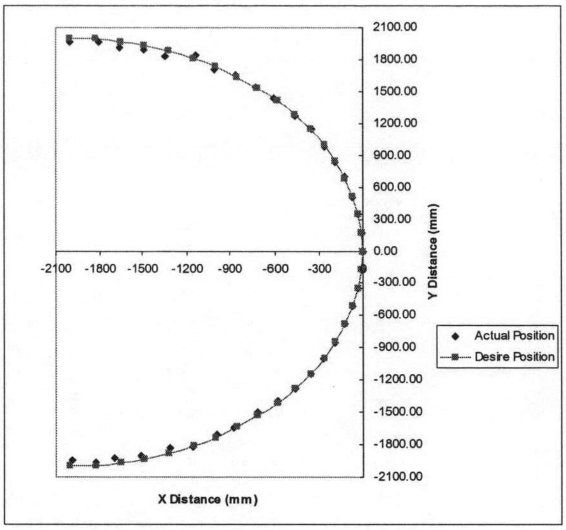

Figure 6.12: Position when turn around a point to the left with 200 cm radius of curvature with speed 15 cm/s

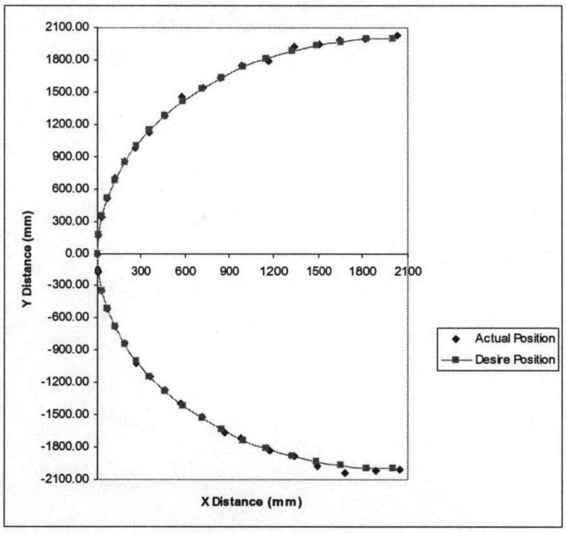

Figure 6.13: Position when turn around a point to the right with 200 cm radius of curvature with speed 5 cm/s

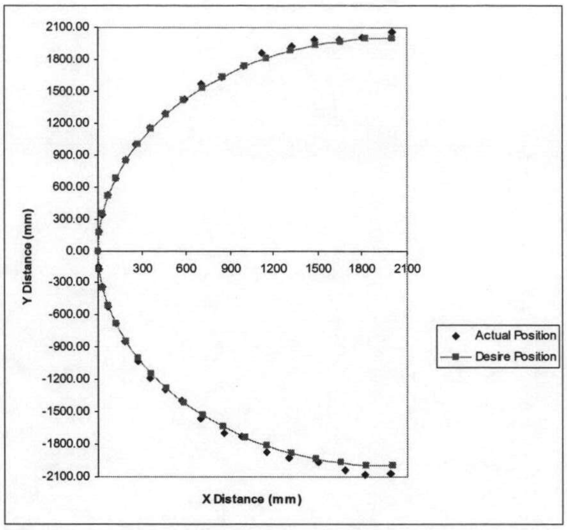

Figure 6.14: Position when turn around a point to the right with 200 cm radius of curvature with speed 10 cm/s

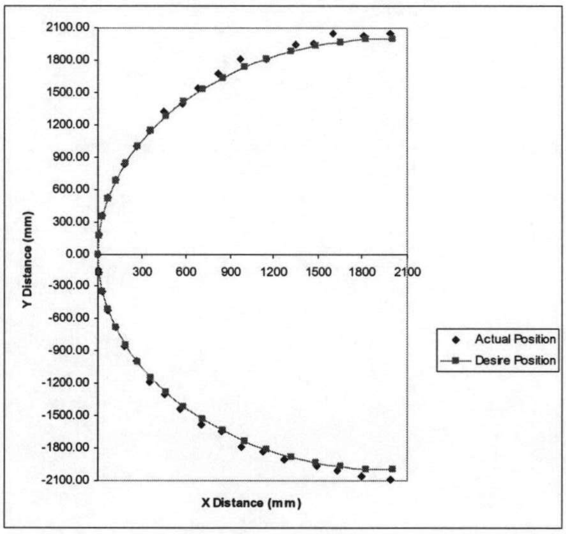

Figure 6.15: Position when turn around a point to the right with 200 cm radius of curvature with speed 15 cm/s

When turn around a point to the left and right side with 100 and 200 cm radius of curvature by using various speeds, the robot also tends to deviate to the left as same as in linear motion.

6.1.3 Rotation in place

The robot is commanded to rotate 1 turn in clockwise and counterclockwise direction, with speed 5, 10 and 15 degree per second.

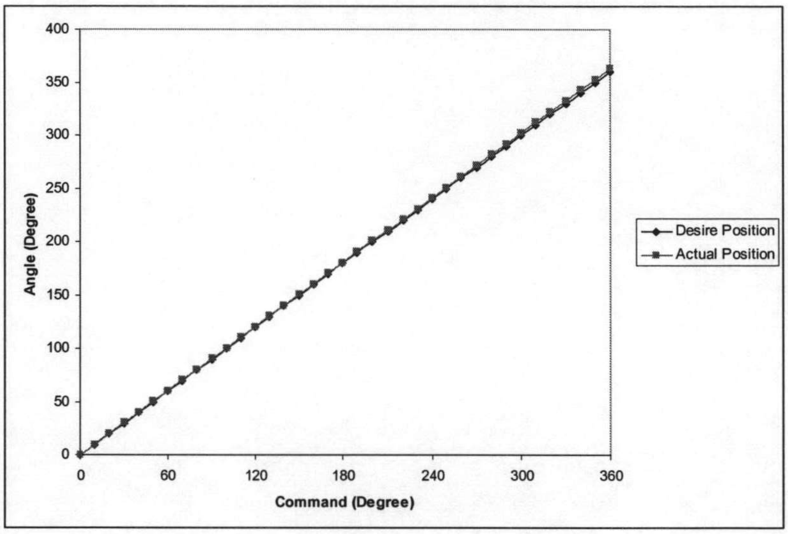

Figure 6.16: Angle when rotating counterclockwise at 5 degree/s.

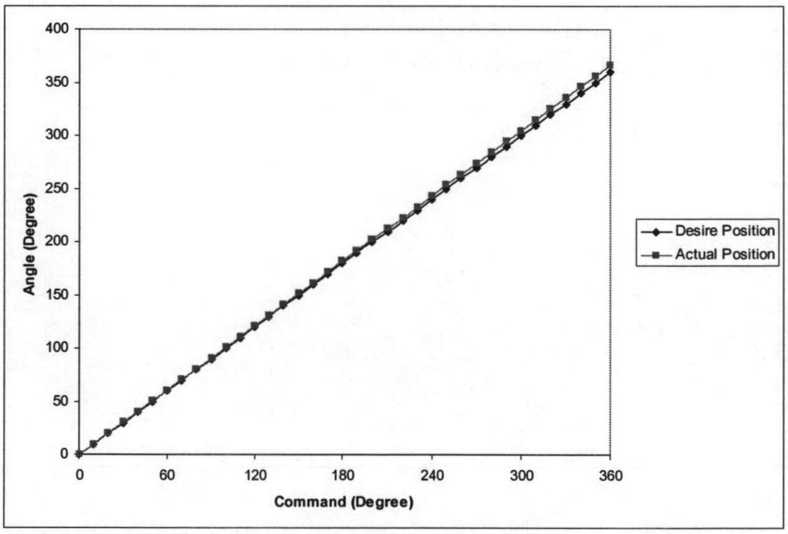

Figure 6.17: Angle when rotating counterclockwise at 10 degree/s.

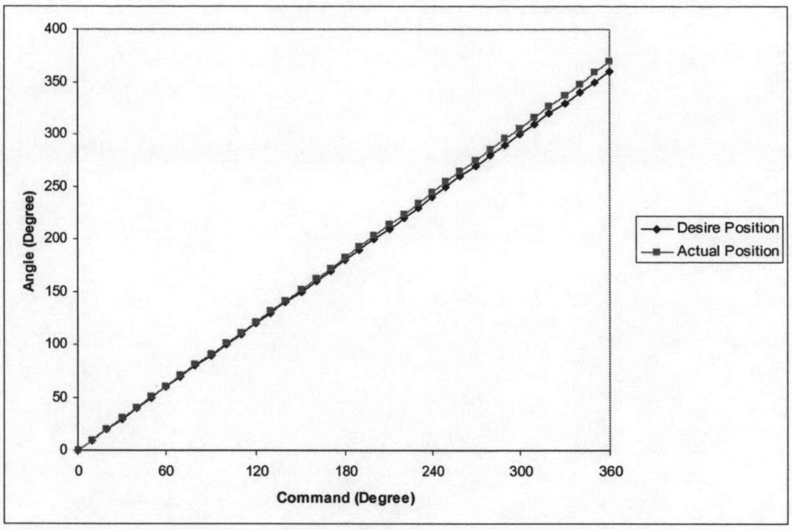

Figure 6.18: Angle when rotating counterclockwise at 15 degree/s.

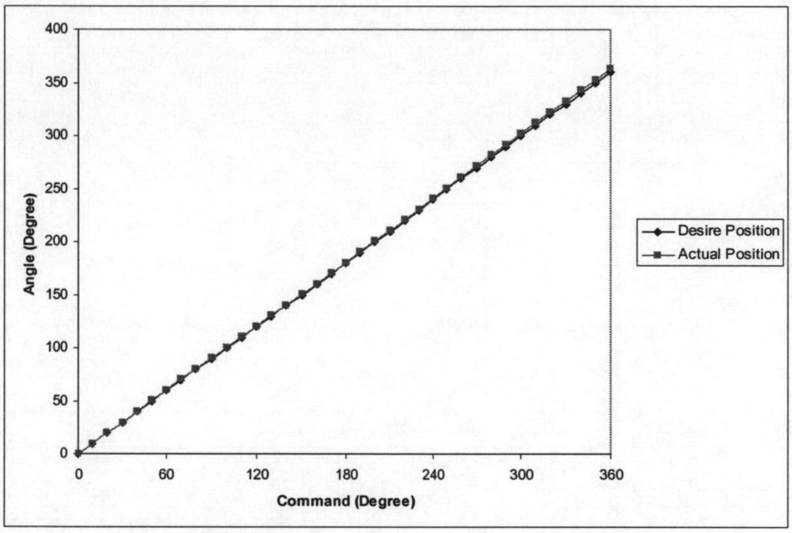

Figure 6.19: Angle when rotating clockwise at 5 degree/s.

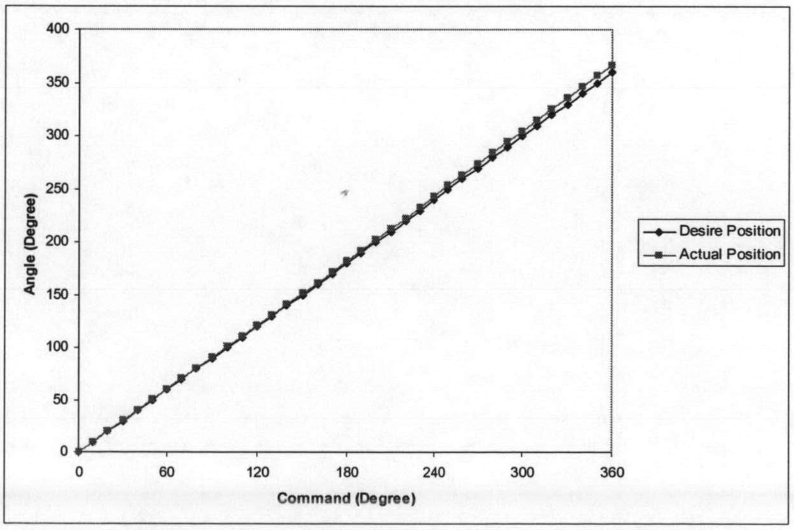

Figure 6.20: Angle when rotating clockwise at 10 degree/s.

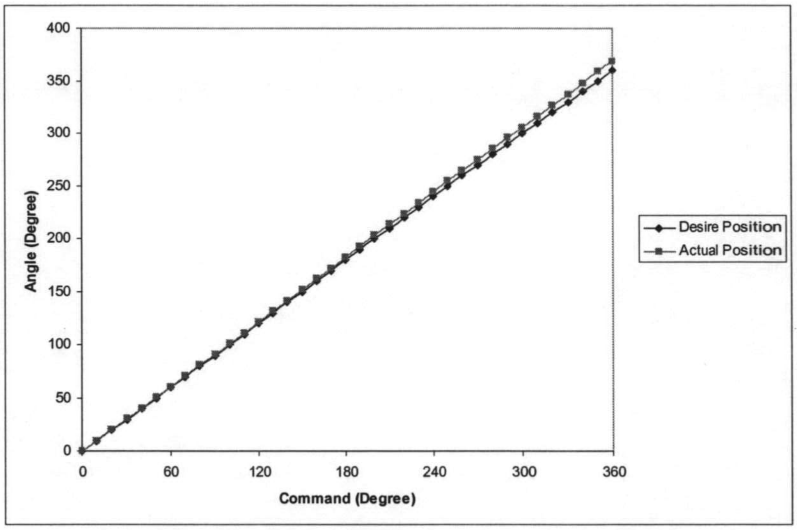

Figure 6.21: Angle when rotating clockwise at 15 degree/s.

The robot always overshoots in both clockwise and counterclockwise direction. The error is increased when using higher speed. The error is about 10 degree per revolution.

The error may be the result from many reasons, such as backlash in the system. The robot's mass also affected the error due to high inertia when rotating with high speed.

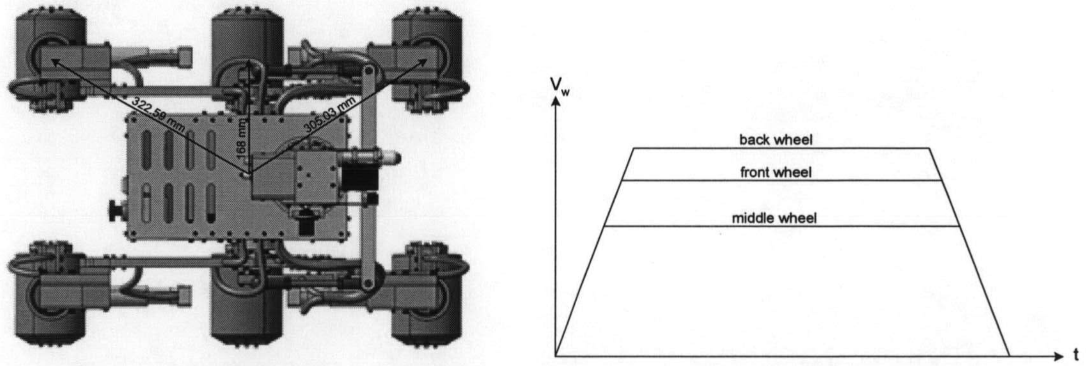

Figure 6.22: Distance from robot's center to wheels and velocity profile

Consider the robot configuration in Figure 6.22, the distance from robot's center to the front, middle and back wheels are 305.03, 168 and 322.59 mm respectively. In the low-level control system, the acceleration of all wheels is defined as a constant. When the robot is commanded to rotate in place, the middle wheels will reach the desired velocity first then follow by the front and back wheels respectively. So, the slip occurred and leads to error when rotating.

6.2 Traction Control

In this section, the traction control system is verified by simulation in Visual Nastran 4D® using Kutta-Merson integration method with 0.005 sec. time step. The simulation divided into 3 cases: slope climbing, travel over a ditch and climbing up a sharp-edge step.

6.2.1 Slope climbing

In Figure 6.23, the robot climbs up a 30-degree slope, with coefficient of friction about 0.5. As a result, in case without control, the robot was running at 55 mm/s and the average slip ratio of all six wheels was almost 0. At $t = 0.5$ sec. the front wheels touched the slope and begin to climb up. Robot's velocity reduced to 25 mm/s. At this time, the slip ratio was around 0.5-0.6, indicated that there was slip occurred. But the robot continued to climb up until the middle wheels touched the slope at $t = 9$ sec. The slip ratio increased around 0.8 and the robot's velocity reduced to nearly zero.

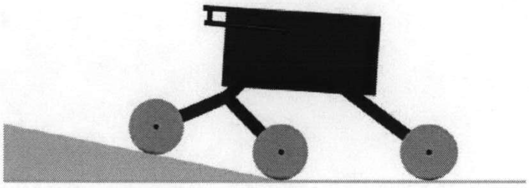

Figure 6.23: Robot climbed up a slope

In case with control, the sequence was almost the same until $t = 0.5$ sec. Then the robot's velocity reduced to approximately 35 mm/s and the slip ratio was around 0.2 when the front wheels touched the slope. At $t = 6$ sec, the middle wheels touched the slope and velocity reduced to about 28 mm/s with S around 0.4. Both back wheels begin to climb up the slope at $t = 15$ sec. with velocity approximately 20 mm/s and slip ratio 0.6.

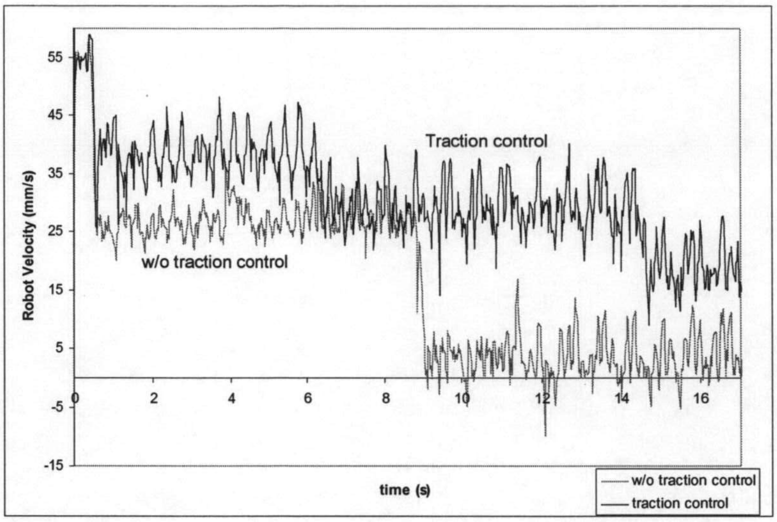

Figure 6.24: Robot velocity when climbed up 30 degrees slope.

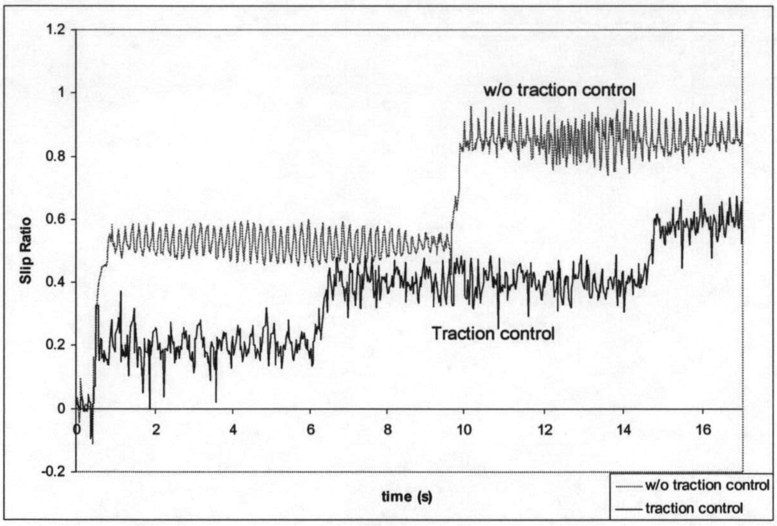

Figure 6.25: Slip ratio when climbed up 30 degrees slope

6.2.2 Traversing over a ditch

In figure 6.26, the robot traversed over a ditch, which has 32 mm depth and 73 mm width with coefficient of friction about 0.5.

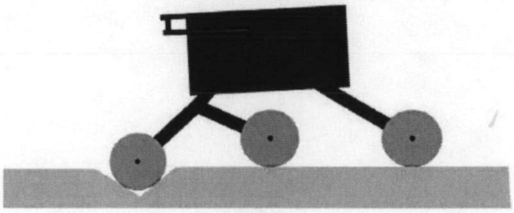

Figure 6.26: Traversing over a ditch

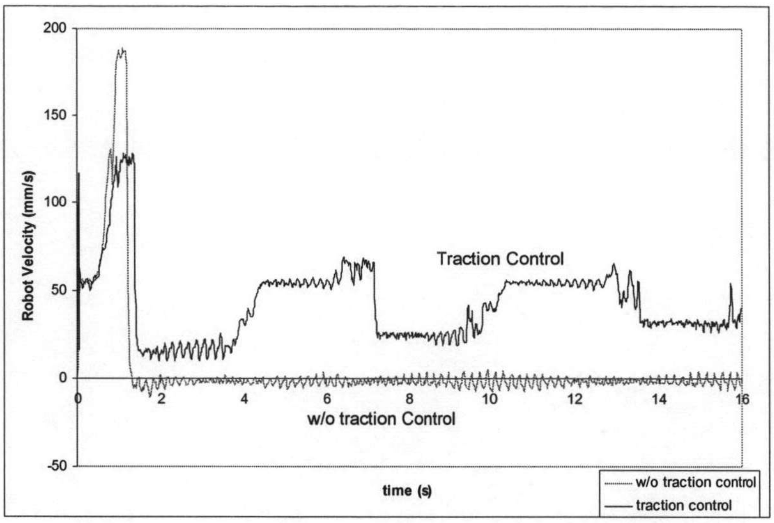

Figure 6.27: Robot velocity when traversed over a ditch

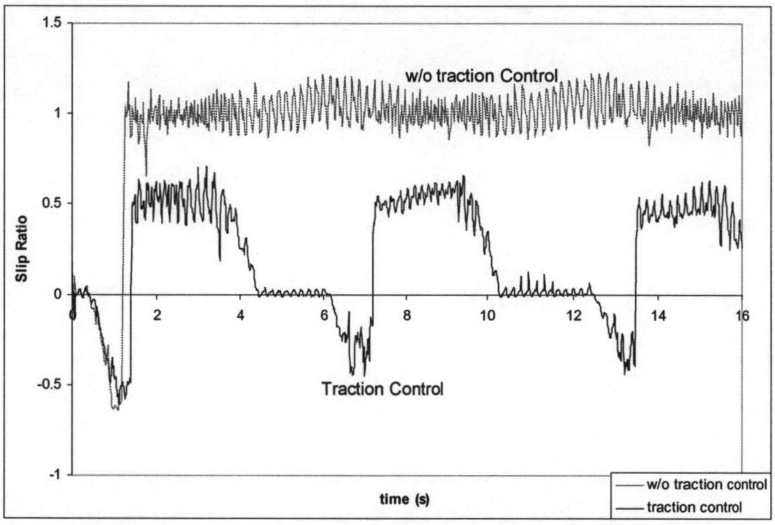

Figure 6.28: Slip ratio when traversed over a ditch

The robot was commanded to move at 55 mm/s, and then the front wheels went down the ditch at $t = 0.5$ sec. The velocity of the robot increased temporary and begin to climb up when front wheels touch the up-edge of the ditch. But the wheels slipped with the ground and failed to climb up. Then the slip ratio went up around 1 ($S = 1$), the robot has stuck and the velocity decreased about zero at $t = 1.5$ sec.

With traction control, after the front wheels went down the ditch, the slip ratio was increased. The controller detected the slip and tried to decelerate to reduce the slip ratio. When the slip ratio decreased around 0.5, the robot stopped sliding and gained sufficient traction then continued to climb up again. Until $t = 4.5$ sec., both of the front wheels went up the ditch completely and the robot velocity increased to the 55 mm/s as commanded. At $t = 6$ sec. the middle wheels went down the ditch. The robot velocity also increased temporary and back to 55 mm/s again when the middle wheels went up completely. The last two wheels went down the ditch at $t = 13$ sec. and the sequence was repeated in the same way as front and middle wheels.

6.2.3 Climbing up a step

In figure 6.29, the robot climbed over a sharp-edge step, which has 30 mm height with coefficient of friction about 0.5.

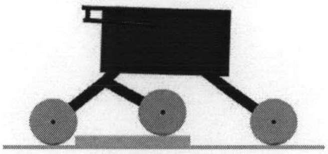

Figure 6.29: Climbing over a step

The robot was commanded to move at 55 mm/s, and then the front wheels touched a step at $t = 0.3$ sec. With traction control, both front wheels tried to climb over an obstacle, the velocity of the robot reduced about zero temporary and increase up to 55 mm/s again when the front wheels climbed up completely. At $t = 6$ sec, the middle wheels begin to climb up, the velocity reduced again then increased when the front wheels drop from an obstacle. The situation repeated in the same way when the back wheels climbed up the step.

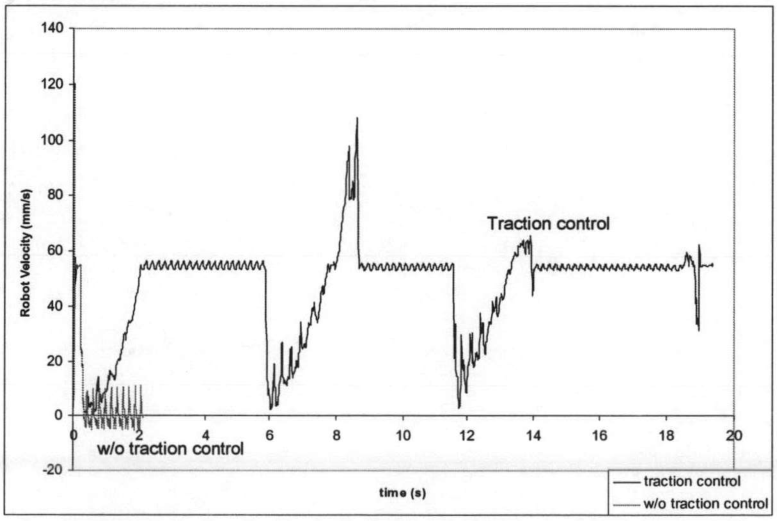

Figure 6.30: Robot velocity when climbed over a step

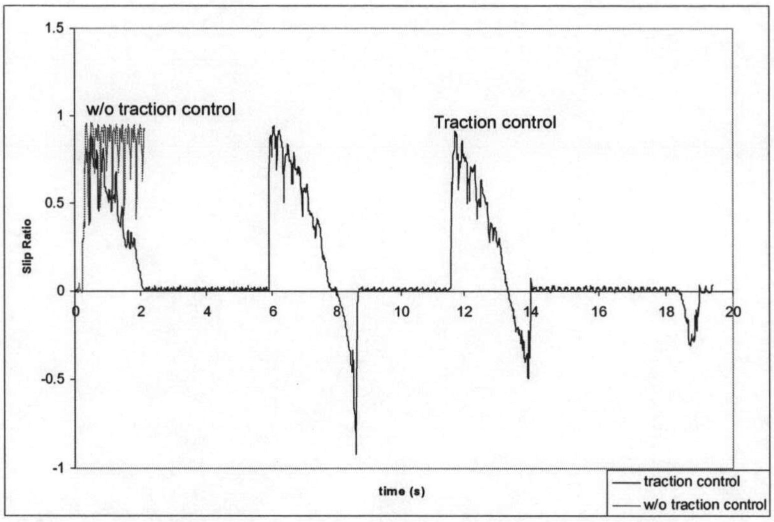

Figure 6.31: Slip ratio when climbed over a step

Without traction control, the robot stuck when both front wheels fail to climb up an obstacle. But the wheels continued to rotate constantly, the slip ratio increased about 1, and then the robot velocity was nearly zero.

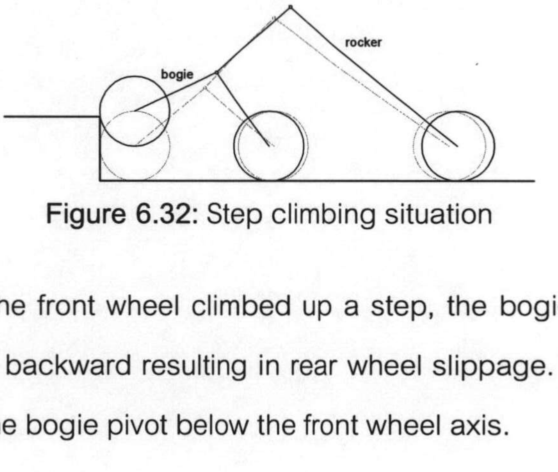

Figure 6.32: Step climbing situation

When the front wheel climbed up a step, the bogie pivot retreated and pushes the rear wheel backward resulting in rear wheel slippage. This problem can be reduced by lowering the bogie pivot below the front wheel axis.

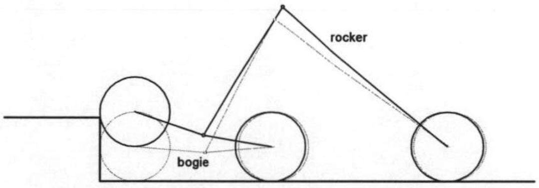

Figure 6.33: Lowering the bogie pivot

Another way to reduce this problem is performing wheelie maneuvers. This method varies the speed of the wheels to articulate the frame, allow the wheels to move closer or further apart. The wheelie maneuvers divided into two stages. First, when the obstacle approaches, speed up the middle wheels and slow down the rear wheels to lift the front wheels. When the front wheels are over the obstacle, return all wheels to normal speed. The second stage is to lift the middle wheels over the obstacle. This can be done by slow down the front wheels and speed up the rear wheels. Then return to normal speed again when the obstacle is under the middle wheels. The rear wheels cannot lift up by this method due to limitation of the rocker-bogie configuration.

6.3 Field Test

The robot was tested outdoor with various conditions of the surfaces, such as climbing over the pavement, climbing up the slope and traverse over obstacles scattered on ground.

Figure 6.34: Climbing up the pavement.

The robot was commanded to move at 5 cm/s and able to climb over the pavement with 10 cm height, perpendicular to the movement.

Figure 6.35: Climbing up the slope.

Climbing up an inclined surface also tested. The slope is about 40 degrees. The robot can climbed up easily. Furthermore, it can stopped and change direction on the slope.

In the experiment, the robot can climbed up steeper slope than the result in simulation. Since the coefficient of friction between wheel and ground in the real world is much higher than simulation and the model of the rolling friction is excluded from the simulation. The geometry of the wheel surface also effect to climbing ability.