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Generalized Steering Strategy for Vehicle Navigation on the Sloping ground

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[Key words] autonomous tractor, sloped terrain, navigation planner, optimal control, steering strategy

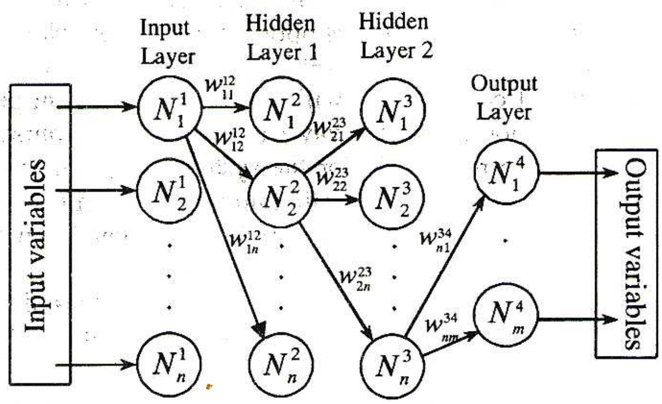
I Introduction

Many of the grasslands of Japan are in hilly areas where farm tractor performs various tasks. But human operators feel discomfort to work on inclined ground due to faulty body alignment. On the other hand decreasing trend of skilled farm workers is a big problem in the agricultural future of Japan. Until now many research work have been conducted on the automatic guidance of farm tractor, but most of them are for flatland environment (Matsuo, 2001; Torii, 2000; Keicher, 2000; Reid, 2000; Mizushima, 2000). Torisu, et al. (2002) and Ashraf, et al. (2002) conducted experiment on the automatic tractor guidance on sloped terrain. Since the vehicle dynamics on slope-land is highly nonlinear, conventional vehicle model and control system cannot be applied to guide the vehicle on sloping land. Therefore, they developed neural network (NN) vehicle model for sloped terrain and trained the NN model for specific inclined surface. They used genetic algorithms (GA) to search the optimal steering angle for that specific inclined surface. However, their system has a major problem: the NN model needs to be trained for each degree of land inclination and to find the corresponding steering controllers; which is very much difficult, time consuming and troublesome. This paper proposed an algorithm to generalize their steering strategy for navigating the autonomous tractor on sloped terrain. The foundation of this paper is based on the study of Torisu and Ashraf. It deals with a navigation planner, which includes NN vehicle model for different degree of slope lands, optimization of the quadratic form objective function by GA, and generalization of the optimal steering angle.

II Navigation planner

1. NN vehicle model for different degree of land inclinations

Unlike mathematical model, structure of NN model itself cannot signify the system behavior. It implies just the arrangement of the input-output variables and also the interconnecting neurons of the network. The weights "w" between inter connecting neurons of the structure of NN vehicle model is shown in Fig. 1. When the structure of NN model is trained for a specific inclined-land, the weight of each interconnecting two neurons of the model gets a constant value during the training process. Then the trained model can express the vehicle behavior only for that specific inclined-land where it was



N_i^p = Neuron number, where p is the layer number and i is the row number
W_{ij}^p = Weight between two neurons of the layers p and $p+1$ from the rows of i and j respectively

Fig. 1 Structure of the NN model and its weight distribution trained. Therefore, the NN model is not general to represent the vehicle behavior for any degree of land inclination. A NN structure can be said as a model after it gets proper training. In this study we developed four NN vehicle model for sloped terrain; i.e., the same structure of the NN model introduced by Torisu (2002) was trained on the contour lines of 0°, 5°, 11° and 15° sloped terrains.

2. Optimization of the quadratic form objective function by GA

In automatic vehicle guidance system a controller is essential to guide the vehicle along desired path. Torisu et al. (2002) used the optical control method for this purpose and designed a quadratic form objective function (Duttan, 1997). But there is a drawback of this control method: the process of getting the optimal control mass is an offline method. Therefore, prior to conduct actual autonomous travel, it is necessary to consider different ranges of possible system errors in the states, and perform simulation using the controller and the weight vectors of the trained NN vehicle model to find the best possible (optimal) control mass for each range of error. Lateral deviation (y) and heading angle (θ) were considered as the sources of system error, where all other errors were ignored. The deviations of vehicle, while traveling along the contour line of sloped terrain, are shown in Fig. 2. Genetic algorithm (GA) was used in the simulation to find the optimal control mass. As shown in Fig. 3, the optimal control mass, obtained from simulation for different sets of lateral deviation and heading angle on each specific sloping land, was arranged in a matrix form, which is called look-up table.

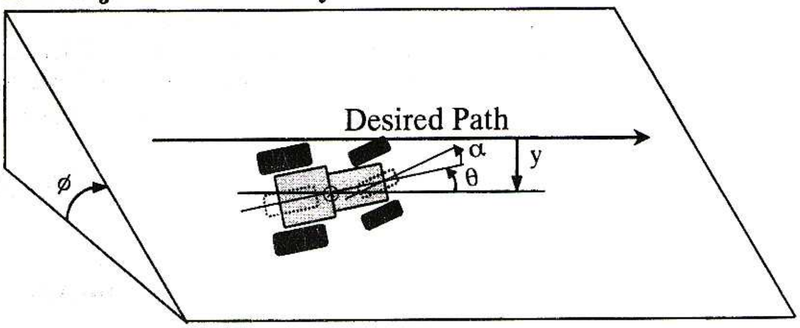


Fig. 2 Vehicle deviation from desired contour-line path

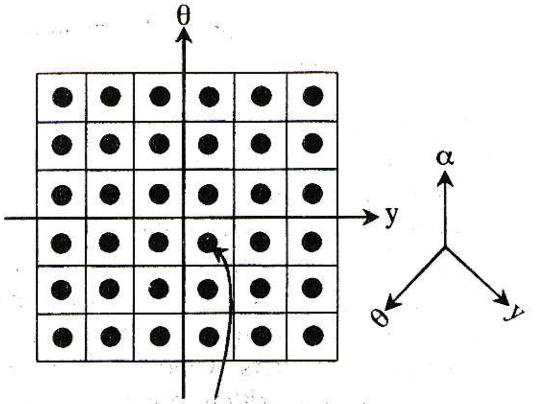


Fig. 3. Formation of Look-up table for optimal steering angle α

The choice of selecting the range of lateral deviation and heading angle, for which the optimal control mass was sought, is optional. But before choosing the deviation range, it is important to keep in mind that: (a) when the vehicle remains far away from the desired course, lump sum preciseness of the optimal control mass will not affect the system performance significantly; (b) when the vehicle posture is not so much away from the desired course, moderate preciseness of the optimal control mass will be reasonable for the system performance; (c) but when the vehicle posture will be very near to the desired course, minimum variation in the optimal control mass will significantly affect the system performance and will produce a serpentine path. Steering angle is considered as the control input.

Considering these factors, therefore, the ranges of lateral deviation and heading angle were chosen in three different intervals, and three separate look-up tables were prepared. According to the preciseness of optimization, the look-up tables were divided into three categories:

a) Precise,
b) Moderate,
c) Rough.

The precise look-up table was prepared for the vehicle motion, when the limit of maximum lateral deviation was within 10 cm and heading angle was within 5°. The limit of maximum lateral deviation and heading angle for the moderate look-up table was within 30 cm and 15° respectively. The rough look-up table was prepared for the lateral deviation and heading angle beyond the range of other two look-up tables.

3. Generalization of look-up table

For each level of land-inclination, above mentioned three look-up tables were prepared separately with the optimal control mass. The precise, normal and rough look-up tables of 5° sloped terrain were compounded into a single look-up table and shown in Table 1. Similar compound look-up tables were prepared for 0°, 11° and 15° sloped terrains. In this table the optimal steering angle is shown for different intervals of lateral deviation and heading angle.

Table 1 A compound lookup table of optimized steering angles for 5° sloped terrain

<table>
<tr><th>Heading angle, θ [°] \ Lateral deviation, y [cm]</th><th><-80 – -80</th><th>-80 – -40</th><th>-40 – -20</th><th>-20 – -10</th><th>-10 – -6</th><th>-6 – -3</th><th>-3 – 0</th><th>0 – 3</th><th>3 – 6</th><th>6 – 10</th><th>10 – 20</th><th>20 – 40</th><th>40 – 80</th><th>80 – >80</th></tr>
<tr><td>>40 – 40</td><td>4</td><td>-7</td><td colspan="5">-15</td><td colspan="5">-20</td><td>-28</td><td>-35</td></tr>
<tr><td>40 – 20</td><td>13</td><td>4</td><td colspan="5">-7</td><td colspan="5">-15</td><td>-20</td><td>-28</td></tr>
<tr><td>20 – 10</td><td rowspan="4">22</td><td rowspan="4">13</td><td>3</td><td>-6</td><td colspan="3">-11</td><td colspan="3">-13</td><td>-18</td><td>-19</td><td rowspan="4">-14</td><td rowspan="4">-20</td></tr>
<tr><td>10 – 5</td><td>7</td><td>3</td><td colspan="3">-5</td><td colspan="3">-7</td><td>-14</td><td>-16</td></tr>
<tr><td>5 – 3</td><td rowspan="2">11</td><td rowspan="2">7</td><td>4</td><td>0</td><td>0</td><td>-3</td><td>-5</td><td>-7</td><td rowspan="2">-7</td><td rowspan="2">-12</td></tr>
<tr><td>3 – 0</td><td>6</td><td>5</td><td>2</td><td>1</td><td>-1</td><td>-3</td></tr>
<tr><td>0 – -3</td><td rowspan="4">34</td><td rowspan="4">22</td><td rowspan="2">13</td><td rowspan="2">12</td><td>9</td><td>7</td><td>6</td><td>4</td><td>2</td><td>-1</td><td rowspan="2">-2</td><td rowspan="2">-6</td><td rowspan="4">-6</td><td rowspan="4">-13</td></tr>
<tr><td>-3 – -5</td><td>11</td><td>11</td><td>9</td><td>6</td><td>5</td><td>5</td></tr>
<tr><td>-5 – -10</td><td>16</td><td>14</td><td colspan="3">11</td><td colspan="3">10</td><td>-1</td><td>-1</td></tr>
<tr><td>-10 – -20</td><td>17</td><td>15</td><td colspan="3">15</td><td colspan="3">11</td><td>8</td><td>-1</td></tr>
<tr><td>-20 – -40</td><td>38</td><td>34</td><td colspan="5">22</td><td colspan="5">13</td><td>5</td><td>-5</td></tr>
<tr><td>-40 – <-40</td><td>40</td><td>38</td><td colspan="5">34</td><td colspan="5">22</td><td>13</td><td>5</td></tr>
</table>

Each cell of the compound look-up table was marked with sequential numbers. From the compound look-up table, symbolically only the precise look-up table with this marking system is shown in Fig. 4. Same procedure was done for the look-up tables of 0°, 11° and 15° sloped terrains. Table 2 was obtained by combining the marked cells of 0°, 5°, 11° and 15° sloped terrains. From Table 2, taking the values of optimal steering angle of any column together with their corresponding slope angle, we developed polynomial equation. For instance, in cell number 2, *i.e.* in column 3 of Table 2, the optimal steering angle values

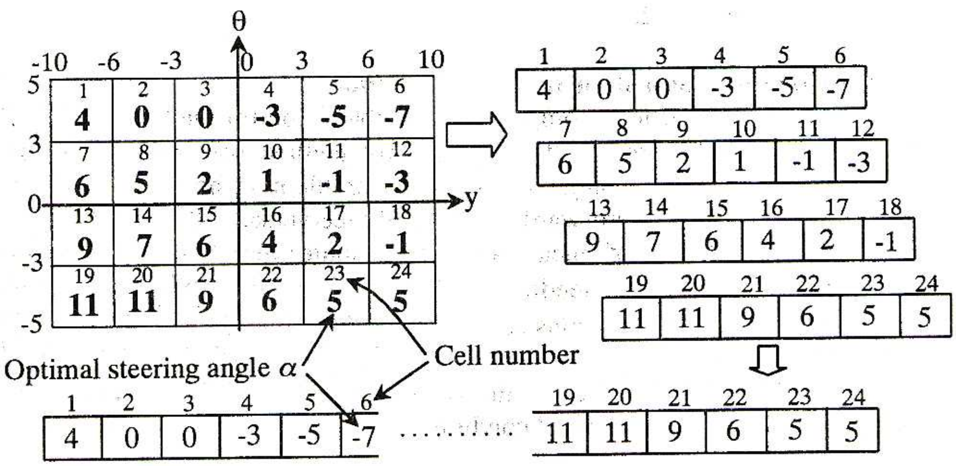


Fig. 4. The precise look-up table for 5° sloped terrain is converted to a row-matrix

for 0°, 5°, 11° and 15° sloped terrains are 0°, 0°, 1° and 3° respectively. Figure 5 is plotted from these values and Eq. 1 is developed using Microsoft Excel software.

Table 2. Single precise look-up table for the optimal steering angles of 0°, 5°, 11° and 15 ° sloped terrains

Slope Angle [°] \ Cell no.	1	2	3	4	5	6	19	20	21	22	23	24
0	2	0	-2	-4	-6	-8	8	6	4	2	0	-2
5	4	0	0	-3	-5	-7	11	11	9	6	5	5
11	2	1	-2	-3	-5	-9	15	12	10	7	5	3
15	5	3	2	1	-3	-7	16	13	9	7	5	3

$$\alpha_2 = 0.0012\phi^3 - 0.0042\phi^2 - 0.0091\phi + 6E - 14 \quad (1)$$

where α is the steering angle, subscript '2' is the cell number, which is the representative of lateral and heading deviations, and ϕ is the slope angle.
Similar procedure was applied for other cell numbers to get the 3rd order polynomial equations. Then all of the developed equations can be represented by Eq. 2.

$$\alpha_E = a_E\phi^3 + b_E\phi^2 + c_E\phi + d_E \quad (2)$$

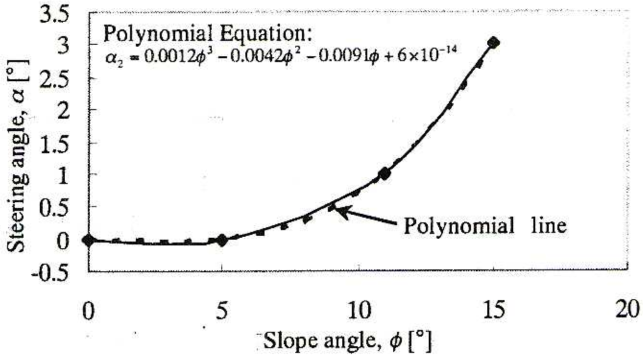


Fig. 5. Generalization of optimal steering angle for certain range of deviations

where *a, b, c* and *d* are the polynomial coefficients, and the subscript '*E*' indicates the cell number for which this formula is applicable. Actually this '*E*' represents the magnitude of lateral deviation and heading angle. Equation 2 is general to represent the optimal steering angle for all cells. Only the values of coefficients *a, b, c,* and *d* will change with the change of *E*. If the coefficient values are known, the optimal steering angle for any lateral deviation, heading angle and degree of land inclination can be obtained. The coefficients of all cell numbers are arranged in a single lookup table. During the autonomous travel, the value of '*E*' will be determined from the sensor information regarding lateral deviation and heading angle. Then the values of the polynomial coefficients *a, b, c* and *d* will be obtained from that specific cell number '*E*'. If the information regarding slope inclination is known from other sensor, the appropriate optimal steering angle can be determined from Eq. 2.

4. Feedforward control for the turning motion

It is quite difficult to accomplish the feedback control method in the guidance of a vehicle along curved path. Therefore, feedforward control method was applied to guide the tractor along four quarter-turns of the rectangular path. The problem is how to determine the switching from the feedback control to feedforward control and vice-versa. When the tractor reaches the predetermined distance from the end of linear path, the computer recognizes the position and changes the control method from feedback to feedforward. The steering angle α begins to increase and when it reaches the maximum (α_{max}), it remains constant until the heading angle of the tractor reaches a predetermined turning angle. Just after reaching this turning limit, the feedforward control switches over to the feedback control for the next path. Therefore, the final condition of the feedforward control in the quarter-turn becomes the initial condition of feedback control for the next linear path.

III Experimental conditions and instrumentation

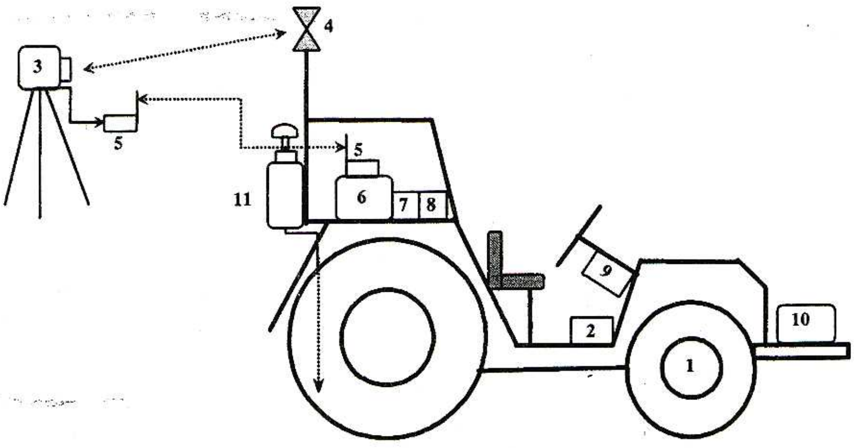
1. Experimental conditions

Two autonomous travel tests were conducted using the developed steering strategy. One test was conducted on a meadow of 8° sloping ground of the Iwate University Takijawa Agricultural Research

Farm, and the other one was conducted on the meadow of the Iwate University Omyojin Research Farm. In both cases the surface of the meadows were undulating and covered with grass. The soil condition was moderately moist and soft in some places. The test run was performed along a 30x15 m rectangular path. The inclination of the test field of Takijawa Farm was almost uniform. But in the Omiojin farm, the travel direction of one rectilinear path was along a contour line of 10° average slope and that of the other was along a contour line of 18° average slope. In both cases the tractor velocity was 0.5 m/s throughout the test.

2. Instrumentation

The tested tractor used in this experiment was an 18 kW four-wheel drive Mitsubishi MT2501D model. Total mass of the tractor is 1125 kg, wheelbase is 1595 mm and tread is 1310 mm. The tractor was equipped with a 100 MHz Pentium PC as the sensor-signal processor and steering control unit. It was also equipped with a DC motor as the steering actuator, a potentiometer to measure the steering angles and a fiber optic gyroscope (FOG) to measure the heading angles. The tested tractor and instrumentation is shown in Fig. 6. The equipment used to measure the vehicle positions was a Total Station of Leica TCA1105 model. A prism, as a pair of Total Station, was mounted on the tractor rear and was placed at a height of 1.89 m from the ground and 1.314 m behind the tractor center of gravity. Two SS wireless modems were used to transmit the signals of the tractor-position from the Total Station to the PC. Data transfer time interval was 0.5 sec.



1: Potentiometer 5: Modem 9: DC motor
2: FOG 6: PC 10: AC generator
3: Total Station 7: AD/DA board
4: Prism 8: Strain amplifier

Fig. 6 Instrumentation in the Tested Tractor

IV Results and Discussion

1. Rectilinear motion

Contour line motion

Figure 7 and 8 show the autonomous traveling trajectories of the tractor along the rectangular path on 8° and 15° sloped terrains respectively. Two longitudinal travel paths were along the contour lines, one lateral travel paths was towards the uphill and another one was towards the downhill directions. The land-inclination of the total travel path on 8° inclined field was near about uniform. But in other test field, the elevation at the starting point of 10° contour path was 0.427 m, and at the endpoint was –0.297 m. The elevation at the starting point of 18° contour path was 2.67 m, and at the endpoint was 4.22 m. Figure 7 and 8 show that even though there are differences in the uniformity of land-inclinations, the developed navigation system could successfully guide the vehicle along the contour paths in both conditions.

Uphill and downhill motion

For the uphill and the downhill motion, it was assumed that the slope-effect (*i.e.*, gravitational force) on the lateral deviation would be negligible in the process of feedback control. Therefore, the optimal steering angle for 0° slope was used for these two paths. But the reality is that there is some effect of slope on the vehicle motions along these two paths. Therefore, in both cases the trajectories of these two paths are less even in comparison to the trajectories along the contour lines.

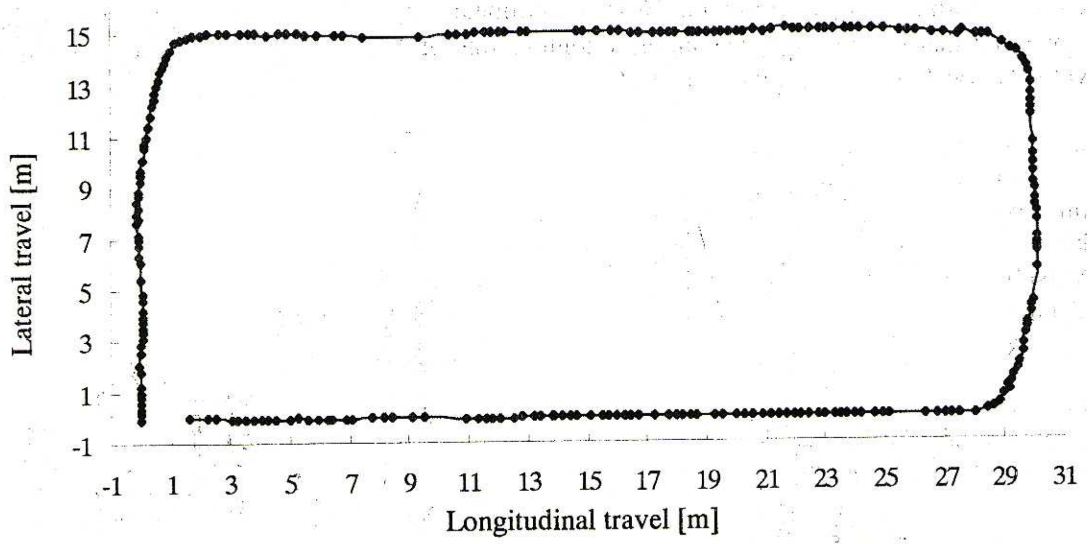


Fig. 7 Autonomous traveling trajectory for along rectangular path on 15° sloped terrain

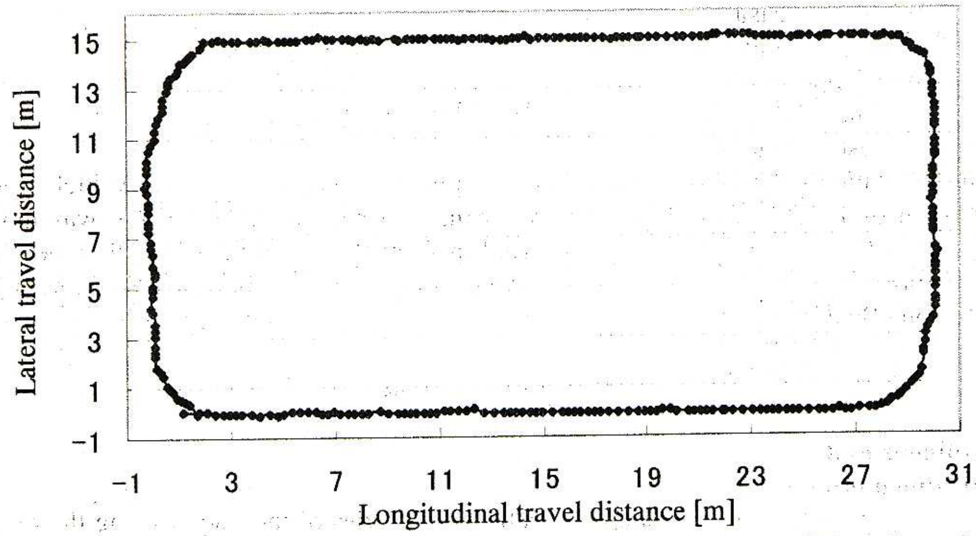


Fig. 8. Autonomous traveling trajectory for rectangular path on 15° sloped terrain

2. Turning motion

The quarter turn motion is a programmed controlled motion using feedforward control. But the convergences of the quarter turns were fairly good. This was due to the soil condition. Since there was no feedback control for the turning motion, the sliding error could not be compensated for and this error occurred.

Overall Rectangular path control

The results discussed for rectilinear motion and turning performance reveals that despite the variations in land-inclination, the combination of feedback and feed forward control methods were successful to guide the tractor along the rectangular path on sloped terrain. The result agreed with the accuracy requirement for fine farming (Lawrence, 1993; Auernhammer, 1991) in flat land. Therefore, this developed guidance system can be used to navigate the autonomous wheeled-tractor along a predetermined rectangular path on a safe range of sloped terrain.

V Conclusion

The automatic tractor guidance system was developed to navigate the tractor along rectangular path on sloped terrain. Using the trained NN vehicle models and the optimal control theory, look-up tables for the optimal steering angles were prepared by GA. Applying the polynomial equation concept, the look-up tables of the optimal steering angle for different land inclination was generalized to navigate the tractor on sloping lands within the range of 0° to 20° regardless of the degree of inclination. The developed navigation planner was successfully applied for guiding the tractor along opposite directions of contour lines and also along uphill and downhill directions of motion. The feedforward control method was successful to navigate the tractor along the quarter turns of the rectangular path.

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