AN AUTONOMOUS TRIMMING SYSTEM OF LARGE GLASS FIBER REINFORCED PLASTICS PARTS USING AN OMNI-DIRECTIONAL MOBILE ROBOT AND ITS CONTROL

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Abstract
This paper describes an automated trimming system of large glass fiber reinforced plastic (GFRP) using an omni-directional wheeled mobile robot (WMR) and its path control method. In trimming GFRP parts, much glass fiber and plastic powder dust occur and it becomes bad visible in environment. It is necessary to correct dead-reckoning errors of the WMR in order to control its moving path. We have discussed an external correction method of the dead-reckoning errors for the WMR using ultrasonic sensor.

Keywords: Mobile manipulator, Handheld grinder, Trimming, GFRP parts, Floor irregularities, Ultrasonic sensor net, Dead-reckoning error correction

1. Introduction

Recently many research works in mobile manipulator have been reported (Fogle, et al., 1992), (Reister, et al., 1993). However, few industrial oriented mobile manipulators were found. Edge trimming process of large GFRP parts is a remaining process to be automated in GFRP manufacturing because the work space of the trimming task for large GFRP parts exceeds the range of the work space of an articulated robot. We had developed a wheeled mobile robot (WMR) equipped with a handheld grinder to trim the large GFRP part. The WMR tracks correctly the desired contour of the GFRP part using its three laser displacement sensors during trimming operation (Nasu, 1997, 1998). But for trimming operation, the WMR must autonomously move between the parts or between the part and the energy station. When WMR moves near to GFRP part, the three laser displacement sensors navigate WMR to trim the GFRP parts. When the WMR moves the workshop floor, the dead-reckoning error is caused by irregularities of the floor. The surfaces of typical factory's floors are strewn with cracks, bumps, and sometimes debris, along with the inherent roughness of the surface.
This paper discusses mainly the external dead-reckoning error correction method of WMR to move autonomously between some GFRP parts or between the part and the energy station. Position estimation is fundamental technology for mobile robot's autonomous travel. In trimming large GFRP parts, much glass fiber and plastic powder dust occur and it becomes bad visible in environment. So it is difficult to estimate position by image processing. Relative positioning methods (etc. distance accumulation) cause accumulation errors. The positioning range is not enough in workshop using active ultrasonic beacons (Seki, 1998'). The positioning accuracy is not enough for WMR using GPS and PHS positioning systems (Suzuki, 1999, Hirano, 1999), although the positioning range is very broad. This study had developed an ultrasonic positioning system for mobile robot moving in trimming workshop using ultrasonic receiver net.

2. Wheeled mobile manipulator system
Workpieces of GFRP, which measure over 2 by 4m, are easily deformed under the external forces and hence the edge trimming process is necessary to guarantee the required accuracy: ±5mm.

In the edge trimming, the wheeled mobile manipulator (WMM) is controlled to track a reference trajectory which is determined by the desired contour of the GFRP parts. The WMM consists of the WMR and a 2D (RP) manipulator. The WMM is approximately 850mm in length, 500mm in width, and 300mm in height, 70kg in weight, wheelbase of 700mm, tread of 530mm, and wheel radius of 100mm. The developed WMM system is shown in Fig.1. In order to determine the center of rotation of the WMR arbitrarily on the floor, a four-wheel-steering (4WS) system is adopted in the WMR. The WMR has a four-wheel-driving (4WD) system and each wheel is steered and driven by two independent DC servo motors. The WMR has also an independent ground clearance control mechanism (driven by a DC servo motor) for each wheel. The 2D manipulator consists of a prismatic joint and a revolute joint and equipped with a handheld grinder. Specifications of the grinder are as follows: rotational speed is 10000rpm, type of the grinding disk is C80M-6, and diameter of the grinding disk is 100 mm. Vertical height of the grinding disk can be adjusted by the revolute joint. The prismatic joint moves the grinding disk along the direction of y axis of the WMR. The grinding force is measured by a force sensor which is attached between the prismatic joint and the revolute joint. The position and orientation of the WMR is detected by using three laser displacement sensors attached at the side wall of the WMR, that measure the distance from the guide path which is set on the floor. The guide path, which is set up along the desired contour of the GFRP, determines the reference trajectory of the WMR.

![Fig.1 Wheeled Mobile Manipulator](image)

![Fig.2 Measuring system of the distance error and orientation error](image)

3. Trajectory tracking
It is required to keep a constant level of the platform for trimming trajectory tracking, even if the mobile robot moves on the floor with irregularities. Assuming planar motions, the robot is controlled so as to constrain the point E located on the grinding disk, to be at a constant distance from guide wall and to maintain the robot parallel to this surface (Fig. 2). Consider the motion of the point E with respect to trajectory coordinate frame \( \Sigma_{\text{tri}} \). The origin O of \( \Sigma_{\text{tri}} \) is located at the foot of the perpendicular from point E to the reference trajectory. \( x \) is the distance error between the point E and origin of \( \Sigma_{\text{tri}} \) (the point O), and \( \psi \) is the orientation error of the grinding disk with respect to axis y of the coordinate frame \( \Sigma_{\text{tri}} \). Using the value of three LDS (\( d_1, d_2, d_3 \)), the error components of the point E are given by:

i) for circular trajectory:

\[
\psi = \arctan(-(E_y - C_y), (E_x - C_x))
\]

\[
x = \|C - E\| - R_{\text{guide}} \tag{1}
\]

ii) for linear trajectory:

\[
\psi = \arctan(P_3 - P_1, -(P_3 - P_1))
\]

\[
x = \|P_2 - E\| \cos \psi \tag{2}
\]

where \( R_{\text{guide}} = \|P_i - C\|, i = 1, 2, 3 \) is radius of circle, \( C \) is measured position of center of circle.

*Fig. 3* Coordinate system of the wheeled mobile robot

This paper defines a feedback control law which locally stabilizes the motion of the WMR to track the desired contour. Assuming that the reference trajectory for the WMR is a smooth curve formed by a constant curvature. The coordinate system is shown in Fig.3. \( \phi_i \) and \( V_i (i = 1, ..., 4) \) represent the steering angle and the translational velocity of each wheel, respectively. By fixing \( V_{ex} = 0 \), motion of the WMR is regarded as rotation about a point P, and hence, the velocity and steering angle of each wheel for given \( \dot{\phi} \) can be obtained. The motion of the point E is given as

\[
\begin{bmatrix}
\dot{x} \\
\dot{\psi}
\end{bmatrix} = \begin{bmatrix}
-V_{\phi} \sin \psi \\
\dot{\theta} - V_{\phi} \cos \psi \\
R + x
\end{bmatrix} \tag{3}
\]

where \( R \) is the curvature of the desired contour. Regarding \( \dot{\theta} \) as the control input to the system (eq.4), a feedback control law is defined by linearizing the system around \( \psi = 0, \ x = 0 \).
\[ \dot{\theta} = K\dot{\zeta} + \frac{V_{oy}}{R}, \quad K = [K_x, K_\psi] \]  

(4)

where \( \zeta = [x, \psi]^T \), \( K_\psi < 0 \), \( K_x > -V_{oy} / R^2 \). \( K_x \) and \( K_\psi \) are determined from simulation and experimental results.

4. External correction system of dead-reckoning error

The suggested positioning system consists of main three parts, transmitter subsystem, receiver net, and communication subsystem (2001, Yu, Nasu).

![Fig. 4 External correction system of dead-reckoning error](image)

![Fig. 5 Ultrasonic sensor net system](image)
a. Transmitter system

Two ultrasonic transmitters $T_1$ and $T_2$ with wide beam $100^\circ$ are fixed at rear and head of a mobile robot, which transmit ultrasonic wave toward ceiling, and constitute the transmitter subsystem.

b. Receiver net

Many ultrasonic receivers are allocated by $d \times d$ interval on the ceiling covering the range where the mobile robot moves, and constitute receiver net. The receivers receive ultrasonic wave from transmitter subsystem, and measure out the transmitting time of the ultrasonic wave from the transmitter to receivers, so the distances between transmitter and receivers can be obtained. The receiver net can be expanded easily, so the positioning range by the proposed positioning system can be widened easily.

The electrostatic transducers used in this research are MA40E7/R made by NAKAMURA Company of Japan.

c. Communication subsystem

The communication subsystem consists of a pair of radio modem. The control computer sends a starting command to transmitter by the communication subsystem, and sends the starting command to receiver net at the same time by wire too.

5. Estimation of position and orientation

For the beam angle of the ultrasonic transducer is wide, many receivers of receiver net receive simultaneously ultrasonic wave from transmitter on mobile robot. The two transmitters on mobile robot are expressed as $T_1(x_1, y_1, 0)$ and $T_2(x_2, y_2, 0)$. Three receivers are chosen as $R_1, R_2, R_3$ from all receivers receiving simultaneously the ultrasonic wave from $T_i$ $(i=1,2)$, and their positions are expressed as $R_1(x_{1i}, y_{1i}, H), R_2(x_{2i}, y_{2i}, H), R_3(x_{3i}, y_{3i}, H)$ respectively (Fig. 6). Each position of the three chosen receivers is known because all receivers are allocated at ceiling in advance. Therefore, the transmitter position $T_i(x_i, y_i, 0)$ $(i=1,2)$ can be get from simultaneous formulations (5). And the horizontal posture of mobile robot $(\theta)$ can be get from formulation (6).

\[
\begin{align*}
(x_{1i} - x_i)^2 + (y_{1i} - y_i)^2 + H^2 &= \rho_{1i}^2 \\
(x_{2i} - x_i)^2 + (y_{2i} - y_i)^2 + H^2 &= \rho_{2i}^2 \\
(x_{3i} - x_i)^2 + (y_{3i} - y_i)^2 + H^2 &= \rho_{3i}^2 \\
\theta &= \arctan\left(\frac{y_1 - y_2}{x_1 - x_2}\right)
\end{align*}
\]  

Fig. 6 Measurement of position

6. Experimental results

To evaluate the performance of the ultrasonic sensor net system we conducted several sample paths of the omni-directional mobile robot. In this section we report results in basic experiments inside our laboratory. All indoor experiments were conducted on used plastic tile floor with some scratches. Fig. 6 shows the sample path of the omni-directional mobile robot. The point A, B, and C in this figure indicate the beginning of run, the middle and the goal, respectively. Experimental results are shown in Table 1, 2, and 3. In these tables the differences between desired position and WMR one mean the dead-reckoning errors of the WMR, and the differences between WMR position and US-values mean the measurement errors of the US-net system.
Table 1 Sample path error before traverse A

<table>
<thead>
<tr>
<th></th>
<th>Position(x, y) [mm]</th>
<th>Orientation θ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired position</td>
<td>500, 500</td>
<td>-30</td>
</tr>
<tr>
<td>WMR position</td>
<td>500, 500</td>
<td>-30</td>
</tr>
<tr>
<td>US-values of WMR</td>
<td>482, 515</td>
<td>-31.1</td>
</tr>
</tbody>
</table>

Table 2 Sample path error at middle point B

<table>
<thead>
<tr>
<th></th>
<th>Position(x, y) [mm]</th>
<th>Orientation θ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired position</td>
<td>1066, 934</td>
<td>-15</td>
</tr>
<tr>
<td>WMR position</td>
<td>1054, 921</td>
<td>-15.6</td>
</tr>
<tr>
<td>US-values of WMR</td>
<td>1046, 907</td>
<td>-16.5</td>
</tr>
</tbody>
</table>

Table 3 Sample path errors at final point C

<table>
<thead>
<tr>
<th></th>
<th>Position(x, y) [mm]</th>
<th>Orientation θ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired position</td>
<td>1500, 1500</td>
<td>0</td>
</tr>
<tr>
<td>WMR position</td>
<td>1487, 1516</td>
<td>0.5</td>
</tr>
<tr>
<td>US-values of WMR</td>
<td>1499, 1498</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 1 shows that the measurement errors by the US-net system are -18mm and 15mm in the x and y in direction, respectively, and -1.1deg in orientation. Table 2 shows that the dead-reckoning errors of the WMR at the middle point B are -12mm and 13mm in the x and y direction, respectively, and 0.6deg in orientation. The measurement errors by US-net are -8mm and -14mm in the x and y direction, respectively, and -0.9deg in orientation. At the final point C the dead-reckoning errors are -13mm and 16mm in the x and y direction, respectively, and 0.5deg in orientation. The measurement errors by the US-net are 12mm and -18mm in the x and y direction, respectively, and 0.3deg in orientation.

We can summarize that the US-net allows measurement of the absolute position of the WMR to within ±20mm in the x and y direction, and ±1.5deg in orientation.

7. Summary

In this paper mainly the external dead-reckoning error correction method of WMR to move autonomously between some GFRP parts or between the part and the energy station. In trimming large GFRP parts, much glass fiber dust occur and it becomes bad visible in environment. In order to correct dead-reckoning errors an ultrasonic positioning system has been developed and implemented on the Yamagata University omni-directional wheeled mobile manipulator for trimming of large GFRP parts. The Ultrasonic positioning system consists of transmitter subsystem, receiver subsystem and communication subsystem. Especially, many receivers are allocated nxn interval on the laboratory ceiling.

To evaluate the performance of the ultrasonic positioning system we conducted several sample paths of the omni-directional mobile robot. The running tests are carried out on the plastic tile floor.
The experimental results show that the ultrasonic positioning system allows measurement of the absolute position of the WMR to within ±20mm in the x and y direction, and ±1.5deg in orientation. We summarized that the ultrasonic positioning system gives to show the effectiveness for the external correction of dead-reckoning errors of the wheeled mobile manipulator in invisible and dusty environment. Furthermore we can suggest that higher accuracy of positioning will be got by improvement of ultrasonic sensing system.

References


