Omni-Directional Robot for Pavement Sign Painting Operations

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Abstract: The current pavement sign marking operations are manually carried out, which are labor-intensive. This method requires blocking traffic for a long period of time resulting serious traffic jam. Also, the workers are exposed to possible injury and even death by passing traffic. This paper deals with the development of a robotic system for automating the pavement sign painting operations. The robotic system consists of gantry frame equipped with omni-directional wheels and paint spray system. The workspace of the gantry robot is extended to one-lane width with the omni-directional wheels that are attached to the corners of the gantry frame. This research also includes the development of font data structures that contain the shape information of pavement signs. The end-effector path is automatically generated with this font data through the procedures of scaling up/down and partitioning the corresponding signs depending on the workspace size. The robotic sign painting equipment and related control algorithms are built and tested with real painting experiments of various signs, which shows satisfactory results.

Keywords: omni-directional robot, pavement sign painting, traffic signs

1. INTRODUCTION

Traffic signs are utilized to provide the drivers of passing vehicles with the information about the state and characteristics of the road. With the aid of the traffic signs, traffic flow can be maintained safely and efficiently. The traffic signs are classified into three kinds; regulatory signs, warning signs, and guidance signs. Among these, the signs that are painted on the pavement surface are referred as 'pavement signs' in this paper. They are very difficult to maintain because of frequent damage due to passing vehicles and complex installing processes. The current method that is adopted in the most of countries to apply the roadway symbols and signs requires the placement of a stencil on the pavement followed with either the application of paint or torch-down of a thermoplastic type material. These procedures are manually conducted, which exposes maintenance-employees to traffic accidents and possible injuries. They are also very slow and labor-intensive operations. Furthermore, these manual operations require blocking traffic for a long period of time and bring serious traffic jam.

There have been just a few studies on automating the sign painting operations in worldwide. Kochekali and Ravani [1] derived a path planning algorithm for stenciling robot of roadway marking. They developed very big articulated robot system for the stenciling operations. Kotani et al. [2] proposed a method for detecting and following a half-faded lane mark on pavement surface using image processing. They built a prototype robot that could repaint half-faded lane mark [3].

Most of researchers listed above have focused on the automatic trajectory generation for painting robot in automotive manufacturing lines. These studies have been performed mainly to achieve uniformity in paint thickness, time-efficiency, and minimal wastage of paint. The issue of automating the pavement sign painting operations has been addressed only by Kochekali and Ravani, and Kotani et al. [1][2][3]. However, Kochekali and Ravani just proposed a path generation algorithm for painting letter signs with general-purpose articulated robot and Kotani et al. focused on detecting and re-painting existing half-faded lane. This paper deals with fully automating the pavement sign painting operations utilizing robotic technology. This study includes a novel design of robot structure that can cover one-lane width, data structure of sign font, trajectory generation algorithm for paint nozzle motion, robot simulator, and experimental verification of the designed system. With this robot system, a single operator within a cab is capable of planning and performing the sign painting operations on-site, so that the dangerous and time consuming manual operations can be eliminated. The robot system is intended to perform painting operations of letter and symbol signs excluding lane mark, since it can be automated more effectively with different approach in authors' viewpoint.

2. DESIGN OF SIGN PAINTING ROBOT

Pavement signs can be classified into letters and symbols. The letter signs include alphabetic words, for example, 'STOP', 'SLOW', '25', etc. Others are the symbolic signs and representative examples are the arrows that indicate traffic flow directions. Although the regulations for drawing the symbols and letters on pavement surface are slightly different in each country, the following common conditions for designing the sign painting robot can be derived.

- Maximum lane width is approximately 3.6 m.
- Heights of letters and signs are usually about 2 m in urban area. However, they become longer in high-speed roadway and sometimes reach up to 5 m.
- A single word sign almost always consists of at least more than two characters, for example, ‘STOP’ sign has 4 characters. Therefore, there is virtually no case that a single character is painted bigger than half-lane width.
- Line width of letter signs is approximately 15 cm.
- Sign painting operations require many heavy components, such as pump, heater, generator, compressed air, etc.
- Robot system is operated in harsh environment.
- Minimum number of working crew should be able to safely operate the robotic system inside truck cab.
- Blocking traffic flow must be minimized.

3. ROBOT MECHANISM

Based on the design considerations previously investigated, the basic robot structure proper to the sign painting operations needs to be determined. Two different types of robot structures are widely used in industry. Cartesian robots consist of two or three prismatic joints that are orthogonally aligned each other. They are sometimes called as gantry robot in industry. On the other hand, articulated robots are made up of revolute joints connected in series. The gantry robots are generally very rigid and easy to control, but comprise small workspace compared to their body size. In contrast, the articulated robots can generate very flexible motion over large workspace but they are relatively weak in stiffness. The most important considerations in designing the structure of the sign painting robot are big workspace and ruggedness. However, both of them can not be simultaneously achieved with either of robot types. As such, we proposed a novel idea of robot structure, of which omni-directional wheel sets are attached to the legs of a gantry robot. Fig. 1 shows the picture of constructed robot hardware. The overall system consists of the gantry robot frame that has 2 degrees of freedom in Cartesian plane, the omni-directional wheel sets that can freely move around on a plane with full 3 degrees of freedom mobility, and the paint spray system.

The gantry robot is a most common type of Cartesian robots. The moving frame (referred as X-axis) is mounted on the linear guides attached on the frame aligned perpendicular to the moving frame. This perpendicular frame is referred as Y-axis and the X-axis is powered by belt-drive mechanism fixed along the Y-axis. Also, the moving head that holds a paint nozzle slides along the X-axis by belt-drive mechanism. The height of the head unit from pavement surface is determined by manually adjusting the lead screw attached along the Z direction. All the belt-drive mechanisms are sealed to prevent the permeation of paint and dust. They convert rotational motions of servo motors to rectilinear motions. The gantry system is designed to have an effective workspace of 1000×2000 mm2, assuming that most of signs are formed with at least more than three characters. Also, this size of robot frame can be easily mounted under or towed by a support truck that carries other equipments. The letters and symbols bigger than this size are handled by extending its workspace with omni-directional wheels.

4. OMNI-DIRECTIONAL WHEELS

The designed gantry system cannot paint a sign that is larger than its workspace at a time. Thus, omni-directional wheels are adopted for overcoming the limited workspace of the gantry frame. Mobile robots with conventional wheels are only allowed to roll and spin, but not to slide sideways. As such, they are not capable of moving sideways or rotating in place. However, with the omni-directional wheel sets, the instantaneous velocities of the robots are not constrained, so that the robot can move to any (X, Y) position with any orientation. When drawing a large sign, total workspace must be divided into some sub-regions that fit into the workspace of the single gantry frame. Then, the gantry robot is shifted on each sub-region and draws the corresponding portion of sign one by one. The gantry robot with the omni-directional wheel sets is more effective in freely shifting to any location and orientation than a mobile robot with conventional wheels.

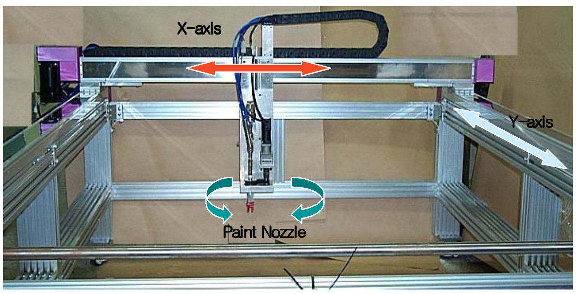


Fig. 1. The picture of the proposed robot mechanism

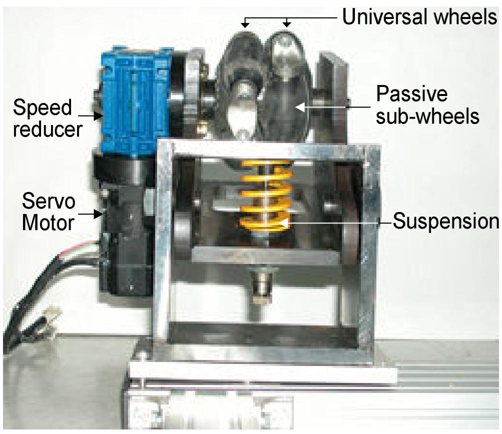


Fig. 2. Picture of omni-directional wheel set

There exist many types of omni-directional wheels (Hong et al. [4]; Asama et al. [5]; Chen et al. [6]). Among these, universal wheel is selected to build the omni-directional wheel set. Fig. 2 shows one set of the omni-directional wheel. The universal wheel consists of several sub-wheels mounted on the circumference of main wheel frame. The sub-wheels are free to rotate about the axis aligned along circumferential direction. The main wheel is driven by a servo motor that is housed in the omni-directional wheel assembly. In order to avoid dead regions between the sub-wheels, two identical universal wheels are overlapped one upon another, such that continuous contact to the ground can be achieved. If at least three sets of omni-directional wheels are aligned on the robot frame with an angle each other, it is possible to control the robot motion having 3 degrees of freedom on a plane. For the sign painting robot, 4 sets of omni-directional wheels are mounted on each corner of the gantry robot frame. One set is redundant for plane motion control but it is necessary to ensure stable support of the gantry frame. Also, each wheel set is designed to have suspension mechanism, so that all the wheels can make secure contact to the ground.

5. PAINT SPRAY SYSTEM

The paint spray system is composed of three components, airless pump, automatic spray gun, and air compressor. The airless pump is the device to compress paint and to maintain regular pressure. Maintaining regular pressure is an important performance of the airless pump for the best quality of painting result. Automatic spray gun is equipped with solenoid valve for the spray timing control that is managed by system controller. According to the shape of spraying trace, many different types of nozzles can be used. Since gothic font letters and symbols are appropriate for roadway signs, a flat-type nozzle is selected in this work. The spraying pattern with this nozzle is a beeline whose length can be adjusted by the height of the nozzle from pavement surface. In order to prevent the dispersion of paint spray by wind, compressed air curtain is installed surrounding the nozzle. It is also important to keep the beeline pattern of the paint spray perpendicular to the direction of nozzle movement in order to maintain uniform width of signs. As such, a rotational joint is added to the end-effecter. Consequently, the end-effecter of the gantry system has total (X, Y, ϕ) motion capability and any shape of signs can be drawn by appropriately sweeping the beeline on pavement surface.

6. ROBOT KINEMATICS

Fig. 3 shows the schematic diagram of the sign painting robot that has four omni-directional wheels. The omni-directional wheels are aligned parallel to the side frames at each corner, such that their driving directions are 90° apart each other as shown in the Fig. 3. Such an alignment enables an easy implementation of the motion parallel to X_m, Y_m axis, which most frequently happen in the sign painting operations. For example, the Y_m axis motion is achieved by driving T_1 and T_3 only and X_m axis motion by T_2 and T_4 only. In addition, the wheels are located at the edges of the frames in order to prevent them from interfering painting area. The coordinate frame (X_f, Y_f) is fixed on the ground plane and the moving coordinate frame (X_m, Y_m) is attached to the center of the robot. L_i is the distance from the i^{th} wheel to the origin along either the X_m or Y_m axis. ${}^fS$ is the pose vector that is defined as

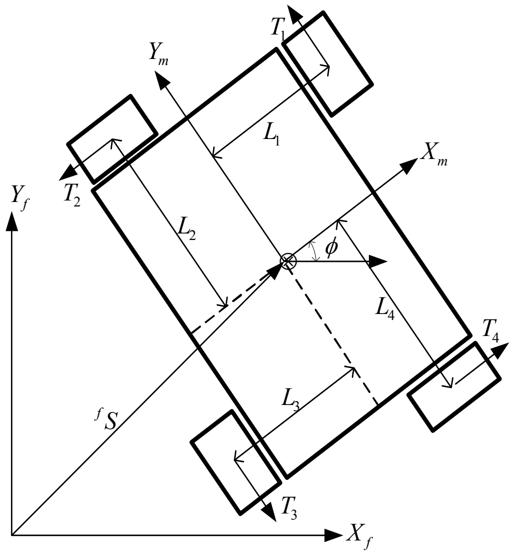


Fig. 3. Schematic diagram to show the kinematic parameters of the painting robot with four omni-directional wheels

$$ {}^fS = \left\{ X_f \ Y_f \ \phi \right\}^T \tag{1} $$

where ϕ is the orientation of the robot with respect to the fixed coordinate frame denoted by the superscript f.

Denote the force vector acting on the painting robot as

$$ {}^fF = \left\{ F_x \ F_y \ M_O \right\}^T \tag{2} $$

where M_O is the torque applied to the robot. The rotational matrix ${}^fR_m$ gives the orientation of the moving frame with respect to the fixed frame and is expressed as

$$ {}^fR_m = \begin{bmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3} $$

The following two equations relate the Cartesian pose and wrench vectors for the moving and fixed coordinate frames

$$ {}^f\dot{S} = {}^fR_m \, {}^m\dot{S} \tag{4} $$

$$ {}^fF = {}^fR_m \, {}^mf \tag{5} $$

The pose and wrench vectors of the robot with respect to the moving coordinate are also denoted as

$$ {}^mS = \left\{ X_m \ Y_m \ \phi \right\}^T \tag{6} $$

$$ {}^mf = \left\{ f_x \ f_y \ M_O \right\}^T \tag{7} $$

To compute the relationship between the robot Cartesian coordinates and the wheel angles, the principle of virtual work is used. First, the wrench vector gives:

$$\begin{Bmatrix} f_x \\ f_y \\ M_O \end{Bmatrix} = \begin{bmatrix} 0 & -1 & 0 & 1 \\ 1 & 0 & -1 & 0 \\ L_1 & L_2 & L_3 & L_4 \end{bmatrix} \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{Bmatrix} \tag{8}$$

or

$$^m f = QT \tag{9}$$

where Q is the Jacobian matrix formed by robot geometry and T_i is the traction force from each wheel. Since the virtual work done is same for the traction forces at the wheels and the wrench of the robot, the following relation will hold:

$$T^T \dot{q} = {}^m f^T \, {}^m \dot{S} \tag{10}$$

assuming that there is no slip in the wheel spin direction, where $\dot{q}$ is the vector for the wheel angular velocities (Wilson et al. [7]). Thus, the inverse kinematics solution of the painting robot can be obtained from Eqs. (9) and (10). Given Cartesian velocity vector, the wheel angular velocities can be found as

$$\dot{q} = Q^T \, {}^m \dot{S} \tag{11}$$

In component form, it is written as

$$\begin{Bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{Bmatrix} = \frac{1}{r} \begin{bmatrix} 0 & 1 & L_1 \\ -1 & 0 & L_2 \\ 0 & -1 & L_3 \\ 1 & 1 & L_4 \end{bmatrix} \begin{Bmatrix} \dot{X}_m \\ \dot{Y}_m \\ \dot{\phi} \end{Bmatrix} \tag{12}$$

That is,

$$\begin{aligned} r\omega_1 &= \dot{Y}_m + \dot{\phi} L_1 \\ r\omega_2 &= -\dot{X}_m + \dot{\phi} L_2 \\ r\omega_3 &= -\dot{Y}_m + \dot{\phi} L_3 \\ r\omega_4 &= \dot{X}_m + \dot{\phi} L_4 \end{aligned} \tag{13}$$

where r is the wheel radius and ω_i are the wheel angular velocities.

7. PATH GENERATION ALGORITHM AND FONT FILE SYSTEM

When the robot is drawing a letter sign, the orientation of the paint line sprayed from the nozzle is usually kept perpendicular to its longitudinal moving direction. On the other hand, for a symbolic sign such as an arrow, the orientation of the paint line is not always perpendicular to the moving direction depending on the shape of the symbol. In addition to the orientation of the paint nozzle, its (X, Y) trajectory must be planned based on the shape of the sign to be drawn. Accordingly, the shapes of the desired signs need to be defined in appropriate way for the designed robot system. Then, the end-effector path will be appropriately planned based on the defined shape information.

These signs are systematically formed with font file. Font is a data structure that contains shape information of letters and symbols. This information is used to generate the end-effector trajectory to paint a target sign. Thus, the format of the font structure must be appropriate to the operational principle of the robot system. The existing fonts are divided into two classes, bitmap and vector fonts, by storing method. The bitmap font is composed of a set of digitized pixels and the vector font is composed of a set of geometric entities such as lines and curves. When applying these fonts to the roadway sign painting system, the vector font is more appropriate than the other since the trajectory control of the painting robot needs interpolation process about the trajectory between target and current positions.

These days, the vector fonts that are used in most of computer systems are called as 'outline fonts' since they contain the outline information of characters in equation form. Painting a sign with flat nozzle is a line-sweeping problem on a plane. The trajectory of the paint line center and its orientation must be clearly defined. The existing outline method is very adequate to provide stylish font to computer systems and related printing devices. However, it is virtually impossible to extract necessary trajectory information for the paint nozzle motion from the outline fonts. Accordingly, a new font file system that is adequate to the sign painting robot was developed rather than using the existing outline fonts. This new font file includes the on/off state of the paint spray nozzle in addition to the vector information for the trajectories of the paint line center and the orientation.

The newly developed font is formatted with three parts, header, index, and data. This is similar to outline font storing method. The header part represents the number of total signs that are defined in the font file. The index part contains the index number of a specific sign and its data size. The data part has geometric information of each sign. Each sign is made of several strokes that are geometric entities such as lines and curves. The line stroke is defined with two end points. Bezier function that is widely used in mechanical design and manufacturing areas is employed to represent the curve stroke in this paper. The general equation of the nth order Bezier function that is made of n+1 control points pi is expressed as (Faux and Pratt [8]),

$$p(u) = \sum_{i=0}^{n} {}_n C_i u^i (1-u)^{n-i} p_i, \quad (0 \le u \le 1) \tag{14}$$

where the coefficient is

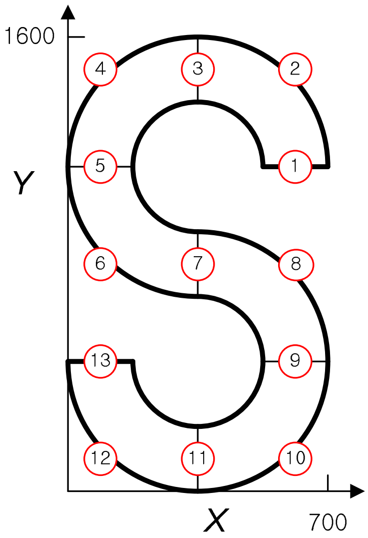
$$_n C_i = \frac{n!}{i!(n-i)!} \tag{15}$$

The shape of Bezier curve can be adjusted by dragging the control points. For most of traffic signs, the 2nd order Bezier curve is enough to precisely describe their shapes, which is simply expressed as

$$p(u) = (1-u)^2 p_0 + 2u(1-u) p_1 + u^2 p_2, \quad (0 \le u \le 1) \tag{16}$$

where p_0, p_2 are two end points and p_1 is the control point around the middle of the curve.

The control points that characterize the lines and curves are listed in the data part. Fig. 4 shows the examples of the data parts for ‘S’ fonts. Each block (code words in a single line) corresponds to one control point and consists of 3 words, functional code and (X, Y) coordinates of the corresponding control point, respectively. The ‘S’ font is composed of 6 segments of the 2nd order Bezier curves that has three control points. The third control point is overlapped to the first control point of the next curve segment, so that there are 13 control points since all the curve segments are seriously connected (one can find 13 lines in the font data except the first line for the coordinate origin in Fig. 4(b)). The (X, Y) coordinates are integers in mm unit. All the fonts are designed based on (700, 1600) basic frame size, which are referred as ‘basic fonts’.



(a) Font ‘S’ and its control points

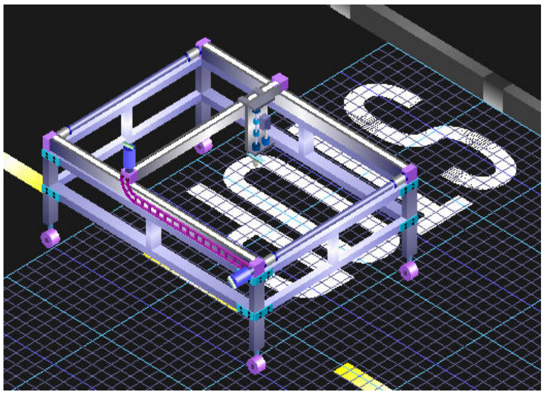
1000001	0	0	//from coordinate origin
7000010	625	1160	//linearly move to pt 1, nozzle off, start pt of Bezier curve
9000120	625	1525	//mid-control pt of Bezier curve, nozzle on
3000120	350	1525	//end pt of Bezier curve, start pt of next Bezier curve
9000120	75	1525	//Bezier curves are repeated in the follows
7000120	75	1160	//3th Beziercurve
7000120	75	800	
1000120	350	800	//4th Beziercurve
7000120	625	800	
7000120	625	440	//5th Beziercurve
9000120	625	75	
3000120	350	75	//6th Beziercurve
9000120	75	75	
7000120	75	440	

(b) Data part of font ‘S’

Fig. 4. Examples of font data

8. EXPERIMENTAL RESULTS

The experiments are carried out with VSP (Virtual Sign Painting) program and actual sign painting robot system. The VSP is an off-line graphic program that simulates the sign painting robot. It is developed to verify the robot path generated by the robot control system, before it is applied to the real painting operations. Figs. 5 through 7 show some example results of the experiments. A ‘STOP’ sign was drawn with the VSP program and the robot system as shown in Fig. 5. This sign was bigger than the size of gantry frame, so that the workspace was partitioned into two sub- regions



(a) Screen capture of Virtual Sign Painting

(b) Painted sign

Fig. 5. Experimental results for ‘STOP’ sign

Fig. 6. Experimental results for skewed and down-sized ‘STOP’ sign

Fig. 7. Experimental results for handicapped sign

and it took 103 seconds to paint the whole sign. In Fig. 6, the 'STOP' sign was scaled down 0.85 times to both directions and rotated 6 degrees about Z-axis. This test was to verify that the robot system had the capability to compensate the misalignment of the robot frame when it was placed obliquely to desired workspace. The total time for actual painting was 90 seconds. Fig. 7 shows the actual painting result of a symbolic sign, handicapped sign. The necessary time for painting this symbolic sign was about 120 seconds. Except these representative examples, many other signs in various situations were tested with the actual robot system.

The required time to draw a single character was at least less than a minute in average. It is very hard to compare this result to that of conventional manual operation due to the lack of statistical data but it is at least 10 times faster than the conventional method in authors' viewpoint. Note that it is required fair amount of time for human operators to deploy and retrieve the painting equipments from the truck bed in manual operations. This paper did not include the mechanism design for deploying and retrieving the painting robot from the support truck. So, it is hard to estimate the total operation time, but assuming that the process for deploying and retrieving the robot is automated with powered actuators, the above hypothetical proposition that the robotic painting is about 10 times faster than the other is still valid. Also, the quality of painted signs was comparable to that of conventional method and it can be improved by carefully adjusting the paint concentration and airless pump pressure, and calibrating the nozzle on-off timing.

9. CONCLUSIONS

In this paper, a novel roadway sign painting system which is capable of painting all kinds of signs, is proposed and constructed. The overall mechanism of the robot system that is determined through carefully analyzing the operational requirements is a gantry frame equipped with omni-directional wheel sets. The omni-directional wheel sets make the robot to freely move on a plane with three degrees of freedom and extend the workspace of the robot system. New font data structures are defined for the painting robot that has flat nozzle paint spray. For the case that the workspace is larger than the basic gantry frame size, the algorithm for partitioning the workspace and the method to extend the corresponding font data is also developed. These algorithms are verified by feeding the resulting path data to the off-line computer simulator. Through actual painting experiments, the validity of the proposed gantry structure with extended workspace is confirmed. The sign painting operation with this system is at least 10 times faster and needs less workers than current manual operations. Lastly, the most important benefit of using this system is that the safety of working crew is ensured and the traffic jam is reduced due to the fast operations.

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