Autonomous Navigation System of Crawler-Type Robot Tractor

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Abstract: The objective of this research was to modify a commercial crawler-type tractor into a robot tractor that can be navigated autonomously by using RTK-GPS and IMU as navigation sensors. Navigation algorithms were developed. Steering control test and autonomous navigation test in farmland were conducted. Steering control test was conducted in different speeds, and the accuracy was evaluated. In each speed, the robot ran with 1–3cm lateral error. Autonomous navigation test was conducted on multi-path map. In headland area, the robot used keyhole turning and transferred to the next path. The robot could finish the multipath navigation successfully.

Keywords: RTK-GPS, IMU, crawler-type tractor, steering control, keyhole turning, robot tractor

1. INTRODUCTION

Hokkaido, the northernmost island of Japan, is central region of agricultural industry in Japan, in spite of its long time winter season and accumulated snow. Hokkaido prefecture has about 83,456 km² land area, which occupies about 22% of Japanese land. Its rich and broad plain fields and primal acceptance of large-scale agricultural production system enabled Hokkaido to become Japan’s capital production area of wheat, paddy, corn, potato, dairy cattle, and so on. Though Hokkaido is such a capital area of agriculture, the shortage of agricultural work force and its aging farmers is happening.

A crawler-type tractor is a vehicle with tracks instead of wheels. Crawler-type tractors are widely used in Japan, especially in paddy fields, because of their high traction and low ground pressure. And they are also used on purpose for snow removal in the winter season. Crawler-type tractors are different from wheel-type tractors in their steering control mechanisms. The tractor controls its direction by changing the rotation velocity between the two crawlers. The two crawlers can spin in the counter direction each other. So it can turn in small radius and even on the spot.

The objective of this research was to develop a crawler-type robot tractor that works in agricultural fields. The authors modified a commercial crawler-type tractor into robot tractor based on RTK-GPS (Real-time kinematic global positioning system) and IMU (Inertial measurement unit) as navigation sensors.

2. MATERIALS AND METHODS

2.1. Research platform and navigation sensors

Table 1. Specifications of a crawler tractor

<table>
<thead>
<tr>
<th>Model</th>
<th>CT801</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive system</td>
<td>Crawler</td>
</tr>
<tr>
<td>Dimensions</td>
<td></td>
</tr>
<tr>
<td>Overall length, mm</td>
<td>3750</td>
</tr>
<tr>
<td>Overall width, mm</td>
<td>1950</td>
</tr>
<tr>
<td>Overall height, mm</td>
<td>2635</td>
</tr>
<tr>
<td>Ground clearance, mm</td>
<td>380</td>
</tr>
<tr>
<td>Weight</td>
<td>kg</td>
</tr>
<tr>
<td>Engine</td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td>4TNV98T</td>
</tr>
<tr>
<td>Type</td>
<td>4-cycle, water-cooled diesel</td>
</tr>
<tr>
<td>Output(kw(ps))</td>
<td>58.8(80)</td>
</tr>
<tr>
<td>Dispacement(cc)</td>
<td>3318</td>
</tr>
<tr>
<td>Fuel Tank Capacity(lit)</td>
<td>150</td>
</tr>
<tr>
<td>Crawler Track</td>
<td></td>
</tr>
<tr>
<td>Length(mm)</td>
<td>2165</td>
</tr>
<tr>
<td>Width(mm)</td>
<td>450</td>
</tr>
<tr>
<td>Tread(mm)</td>
<td>1500</td>
</tr>
<tr>
<td>Brake</td>
<td>Wet disk</td>
</tr>
<tr>
<td>Max, travel speed (km/hr)</td>
<td>18</td>
</tr>
<tr>
<td>Front</td>
<td></td>
</tr>
<tr>
<td>Rear</td>
<td></td>
</tr>
</tbody>
</table>

Fig.1. CT801 (YANMAR)
Figure 1 shows the research platform, a YANMAR CT801, a crawler-type standard tractor was used in this research. Table 1 shows its specification. Figure 2 shows schematic diagram of the robot tractor. RTK-GPS and IMU were used as navigation sensors to determine lateral and heading errors which were necessary in to evaluate the autonomous navigations. Figure 3 shows the RTK-GPS’s (Legacy-E, TOPCON) antenna and receiver. To obtain the absolute position of the robot vehicle, an VRS (Virtual reference station) was used with positioning accuracy of ±2 cm. Fig.4 shows IMU (Inertial measurement unit) (JCS-7401A, Japan Aviation Electronics Ind., Ltd.) used as the posture sensor that could obtain roll, pitch and yaw, and angular velocity of the robot vehicle. It could measure roll and pitch angles within ±45° and yaw angle of ±180°. The IMU has a drift error of 0.5deg/hour. The error was corrected dynamically using sensor fusion algorithm based on IMU and GPS signal.

Control PC in the vehicle calculated vehicle’s functions for autonomous navigation using developed algorithms and navigation maps. ECU (Electrical control unit) was developed to convert control PC’s digital signal to analog signal to operate the vehicle. ECU has the CAN (Control area network) bus interface and communicated with the control PC. ECU sent analog signals to vehicle’s actuators.

Vehicle’s functions, forward and backward movement, steering angle, height of three-point link hitch, engine speed, PTO’s turning on and off, were controlled by ECU.

2.2 Sensor fusion

To obtain the lateral error direction of the robot vehicle, an LSM (Least square method) was used (Kise 2003). Figure 5 shows the vehicle dynamics using the RTK-GPS and IMU sensor fusion.

The robot vehicle's absolute position \((X_{k+1}, Y_{k+1})\) can be calculated using (1) and (2).

\[
X_{k+1} = X_k + \int_k^{k+1} V(t) \sin \phi(t) \, dt \\
\approx X_k + \frac{1}{2} V_k \Delta t (\sin \phi_k + \sin \phi_{k+1}) \quad (1)
\]

\[
Y_{k+1} = Y_k + \int_k^{k+1} V(t) \cos \phi(t) \, dt \\
\approx X_k + \frac{1}{2} V_k \Delta t (\cos \phi_k + \cos \phi_{k+1}) \quad (2)
\]

Where:

\(X_{k+1}, Y_{k+1}\) = absolute position of the vehicle, m

\(V_k\) = travel speed, m/s

\(\phi_k\) = absolute heading direction of the vehicle, deg
The absolute heading direction of the robot vehicle can be calculated using (3).

\[ \phi_k = \phi_{IMU_k} + D_k \]  

Where:

\[ \phi_k = \text{absolute heading direction, deg} \]
\[ \phi_{IMU_k} = \text{relative angle measured by the IMU, deg} \]
\[ D_k = \text{correction value which compensates the drift error, deg} \]

The vector of the vehicle position can be calculated using (4) and (5)

\[ e_{p_k} = \begin{pmatrix} X_{k+1} - X_k \\ Y_{k+1} - Y_k \end{pmatrix} \]  \hspace{1cm} (4)
\[ e_{\theta_k} = \frac{v_k \Delta t}{2} \left[ \sin \phi_{k+1} + \sin \phi_k \right] + \left[ \cos \phi_{k+1} + \cos \phi_k \right] \]  \hspace{1cm} (5)

Evaluation function to decide \( D_k \) was defined as (6).

\[ I_k = \sum_{i=k-N}^{k} \left\| e_{p_{i-1}} - e_{\theta_{i-1}} \right\|^2 \]  \hspace{1cm} (6)

Since \( I_k \) is sum of the error, a proper \( D_k \) can be calculated by using (7) that minimizes the \( I_k \)

\[ \frac{dI_k}{dD_k} = 0 \]  \hspace{1cm} (7)

Where:

\[ N=\text{number of navigation points} \]
\[ e_{p_k} = \text{vector of the vehicle position by position sensor} \]
\[ e_{\theta_k} = \text{vector of the vehicle position by posture sensor and velocity sensor} \]

(8) can be described from (1) to (6)

\[ I_k = \sum_{i=k-N}^{k} \left( dX_i^2 + dY_i^2 + S_i^2 + C_i^2 - 2(dX_i C_i + dY_i S_i) \cos D_k + 2(-dX_i C_i + dY_i S_i) \sin D_k \right) \]  \hspace{1cm} (8)

Where:

\[ dX_i = X_i - X_{i-1} \]  \hspace{1cm} (9)
\[ dY_i = Y_i - Y_{i-1} \]  \hspace{1cm} (10)
\[ S_i = \frac{1}{2} V_i \Delta t (\sin \Phi_{IMU_i} + \sin \Phi_{IMU_{i-1}}) \]  \hspace{1cm} (11)
\[ C_i = \frac{1}{2} V_i \Delta t (\cos \Phi_{IMU_i} + \cos \Phi_{IMU_{i-1}}) \]  \hspace{1cm} (12)

Finally,

\[ D_k \] is calculated using (7) and (8).

\[ D_k = \tan^{-1} \left( \frac{\sum_{i=k-N}^{k} (dX_i C_i - dY_i S_i)}{\sum_{i=k-N}^{k} (dX_i S_i + dY_i C_i)} \right) \]  \hspace{1cm} (k > N)

2.3. Navigation map

![Fig.6. Navigation map](image)

Figure 6 shows the straight lines composed of three dimensional points which were created by GIS. The robot works following the navigation map. Navigation points were defined as three dimensional Euclidean space \( \mathbb{E}^3 \) shown as (14) (Kise 2003).

\[ \Omega = \{ \omega_i | \omega_i \in \mathbb{E}^3, 0 < i \leq N \} \]

where:

\[ \omega_i = (lat_i, lon_i, code_i) \]

Where:

\[ lat_i, lon_i: \text{Latitude and longitude of navigation points in WGS-84 coordinate} \]
\[ code_i: \text{Codes of vehicle’s jobs} \]

2.4. Steering control algorithm

![Fig.7. Steering control](image)

The robot changes its steering angle dynamically on the straight lines of navigation map. Steering angle \( \delta \) was calculated using PID control based on lateral error \( d \) and heading error \( \Delta \phi \) shown as (15).

\[ \delta = a_1 d + a_2 \Delta \phi \]  \hspace{1cm} (15)
2.5 Keyhole turning

After the robot finishing a path, it turns in the headland to enter the next path. Keyhole turning is a way of turning that contains no backward movements. Diagram of a keyhole turning is shown in Fig.8.

During this turning, the robot tractor turns in the same radius, so the influence on the ground is thought to be almost constant. The radius can be changed by the ground condition. In this figure, vehicle advances on point-A, point-B, point-C, point-D, in order. Equation (4) was used to represent $\theta$.

$$\theta = \cos^{-1}(\frac{w}{2 * r})$$

(4)

Where:
- $\theta$: turning angle from point-A to point-B
- $w$: width between two working lines
- $r$: turning radius

2.6 Autonomous navigation tests

Automatic navigation tests were conducted on single-line path and multline paths. At first, single-line path navigation test was conducted on a road in fields to test the accuracy of steering control. The robot followed the line using algorithm shown in (3) and Fig.3 in different speeds. The gains were changed as to the speed. In each speed, the accuracy was evaluated as lateral and heading errors. Then autonomous navigation test was conducted. Four path lines were created by GIS, and in headland area the robot turned with keyhole turning that used algorithm shown in (4) and Fig.4. The speed was about 1m/s on straight lines and about 0.4m/s during headland turning. Acceleration speed, PTO and the height of three-point hitch were also controlled in this navigation. On path lines, acceleration speed were elevated, PTO rotated and three-point hitch was moved downward. During turning, acceleration speed was reduced, PTO stopped and three-point hitch was moved upward.
3. RESULTS AND DISCUSSION

Table 2 shows the RMS lateral and heading error of single path navigation test in each speed. The lateral error was about 1–3 cm and the heading error was less than 1 deg. This result suggested the robot has enough accuracy to satisfy automatic navigation in a speed less than 2 m/s. Figure 9 shows the trajectory of multipath navigation. The robot followed the navigation map and worked its jobs on straight lines. In headlands, the robot turned using keyhole turning algorithm and entered to next path with 4–10 cm errors. Figure 10 and 11 shows the transition of lateral and heading error respectively. The lateral error at the beginning point of each path was converged gradually.

4. CONCLUSION

The authors modified a standard crawler-type tractor into a robot tractor that controls functions electrically and navigates itself automatically following a navigation map. Navigation map was created by the GIS. Steering control algorithm and keyhole turning algorithm was developed and autonomous navigation tests were conducted. On a single straight line path, the robot ran with 1–3cm lateral error and less than 1 deg heading error at the speed of 0.6–2 m/s. This result suggested that this agricultural robot had enough ability to work on straight lines at the speed less than 2 m/s. On multiline path, the robot controlled its functions such as speed, steering angle, PTO, tree-point hitch, and in headland area, it turned with keyhole turning. The robot finished its autonomous navigation successfully.

REFERENCES


<table>
<thead>
<tr>
<th>Speed,m/s</th>
<th>r.m.s lateral error,mm</th>
<th>r.m.s heading error,deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>10</td>
<td>0.24</td>
</tr>
<tr>
<td>0.9</td>
<td>18</td>
<td>0.47</td>
</tr>
<tr>
<td>1.3</td>
<td>29</td>
<td>0.76</td>
</tr>
<tr>
<td>1.7</td>
<td>22.3</td>
<td>0.63</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>0.54</td>
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