Proceedings of the 7th JFPS International
Symposium on Fluid Power, TOYAMA 2008
September 15-18, 2008

OS1-2

STEERING CONTROL SYSTEM FOR AUTONOMOUS TRACTOR

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ABSTRACT

An automatic power steering control system is modified to a tractor of 66kw engine power and using a navigation system of optical fiber gyroscope(IMU) and real-time kinematic GPS which are hybrid combined, the movement of the vehicle in the field is analyzed dynamically using a kinetic movement model of tractor to determine the parameters of the model. The tractor equipped with a planter was successfully controlled and was able to trace the target line correctly within 10cm by the method of adaptive travel control using the movement model of the vehicle considering the hydraulic time delay of the power steering mechanism.

KEY WORDS

Steering Control , Autonomous ,Tractor, , Vehicle modeling , Filtering,

NOMENCLATURE

ψ : Vehicle running direction
θ : Direction of vehicle body center line
φ : Steering angle
K_f : Cornering power of front wheel
K_f : Cornering power of rear wheael
v : velocity of vehicle
β : Slip angle λ
λ : Time rag of hydraulic operation
ω : Rotational rate
μ : Rolling resistance
$\square_w$: wheel base (suffices f:front, r:rear)
m : Mass of vehicle

INTRODUCTION

The speedup of the work is gradually highly required with the extension of the size of operational holdings per one farmer. However, the need for accurately controlling the implement becomes inevitable. Automatically steered farm equipment has many advantages of increasing agriculture accuracies at high speed operation including relieving the driver of the tedious task of accurately steering the vehicle, operation in low visibility circumstances such as at night. Many agricultural operations pull towed implements. It will become necessary to accurately control towed implements.

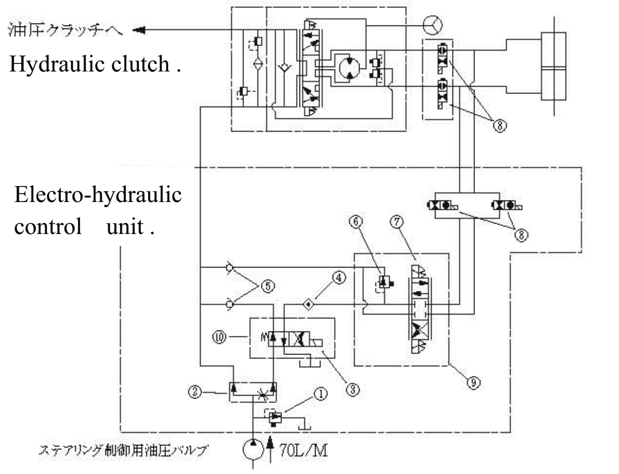
Tracked tractors are now used increasingly among farmers in Japan because of its soft compaction, strong fraction force, ability to work on the weak ground and stability in the high-speed field work. The operability and steering mechanism are constructed, and the running and turning performance is fairly improved nowadays. The operation is possible of the sense which is similar to the wheel tractor, and possible to work comfortable. However heading control of tracked vehicles at high speed is difficult for automatic driving or human driving with high accuracy because of the slippage between the crawlers and the ground. There has also been work done on the control of wheel tractor implements, using GPS measurements, although there are no details on the model and control algorithms for the tracked tractors or semi-crawler tractor.

This paper describes a modeling of the steering actuation of a crawler tractor and a semi-crawler tractor and an extended Kalman filter to estimate the position, direction, attitude, speed of the tractor required for the state feedback algorithm and robustic adaptive control method of the electro-hydraulic system of the tractor. The linearization of the tractor-implement model is validated through a series of the line tracking experiments on a semi-crawler tractor and a planter.

METHOD

Vehicle Hardware and Control system

A semi-crawler tractor (front wheel drive, rear crawler drive tracked vehicles, KUBOTA Ltd.M90-PC FQ1BMAL) of 66kW(90PS) was converted to automatic controlled Tractor. The following functions are controlled by microcomputer through D/A converter: steering, throttle and tri-link. The following are controlled by microcomputer through digital parallel I/O interface: forward, reverse and idle; and PTO. Front wheels are actuated using a modified electro-hydraulic steering unit installed parallel to the power steering system. The wheel angle is sensed by encoder equipped front wheel shaft The microprocessor converts volt from the control computer into electro current , which are sent to the power circuits that control the steering servo valves. The steering valves are controlled by the method of PID control.



1 relief valve ,2 separate valve, 3 electromagnetic valve, 4 filer, 5 check valve, 6 relief valve, 7 servo valve, 8 stop valve, 9 manihold

Figure 1 Hydraulic system of the automatic power steering control

Throttle and lift link are controlled by potentiometer. A wire connected to a geared DC motor with a clutch mechanism to maintain constant torque pulls the clutch or the brake pedal. PTO and other on-off switches are controlled by relay systems through parallel I/O interface board. The tractor is equipped with the IMU (JCS-7401A, Nihon Koukuu Denshi Co., Ltd.) which can output rotational angle and

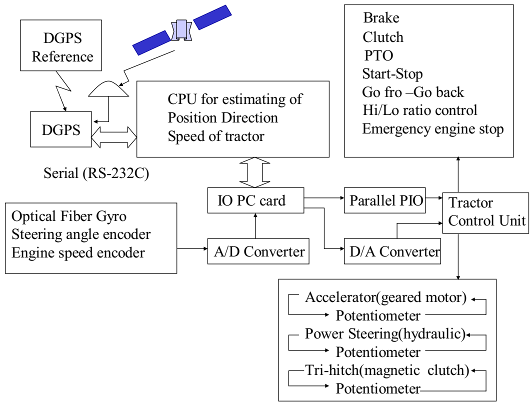


Figure 2 Schematic diagram of the computer control system of autonomous tractor.

velocity of each yaw, pitch, roll rates. The accuracy of the IMU is 0.2 degree of accuracy and drift of 5 degrees/hour. The RTK-GPS (SR530 , Leica Co., Ltd.) of accuracy within 2 cm and sampling rate 10Hz is also equipped with the tractor. The data of GPS are transferred through RS-232C interface to a notebook computer and the position, heading angle, attitude, speed of the tractor is calculated through a extended Kalman filter algorithm with the data of IMU.

equations.

Model of vehicle movement

In the flat field and hydraulic control time delay of front wheel of a tractor was made and the method of predictive motion control was applied to control the steering angle of an autonomous tractor by prediction of the motion of a vehicle in every 0.1 second based on the position, direction and velocity data from GPS and FOG. A X-Y coordinate axis is taken like Figure 3, then the running direction ψ and the direction of vehicle body center line θ equations are follows from the force ff,fr balance in the perpendicular direction to running direction of center of gravity and the moment balance in the circumference of center of gravity.

$$mv\ (d\phi/dt) = -2(K_f+K_r)\beta - 2(K_f \square_f - K_r \square_r)\cdot (d\theta/dt)/v + 2K_f\phi \qquad (1)$$

$$I_z(d^2\theta/dt) = -\{2(K_f\square_f - K_r\square_r) + \mu_f mg\square_r\}\beta - K_f\square_f^2 + K_r\square_r^2)(d\theta/dt)/v + 2K_f\square_f\varphi$$

The locus of vehicle center of gravity and the direction of the vehicle are calculated on the base eqn.(1),(2). When the velocity of vehicle is constant, then these equations are calculated as follows.

$$\beta = \left(1 - \frac{m\square_f}{2K_r\square_w} v^2\right)\left(\frac{\square_r}{\square_w}\right)(\varphi / R) \qquad (2)$$

$$\omega = \left(1 - \frac{\mu_f m g \Box_r}{2K_r \Box_w \Box_r \ \Box_w}\right)\left(\frac{V}{\quad}\right) (\varphi / R) \quad (3)$$

$$R = 1 - \{(K_f \Box_f - K_r \Box_r)(mv^2 + \mu_f m g \Box_r) + \mu_f m^2 g \Box_r v^2 / 2\} / (2 K_f K_r \Box_w^2) \quad (4)$$

Steering control method

The steering angle φ(k) is controlled so as to trace the target line Y-axis. The direction θ' and x' after short time λ second are estimated with the eqn .(6),(7). The φ(k) is controlled so as to follow eqn.(5) relation. This eqn.' s relation means the direction of the vehicle is to proportional to the offset of the vehicle.

$$\theta' = f(x', v(k)) = -K(\lambda) \cdot x' \quad (5)$$

Where,

$$\theta' = \theta(k) + \omega(k) \cdot \lambda \quad (6)$$

$$x' = x(k) + v(k) \cdot \lambda \cdot \sin(\psi(k) + \omega(k) / 2 \cdot \lambda) \quad (7)$$

ψ(k) and ω(k) are small, so approximately replaced as follows eqn.

$$\sin(\psi(k) + \omega(k) / 2 \cdot \lambda) = \psi(k) + \omega(k) \cdot \lambda / 2 \quad (8)$$

So, objective steering angle φi(k) is obtained from (5)-(8) eqn.

$$\varphi_i(k) = -R \cdot \Box w / Q \ \{(1 + K(\lambda)\, v(k)\, \lambda)\ \theta(k) + K(\lambda)\, x(k)\} / \{v(k)\, \lambda (1 + K(\lambda)\, v(k)\, \lambda / 2)\} \quad (9)$$

Where, $Q = (1 - \mu_f m g \Box_r / 2 K_r \Box_w)$ (10)

Using a simulation model for a tractor mobile trace, after examining several functions f (x', v), determined when strait traveling,

$$f(x', v) = (1 + 3v) \bullet x' |x'| < \pi/2 \bullet (1 + 3v)) \quad (11)$$

There is a relationship of dy / dx = 1 / tanθ, so if we suppose that Eq. (5) is satisfied, then the traveling trace is calculated by solving the differential equation of dy / dx = 1 / tan (f(x, v)). The relationship between offset x and vehicle direction θ' for vehicle control in strait traveling is expressed by Eq. (5).These parameters were fixed in the experiment.

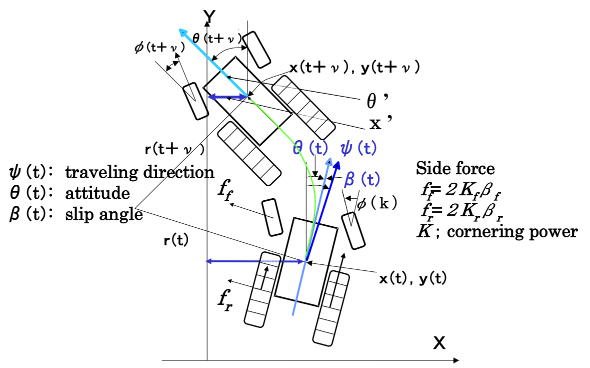


Figure 3 Schematic diagram of movement of tractor.

Experiment of automatic planting in the field

The semi-crawler tractor of 66kW(90 PS) was developed in our laboratory (Figure 4). After equipping this tractor with a planter for soybeans 2.52 m in work width, we conducted an experiment of automatic planting in the field 10 × 385 m in area at 1.3 m/s in travel speed (engine: 1800 rpm). At the end of the field, the system calculated target steering angle and executed a turn to bring the tractor assembly to the next ridge. After directing the tractor to the next ridge, the system measured the position and direction by FOG, GPS and collected the direction offset of the fiber-optic gyro output.

Figure 4 Autonomous Semi-crawler tractor

RESULT and DISCUSSION

Responsibility of hydraulic steering control system

The response of the hydraulic power steering control system is shown in Figure 5 when the target steering angle is 10degree and initial steering angle is 0 degree. The steering angle is controlled linearly and controlled within 1 second. The idling time rag is about 0.2second.The process of the output volt from the computer PID control and measured steering angle is shown in Figure 6.

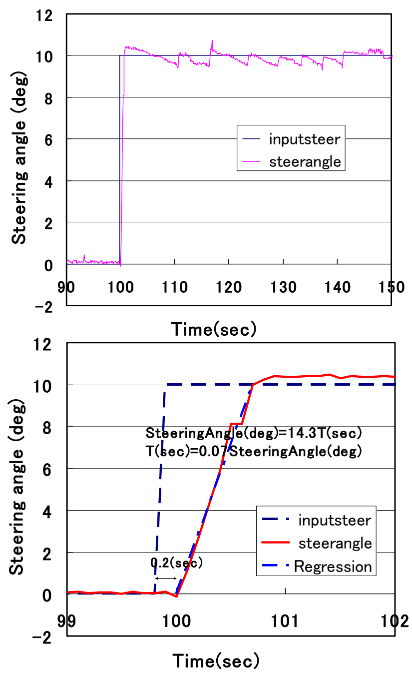


Figure 5 Response of electro-hydraulic power steering by PID control

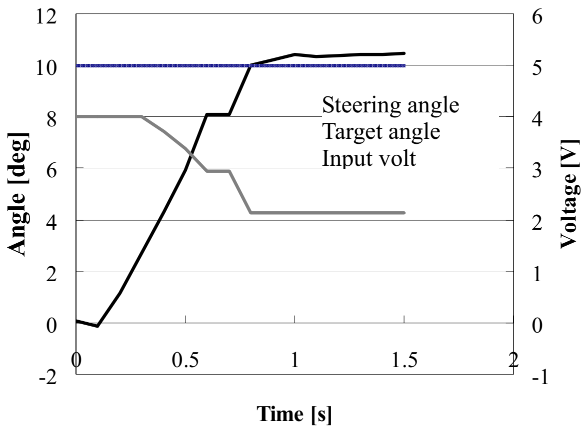


Figure 6 PID steering control

Characteristic of turning of the sem-crawler tractor

The tractor travel first straight 10m and next turn right on fixed steering angle by computer control as Figure 7 and the direction of the tractor is measured by FOG and the track is measured by RTK which's accuracy is 2 cm.

The relationship between the turning radius and the steering angle is examined in the field and the slip angle, the cornering power are calculated using these eqns..

$$\beta=\psi-\theta \tag{12}$$

$$Kf=\square_r\, mv\omega/(2Ca\square_w) \tag{13}$$

$$Kr=\square_f mv\omega/(2Cb\square_w) \tag{14}$$

When

$$Ca=\varphi-\square_f\omega/v-\beta,\quad Cb=\square_r\omega/v-\beta \tag{15}$$

The velocity of the vehicle is changed 0.5,0.75,1m/s and the steering angle is changed from 5 to 40degree every 5degree step. The relationship between the turning radius and the steering angle is shown in Figure 8. The turning radius is revealed as exponential function of steering angle with high correlation .

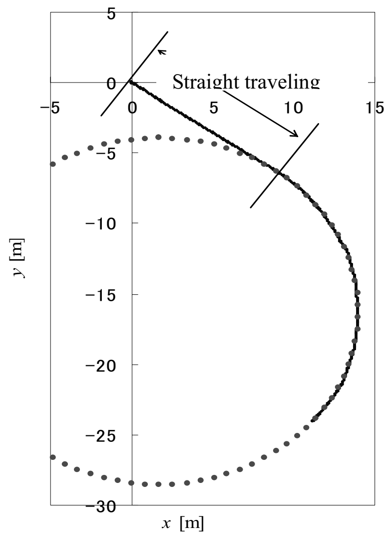


Figure 7 Turning trace of semi-crawler tractor

The cornering power Kf,Kr is calculated by eqn.(13),(14) as Figure 10.The cornering power of the rear track Kr increase with the steering angle grow while Kf decrease. By using this factor, turning radius is esteemed correctly with in 6 cm accuracy.

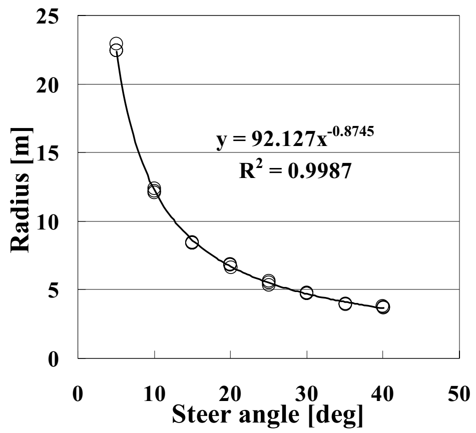


Figure 8 Relationship between steering angle and turning radius(V=0.75m/s)

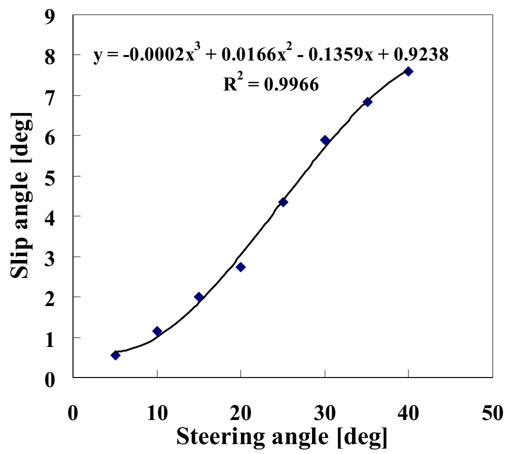


Figure 9 Relationship between steering angle and slip angle

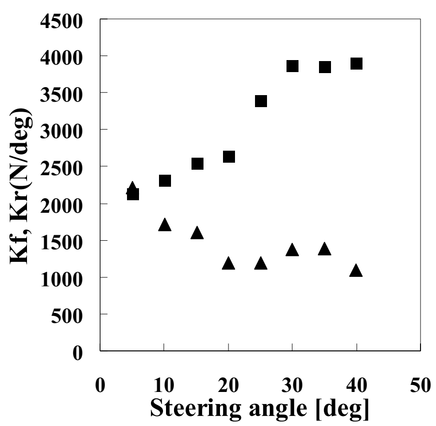


Figure 10 Cornering power Kf(front wheel;▲),Kr(rear track;■)(V=1m/s)

Simulation of the steering control and movement of vehicle

The result of simulation of the movement of the semi-crawler tractor by the predictive steering control method is shown in Figure 8. The steering angle is calculated considering the hydraulic cylinder's operational time lag and direction swinging which is supposed to occur by inequalities of the ground. Figure 11 show steering angle, direction of vehicle, x-position difference from the target line by adjusting predicting time lag. The tractor is more adequately controlled by predictive time 1s than 0.5s7s.

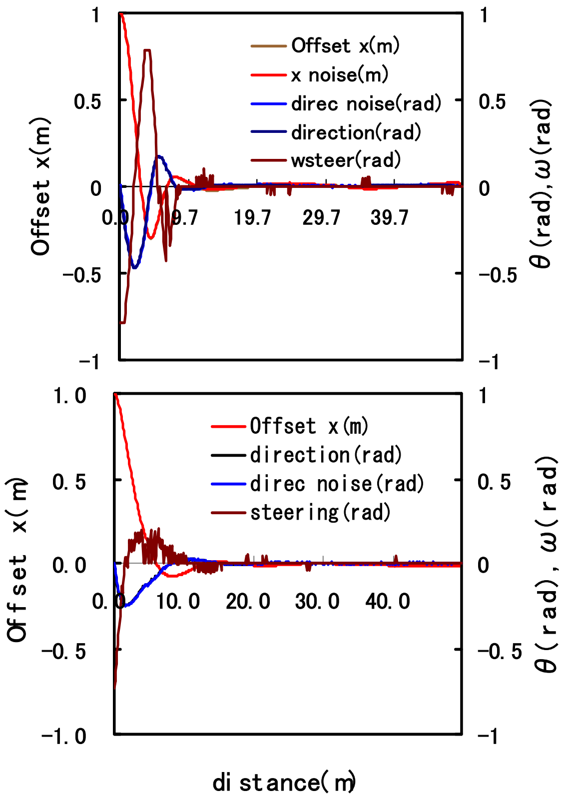


Figure 11 Comparison of dynamics for path tracking of vehicle between the predictive time o.5s(upper) and 1s(lower)

Automatic planting in the field

The tractor plant soybeans automatically by the round trip work of the straight distance 380m without the trouble at 1.3m/s speed for more than 30 minutes (experiment time).

Each lines is parallel and almost straight with equal interval. The tractor was controlled within 10 cm (RMS 5.2cm)of accuracy(Figure12-14). The tractor raise up planter and turn to next line automatically at the end of the operation area and select next target line which is generated by computer, and adjust the position and direction, after entering operational area, down planter and raise up engine revolution, and go forth. There is no meandering under the method of forecasting a position and direction of tractor. The traces of the seeding were parallel and equal to the target line and the edge of the trace was almost same.

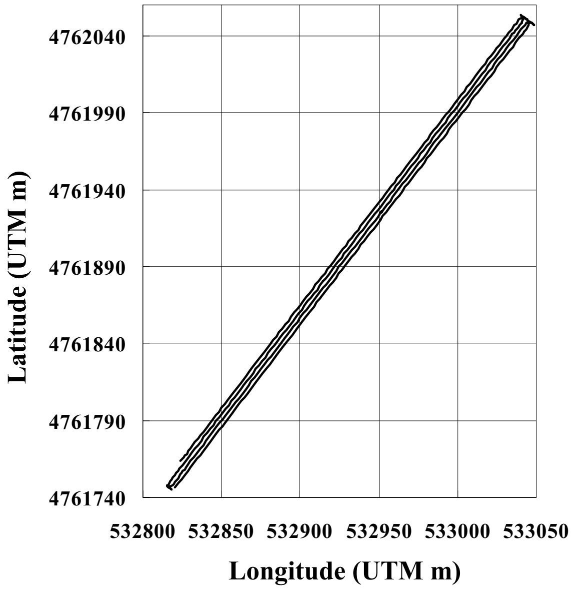


Figure 12 Track of autonomous tractor working on planting

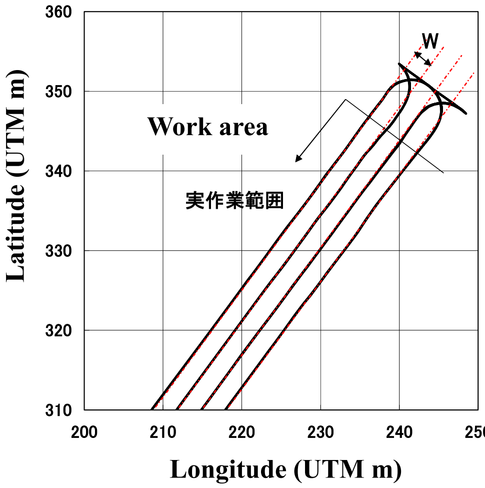


Figure 13 Track of the autonomous tractor working of planting(target line and actual track)

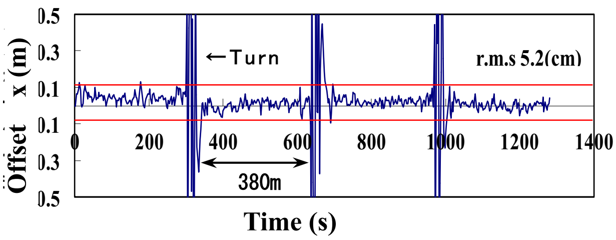


Figure 14 Offset x track of autonomous semi-crawler tractor

Figure 15 Planting soybeans by autonomous semi-crawler tractor (2007.5.29)

Figure 16 Comparison of plant raw (soybean) by automatic and manual operation

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