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Development of Electrical Control Device for Autonomous Tractor

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Introduction

The higher industrialization makes farming labor shorter with not also reduction of quantity like as agricultural population but also deterioration of quality like as old age or women in Korea.

Most of farmers magnified their farm land for increasing income, but they have been in difficulties because of employment of skillful driver of farm machinery and ensurance farm labor which needs finishing seasonable works.

To solve above problem, it is widely proceeding to robotization throughout all the field of agriculture. Robotization of farm works might be premise of moving robot in land-dependant-agriculture and performance of farming robot be dependent on autonomous traveling technology which can trace a desired path with small tracking error.

For autonomous traveling, it might be controlled electrically that operating device of tractor which has been handled by human and coped with variable environment detecting interference on the path.

Recently technologies of robot and autonomous traveling for labor-saving in farm works have been widely developed with sensors and navigation algorithms.

Yukumoto et al.(1997) tested to cultivate by an unmanned tractor on which electro-hydraulic actuator, IMU and laser distance meter mounted, and tracking error was less than 10cm.

Parkinson et al.(1997) tried to operate a tractor autonomously on desired path with a few cm by using CDGPS which modified landing control system for air vehicle.

Most study on the autonomous tractor had paid relatively low attention to set up design data of actuator with sensor, because being given much weight on navigation algorithm.

In this study, a compatible actuator for an unmanned tractor was developed and evaluated it's performance. Detailed objectives were:

1. to investigate design factors for electronic steering control of tractor,
2. to develop actuator and system controller, and
3. to evaluate tractor control system through traveling test.

Procedures And Methods

1. Design of steering controller

(1) Steering model of wheel type tractor

Assumptions were made for decision of steering rate in 2D geometry model of steering system.

They were:

- ○ differential gear act ideally to turning radius,
- ○ slip toward traveling and lateral direction to be ignored, and
- ○ dynamic limitation of tractor to be ± 35 degree as maximum steering angle and 23km as maximum speed.

When a tractor traveled to z(m) distance with steering rate α, moving distance of center of front wheel toward x, y axle was,

$$x = z\cos(0.5\alpha z + \delta_i + \theta_i)$$
$$y = z\sin(0.5\alpha z + \delta_i + \theta_i) \quad (1)$$

Coordination of the modeled tractor on x, y plane was,

$$\begin{bmatrix} X_{i+1} \\ Y_{i+1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & X_i \\ 0 & 1 & Y_i \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \quad (2)$$

Yaw angle from center line on the tractor was,

$$\theta_{i+1} = z(0.5\alpha z + \delta_i)/L + \theta_i \quad (3)$$

The rotated angle of x, y plane about z axis was,

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$$R_\theta = \begin{bmatrix} \cos\theta & \sin\theta & 0 & 0 \\ -\sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

where

- z : traveling distance of tractor during steering (m)
- δ : steer angle of front wheel about center line on tractor(rad)
- θ : yaw angle about center line on tractor (rad)
- α : steering rate(rad /m)
- L : distance between center of front wheel and center of rear wheel(m)

Maximum steering angle which tractor could keep stable turning was,

$$\frac{Wv^2 y_s}{gr} \geq Wx_g, \qquad r = \frac{L}{\sin\theta} \quad (5)$$

where

- W : weight of tractor(N)
- g : acceleration of gravity(m/s²)
- v : speed of tractor(m/s),
- r : turning radius (m)
- ys : vertical distance between ground and weight center of tractor (m)
- xg : horizontal distance between grounding surface of wheel and weight center of tractor (m)
- L : distance between front and rear axle(m)

Therefore, maximum steering angle limited by tractor speed was

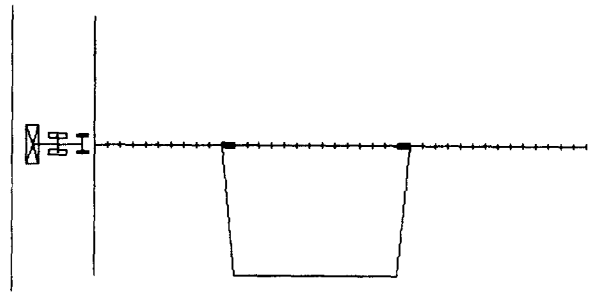
$$\theta = \arcsin\left(k\frac{L}{v^2}\right) \quad (6)$$

(2) Steering simulation

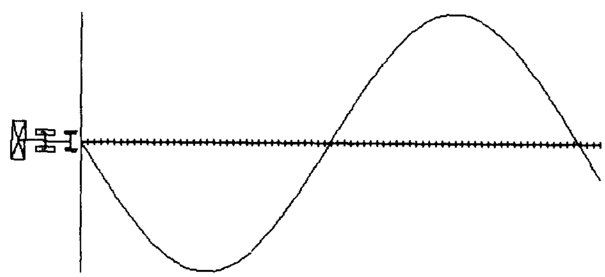
The steering simulation was performed on sinusoidal and crank-shaped curves as virtual paths in personal computer(Pentium Ⅱ 300Mhz). Variable ranges was listed in table 1.

Table 1 Range of simulated variables

Variable	Range
Target point	0.5m ~ 4.5m
Steering rate	0.08 ~ 0.20rad/sec
Speed	0.2 m/s ~ 6 m/s



Crank-shaped path



Sinusoidal path

Fig. 1 Virtual path drawn in simulation S/W.

Designed resolution of steering was set at 0.2 degress and steering speed was 1.8 sec for 70° (35°).
The torque for steering was

$$T_a = \frac{(Jm + Jl)}{g} \times \omega = \frac{(Jm + Jl)}{g} \times 2\pi \times \frac{(fl \times 1.8)}{360} \times \frac{1}{ta}$$
$$Jl = Js + Jg_1 + Jg_2 + Ph = 184.8 N{\cdot}cm \quad (7)$$

where

- Ta : steering torque (N · cm)
- Jm : inertia moment of steering motor (N · cm²)
- Jl : inertia moment of load (N · cm²)
- ω : angle acceleration of motor (rad/sec²)

2. Design of driving control device

(1) Brake control device

Efficiency of braking torque depended on the pressure of hydraulic oil in driving cylinder which controlled solenoid valves. We used experimental formula that was proposed by Hedrick in order to control the press force of brake pad.

$$T_{br} = K_{br} \cdot P_{break}, (K_{br} = 1.11 N \cdot m / kPa) \quad (8)$$

where

- Tbr : brake torque
- Kbr : transfer constant

P_{brake} : pressed force on brake pad

$P_{brake} = C \cdot P_{input}$

P_{input} : input force from outside for driving brake

C : transfer constant

(2) Clutch and transmission control device

In most of tractors, the characteristic curve of speed engaged by gear stage expressed as

$$V_{d1} = (aT_a^3 + bT_a^2 + cT_a + d)\frac{N_a}{N_r} \tag{9}$$

V_{dl} : speed of tractor

T : Stage of reduction gear

N_a : measured engine rpm

N_r : rated engine rpm

a,b,c,d : constant

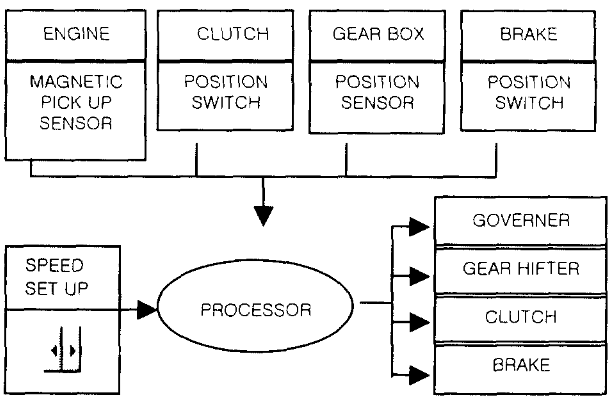


Fig. 2 Schematic block diagram of speed controller.

Speed controller was designed to change speed automatically by controlling governor position, clutch position and gear stage according to the amplitude of voltage as input signal from main processor or operator(Fig. 2)

(3) Detection of device position

Position of continuous control device for operating tractor was detected by a potentiometer which was connected with steel wire. Position of stage control device was detected by comparing voltages of potentiometer and reference that calibrated according to each stage(Fig. 3).

(4) Algorithm for processing sensor signal

Input analog signal from the position detector was mixed with noise caused by switching frequency of power supply and tractor vibration. To remove the noise in sensor, we used a low pass digital filter which was designed as 10Hz of cut off frequency. Amount of calculation in these finite impulse response filter increased rapidly according to extending filter tab of sampling frequency. To solve this problem, a modified finite impulse response filter was developed by a filter algorithm below.

Filtering algorithm

$$y_k = \sum_{m=0}^{N-1} \frac{1}{N} x_{k-m} \tag{10}$$

y_k : output value of filter

x_k : input value of filter

N : number of filter tab

Cut off frequency

$$N = \frac{f_s}{f_c} \times 0.293 \tag{11}$$

fs : Sampling Frequency

fc : Cut off Frequency

N : number of filter tab

(5) Traveling algorithm for evaluation of system

To evaluate traveling performance of the unmanned tractor, following algorithm was applied.

$$\begin{bmatrix} \dot{X}_{trac} \\ \dot{\theta} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} 0 & V_{x0} & -\frac{V_{x0} l_1}{(l_1 + l_2)} \\ 0 & 0 & -\frac{V_{x0}}{(l_1 + l_2)} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} X_{trac} \\ \theta \\ \phi \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u \tag{12}$$

l_1 : distance from the centroid to the front axle

l_2 : distance from the centroid to the rear axle

L : $(l_1 + l_2)$

X_{trac} : The deviation of lateral position

θ : The deviation of heading angle

ϕ : The deviation of steering angle

To bring the deviation of lateral position and tractor heading as shown in Fig. 4 into almost zero, output steering angle was determined.

$$\phi_{x+1} = A_x \dot{\theta} + B_x X_{trac}$$

$$(A_x = \frac{L}{3V_{x0}}, B_x = k_1(6X_{trac})^{\frac{1}{3}}(V_{x0})^{\frac{-2}{3}}) \tag{13}$$

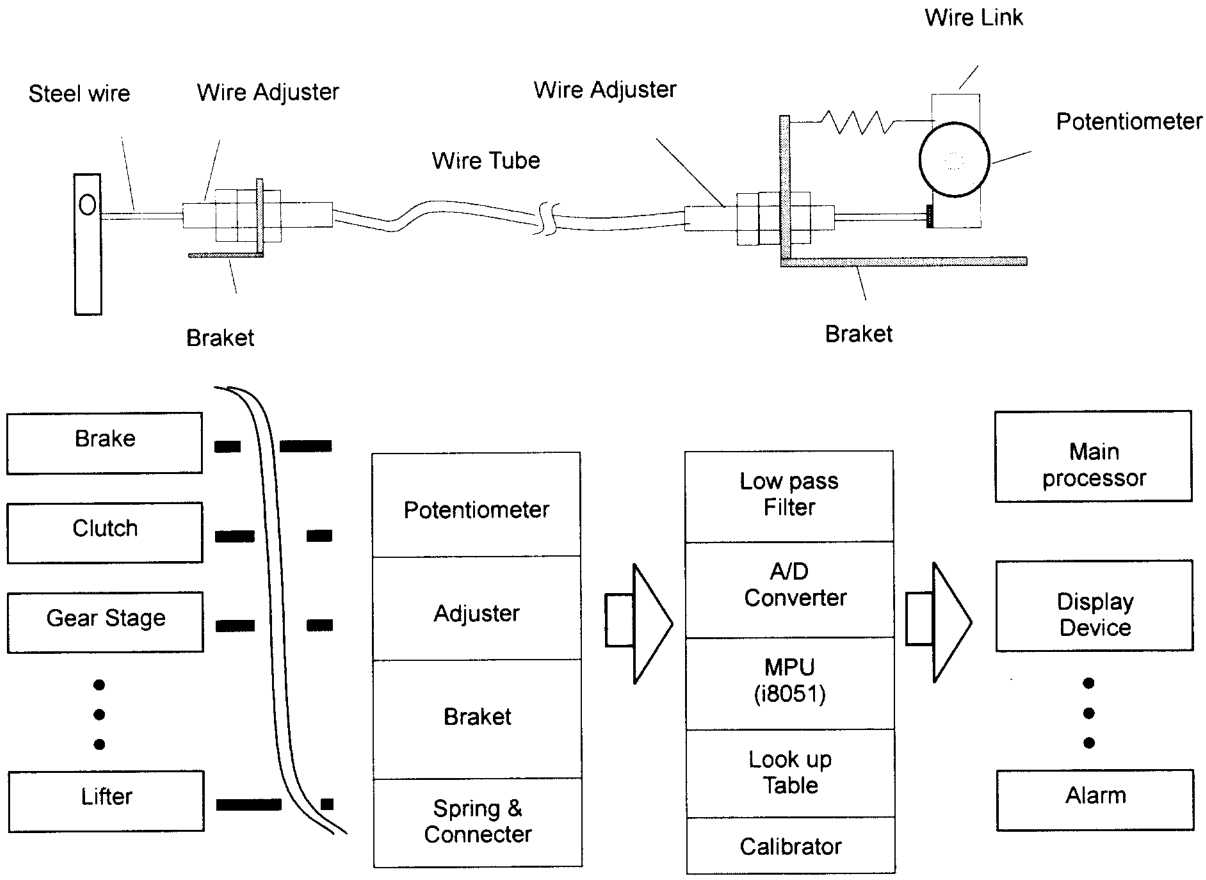


Fig. 3 Schematic diagram of position controller for operating lever.

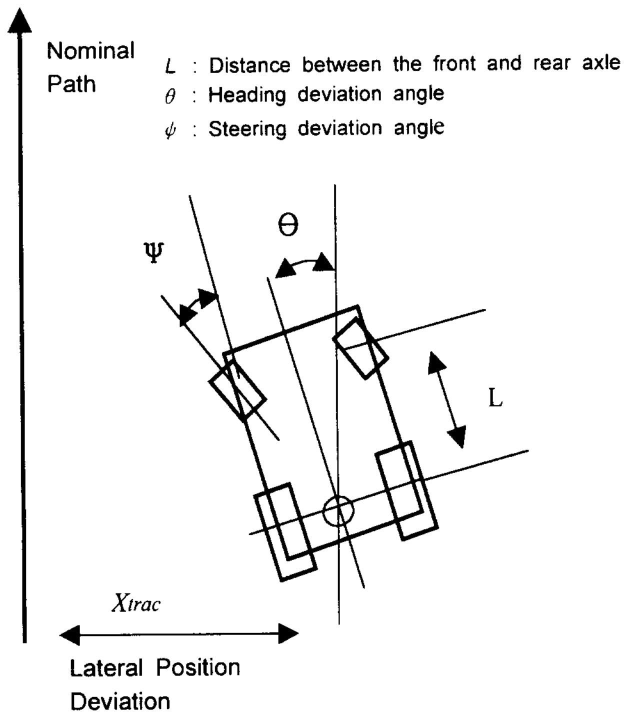


Fig. 4 Diagram of lateral position deviation and tractor heading angle.

(6) System controller

A system controller was designed in order to make a decision output command that was based on the path and position data through a DGPS and a laser finder(Fig. 5). Sensor data of tractor inside was also transmitted to the system controller with 10Hz refresh time through serial communication.

Results And Discussions

1. Steering control device

(1) Control simulation

Fig. 6 shows the maximum deviation of tracking on a sinusoidal path at variable steering rates and distances of target points on x, y plane which x axis was distance to target point, and y axis was deviation. Maximum deviation decreased some in range of 1.5~2.0m, included some alternant tracking in range less than 1.5m, and increased rapidly in range above 2.0m as target point for tracking.

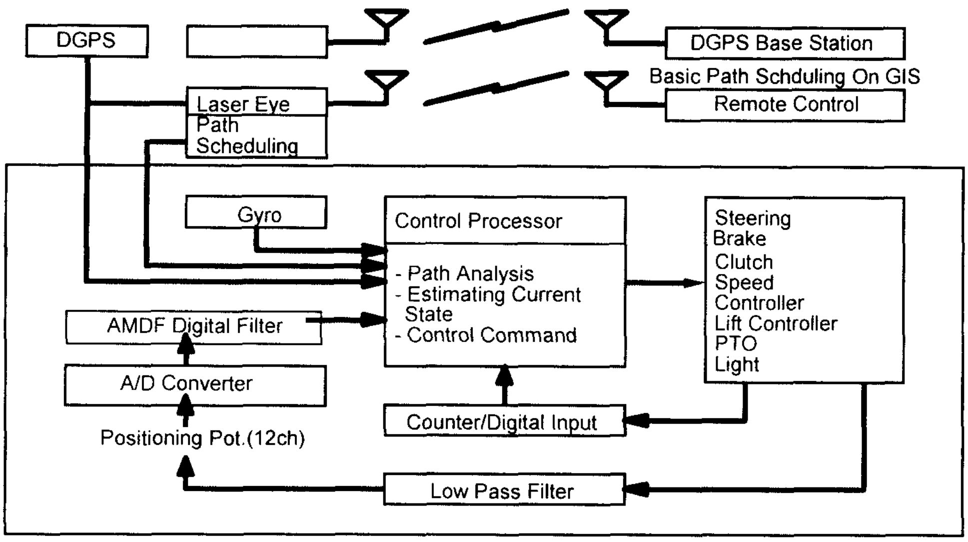


Fig. 5 Schematic diagram of system controller.

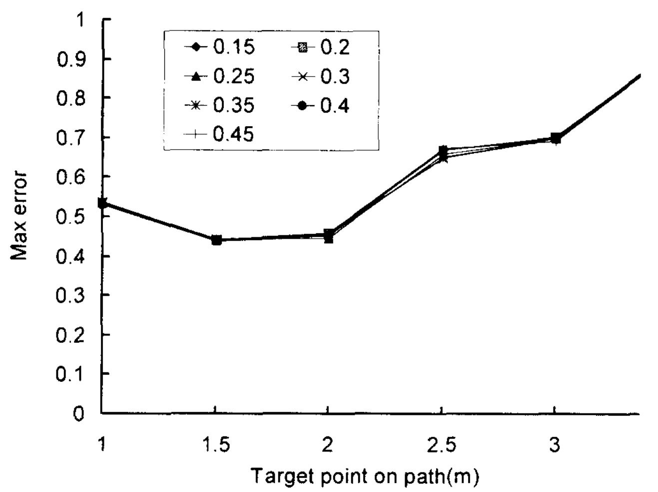


Fig. 6 Maximum error at each target point and steering rate on sinusoidal path.

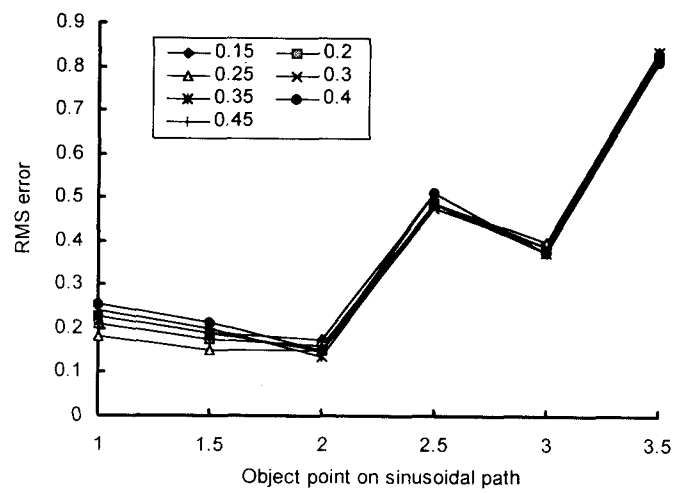


Fig. 7 RMS error at each object point and steering rate on sinusoidal path.

Fig. 7 shows rms deviation of tracking on the sinusoidal path at variable steering rates and distances of target points on x, y plane which x axis was distance to target point, y axis was deviation. Deviation in rms was influenced by steering rate when target point was less then 2.0m, influenced by only distance to target point when target point was above 2.0m, and increased by alternant tracking when target point was less then 1.5m.

Steering simulation by the virtue model of tractor indicated roughly the characteristic of steering, but its results was restricted to predefined condition for traveling.

(2) Manufacturing and test

Steering actuator was manufactured by fabricating a DC motor with reduction gear and a rotary potentiometer with non-contact type 5 turns. Fig. 8 shows the picture of the developed steering control unit.

Initialization time of this actuator was about 3.6 sec. and was able to control speed from 1.6 sec to 9.4 in full steering angle($-35^\circ \sim +35^\circ$) with keeping 180 N · cm as load torque.

2. Brake control device

Brake actuator was manufactured by fabricating a hydraulic cylinder and a pressure transducer(Fig. 9) to realize Hedrick's experimental formula.

This actuator had response time of 160ms, control pressure resolution of approximately 0.13Mpa and was able to control by 16 Hz as PWM frequency.

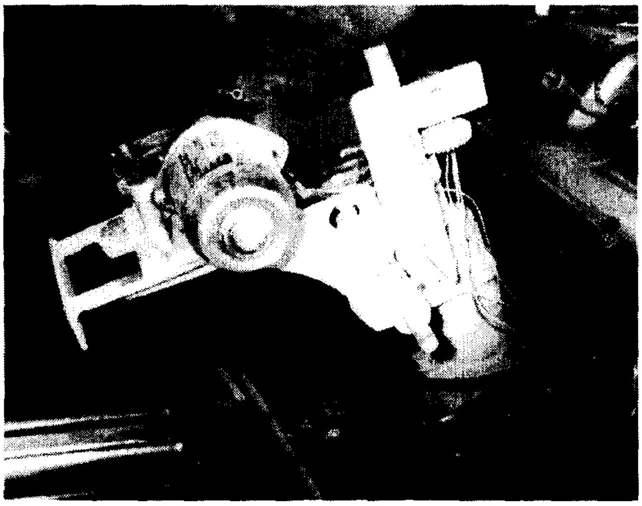


Fig. 8 Picture of steering control unit.

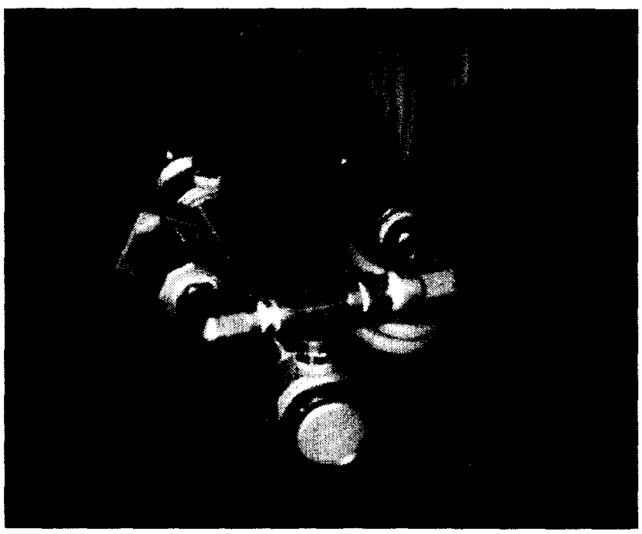


Fig. 9 Picture of brake control unit.

3. Transmission control device

Gear shifter as shown in Fig. 10 was manufactured by fabricating hydraulic cylinder and a position switch for changing speed. Characteristic constant of transmission in formula(9) was set as a= 0.0157, b=-0.0614, c=0.3456, d=0.2357.

This device was controlled by a processor which could receive current engine speed from a magnetic pick up sensor and set speed as input, which could generate output control command for governor and gear shifter.

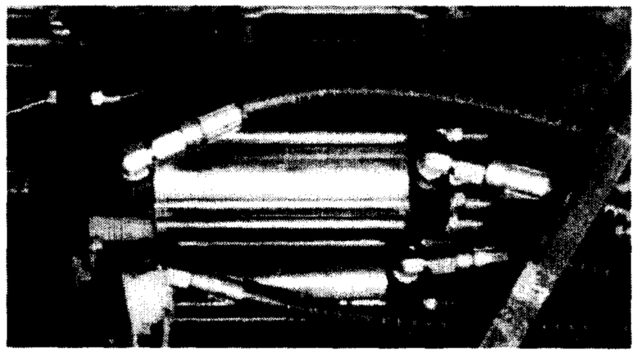


Fig. 10 Picture of transmission control device.

When stage of reduction gear was changed, generated fluctuation of engine speed was from 80rpm to 250rpm. Tested results of changing speed was shown in fig. 11.

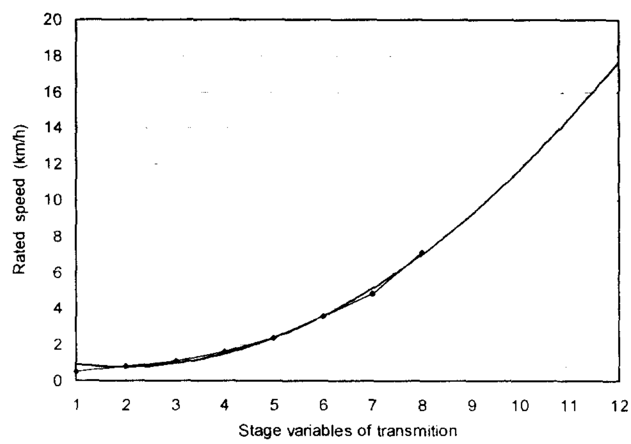


Fig. 11 The Result of Speed Controller.

4. Field test

Manufactured each control device, DGPS, rate gyro and wireless modem were mounted on a base tractor (26 ps) made by Daedong in Korea(fig. 12). Tractor weight increased up to 78 kg did not appear to change turn radius and steering performance except increase of 7 cm in brake distance at 21km/h as maximum speed.

The tests were performed at the experimental farm of NAMRI with DGPS coordinates as shown in Fig. 13. When tractor started away from 1m at desired path, tractor approached to desired path in 3 sec. with less than 30cm as tracing error. During tracking path, tractor kept less than 20cm deviation on the strait path and kept less than 50cm deviation. on the sinusoidal path with 6m turning radius as shown fig. 14.

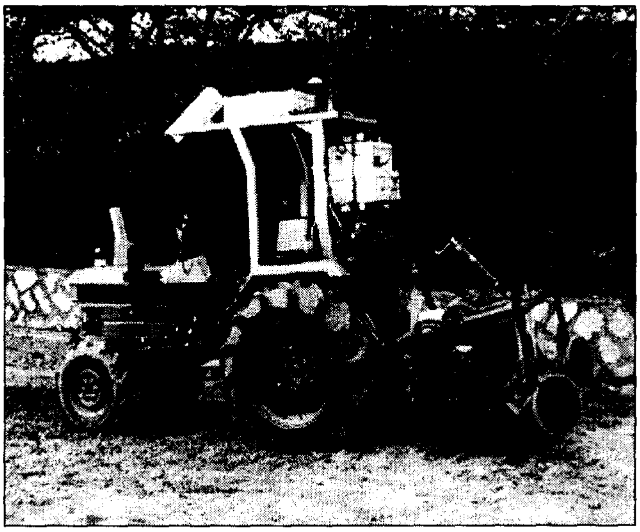


Fig. 12 Picture of prototype autonomous tractor.

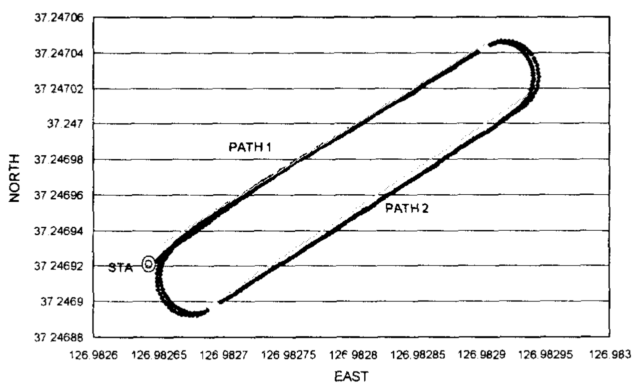


Fig. 13 The result of tracking path by DGPS coordinates.

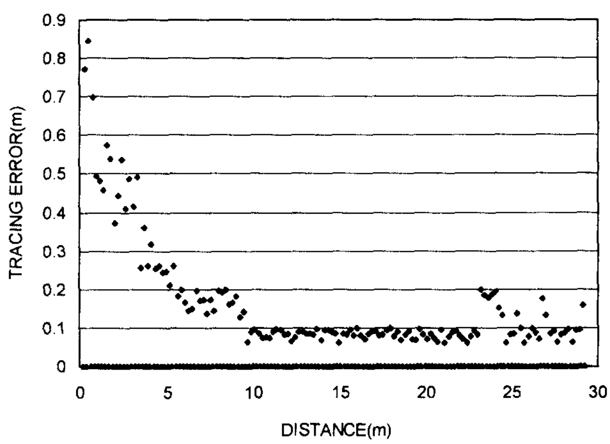


Fig. 14 Error range during tracking desired path.

Conclusions

1. A steering control unit in a closed loop using a DC motor and a encoder was fabricated. The test results showed that the resolution of control angle, full steering angle, and full steering time were 0.2, ±35, and 1.8seconds, respectively.

2. Using a hydraulic cylinder, a pressure transducer and the Hedrick's experimental equation, a brake control unit was constructed. Its response time and pressure control resolution were 160ms and 1.33kg/cm^2, respectively.

3. A sensor block and a interface unit that could measure the position of actuators remotely were developed with the combination of wire links. To obtain stable signal, an AMDF digital filter was designed with the cutoff frequency of 11Hz.

4. A speed control unit was developed with the combination of a gear shift and a governor controller.

5. When the developed autonomous tractor was tested on the planned path with the position signal from DGPS receiver, the RMS position errors were 20cm for straight paths and 50cm for curved paths.

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