AUTONOMOUS LOADING OF ROCKS BY USE OF INTELLIGENT LOADERS WITH A VISION SYSTEM
— A CONCEPT OF AUTONOMOUS LOADING AND PATH GENERATION —

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ABSTRACT

A wheel loader is the major vehicle that has been used for scooping, carrying and loading of crushed ores in open pit mines. This paper describes a path generation method for autonomous control of the wheel loader. From the viewpoint of stability of movement and easy control to move along the designed path, smoothness and simple calculation of command value are necessary for the path. In order to satisfy these conditions, a path generation method using a clothoid curve is proposed. A clothoid curve has a continuous changing curvature that is proportional to the length of the curve, and provides continuous changing of steering angle. Furthermore, the interpolation between the start and end point of the loader is proposed, which consists of clothoid curve segment and straight line segment. V-shape curve including backward path and forward path is also generated with considering the avoidance of rapid turning.

INTRODUCTION

A wheel loader is the major vehicle that has been used for scooping, carrying and loading of crushed ores in open pit mines. Usually, this machine is operated by an expert operator. But, if this machine is used in the dangerous field such as the disaster place or in the task to develop the space resources, the unmanned automation technology is necessary. In order to realize the full automation of wheel loader task, the loader needs to have an ability to recognize the working environment, to plan the scooping and loading task and to execute the task autonomously. Various researches have been already conducted for mobile robots. However, since the working environment of a wheel loader is rough terrain and is changing according to the advance of the task, the full automation of wheel loader task is much more complicated as compared to another types of mobile robots that are operated in the artificial environment. Furthermore, an articulate steering is used for the wheel loader, which is peculiar to a wheel loader. Although the articulate steering has an advantage of small steering radius, the trajectory tracking control is very complicated because the tire is easy to slip in steering.

The purpose of this study is to investigate the automation technology to achieve the full automation of the wheel loader task. In this paper, only path generation is described.

It is necessary that the function of loader path has a continuous 2nd derivative, that is, a continuous curvature. Furthermore, the loader path should be smooth, because the smooth path, that is effective in trajectory tracking control, derives continuous steering angle and continuous acceleration due to the centrifugal force. Additionally, it is very important that command values such as steering angle and velocity at each point on the designed path are simply calculated. To satisfy these requirements, a path generation method using clothoid curve is proposed. Furthermore, when the initial point and target point of the loader are given, V-shape curve including forward path and backward path is adequate because of the limited narrow space where a wheel loader moves. Thus interpolation method is also proposed.

CONCEPT OF AUTONOMOUS LOADING TASK

The final goal of this study is to achieve the full automation of the wheel loader task. A concept of autonomous operation is as follows: the wheel loader has a vision system and it recognizes the relative position and direction between the wheel loader and the target point (scooping point) located at the skirt of the rock pile. Then, the whole path of the wheel loader is generated based on the target point obtained by the vision system, and the wheel loader moves autonomously along the desired path. When the loader reaches the target point, the loader penetrates the bucket into the rock pile and then scoops the crushed ores. After the loader scoops the crushed ores, the vision system recognizes the position and direction of the dump truck. Then, the whole path of the wheel loader to the dump truck is generated, and again the wheel loader moves autonomously along the desired path to the dump truck. When the loader reaches the dump truck, the loader recognizes the vessel of the dump automatically, and then the loading task is carried out. In the next chapter, the detail path generation method will be described.

CLOTHOID CURVE

A clothoid curve is the curve whose curvature is proportional to the length along the curve, and is given by

$$Cv(s) = k \cdot s + Cv_0 \qquad (1)$$

Where s is the length, Cv(s) is the curvature and k is the coefficient, which is called sharpness [1]. The direction of the tangent vector is the integration of the curvature, and is expressed by Eq. (2).

$$\theta(s) = \int_0^s \left(k \cdot s + Cv_0\right) \cdot ds = \frac{1}{2} \cdot k \cdot s^2 + Cv_0 \cdot s + \theta_0 \qquad (2)$$

Therefore, the x and y coordinates of the curve are given by

$$x(s) = x_0 + \int_0^s \cos\left(\frac{1}{2}\cdot k\cdot s^2 + Cv_0\cdot s + \theta_0\right)\cdot ds \tag{3}$$

$$y(s) = y_0 + \int_0^s \sin\left(\frac{1}{2}\cdot k\cdot s^2 + Cv_0\cdot s + \theta_0\right)\cdot ds \tag{4}$$

To obtain simpler equations, initial states (Cv_0,θ_0, x_0 and y_0) are set to zero. Furthermore the coordinates x and y are expressed in term of the direction θ.

$$x(\theta) = \frac{1}{(2k)^{1/2}}\int_0^\theta \frac{\cos\theta}{\theta^{1/2}}\cdot d\theta \tag{5}$$

$$y(\theta) = \frac{1}{(2k)^{1/2}}\int_0^\theta \frac{\sin\theta}{\theta^{1/2}}\cdot d\theta \tag{6}$$

The right hand side of these equations is called Fresnel integration. Since the integrated term in these equations can be expanded into a series term and expanded series term can easily be integrated, the following equations are obtained.

$$x(\theta) = \frac{2\theta^{1/2}}{(2k)^{1/2}}\left(1 - \frac{\theta^2}{10} + \frac{\theta^4}{216} - \frac{\theta^6}{9360} + \cdots\right) \tag{7}$$

$$y(\theta) = \frac{2\theta^{3/2}}{3(2k)^{1/2}}\left(1 - \frac{\theta^2}{14} + \frac{\theta^4}{440} - \frac{\theta^6}{25200} + \cdots\right) \tag{8}$$

Using above equations, it is possible to obtain the x and y coordinates at each point on the curve without carrying out the numerical integration that requires much calculation cost. However, it should be noted that the direction θ should be less than 45° with taking the accuracy of approximation into consideration.

We introduce the double clothoid or the clothoid pair according to Kanayama and Miyake [(1)]. As shown in Figure 1, the clothoid pair consists of two clothoid curves that are connected at the maximum curvature on each curve and has different sign of sharpness k for each curve. Since the clothoid pair has zero curvature at both ends, straight lines can be connected at both ends. Clothoid pairs can interpolate between many straight lines. In result, smooth path including straight lines and clothoid pairs is generated. Incidentally, by using the connecting point ($x_m(\theta)$, $y_m(\theta)$) that is obtained by Eqs. (7) and (8), the end point (x_p, y_p) is expressed by

$$\begin{bmatrix} x_p \\ y_p \end{bmatrix} = \left(x_m(\theta) + \frac{y_m(\theta)}{\cot\theta} \right) \cdot \begin{bmatrix} 1+\cos(2\theta) \\ \sin(2\theta) \end{bmatrix} \tag{9}$$

As mentioned earlier, with considering the accuracy of Eqs. (7) and (8), the direction of the end point is less than 90° (that is, 2θ ≤ 90° in Figure 1). Therefore, if the direction of the target point is above 90°, the path must consist of two clothoid pairs at least.

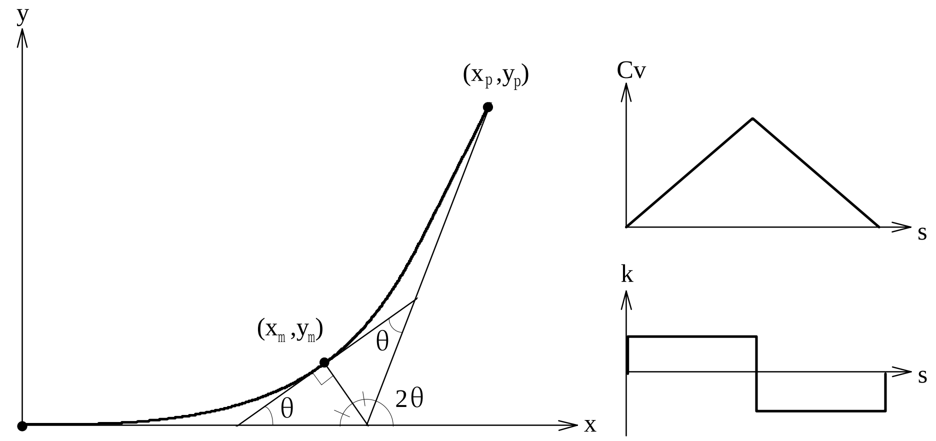

Fig.1 Clothoid pair, curvature and sharpness

PATH GENERATION

The path has the constraint that the curvature at the initial point and the end point must be zero with considering the stability of the wheel loader, because these points are scooping point or loading point. When the position (${}^{W}x_t$, ${}^{W}y_t$) and the direction ${}^{W}\theta_t$ of the target point are given, the path generation method consists of following steps: where w indicates the world coordinates.

(1) The curve segment whose direction of the end point is equal to the direction of the target point is generated with using one or two clothoid pairs. Let (${}^{LN}x_p(\theta_N)$, ${}^{LN}y_p(\theta_N)$) be the local coordinates position of the end point of the Nth clothoid pair. Then, the end point of this curve segment, which is defined by (${}^{W}x_p$, ${}^{W}y_p$), is expressed as follows:

$$\begin{bmatrix} {}^{W}x_p \\ {}^{W}y_p \end{bmatrix} = R(\theta_1) \cdot A_2 \cdot \begin{bmatrix} {}^{L2}x_p(\theta_2) \\ {}^{L2}y_p(\theta_2) \end{bmatrix} + A_1 \cdot \begin{bmatrix} {}^{L1}x_p(\theta_1) \\ {}^{L1}y_p(\theta_1) \end{bmatrix} \tag{10}$$

Where, $R(\theta_N)$ is the rotation matrix given by

$$R(\theta_N) = \begin{bmatrix} \cos\theta_N & -\sin\theta_N \\ \sin\theta_N & \cos\theta_N \end{bmatrix} \tag{11}$$

The clothoid pair is classified into four types by its moving and turning direction, which is indicated by A_N. Then, α_N and β_N have the value of 1 or –1.

$$A_N = \begin{bmatrix} \alpha_N & 0 \\ 0 & \beta_N \end{bmatrix} \tag{12}$$

Here, the sharpness k is constant, and ${}^W\theta_t = \alpha_1\, \beta_1\, \theta_1 + \alpha_2\, \beta_2\, \theta_2$.

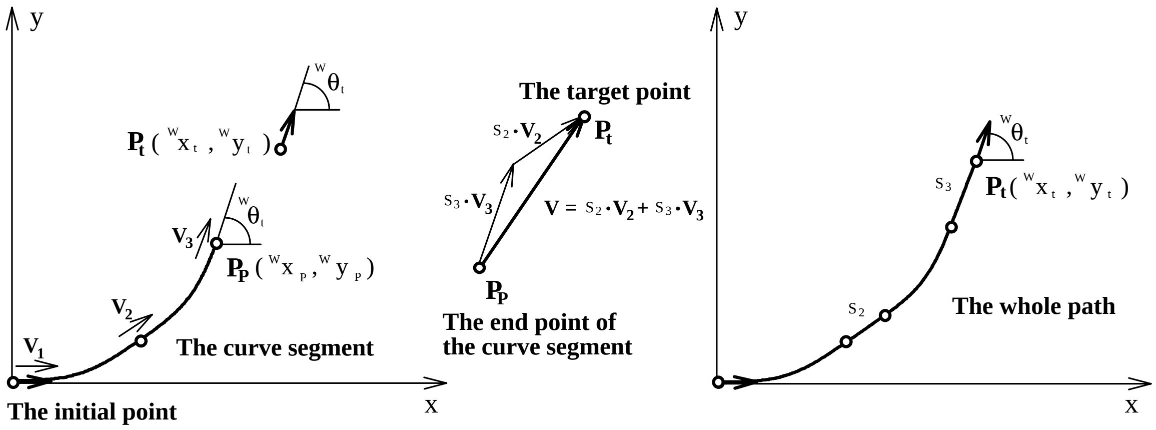

Fig.2 The curve segment consisting of two clothoid pairs (1)
and connection of two straight lines (2)

(2) The vector which links the target point and the end point of the curve segment generated in step (1) is resolved into two straight line vectors which can connect to both ends of the clothoid pair. Connecting two resolved straight lines to each end, the whole path is generated (See Figure 2). Where, there are two or three straight line vectors and one or two linearly independent pair of these vectors unless the direction of the target point is zero.

(3) As mentioned earlier, since there are four types of the clothoid pair, there are sixteen types of the curve segment that consists of two clothoid pair. Taking the curve segment that has one clothoid pair into consideration, twenty types of the curve segment are obtained. In any types, the path is generated with using the process (1) and (2). The path which the total movement length become minimum is selected.

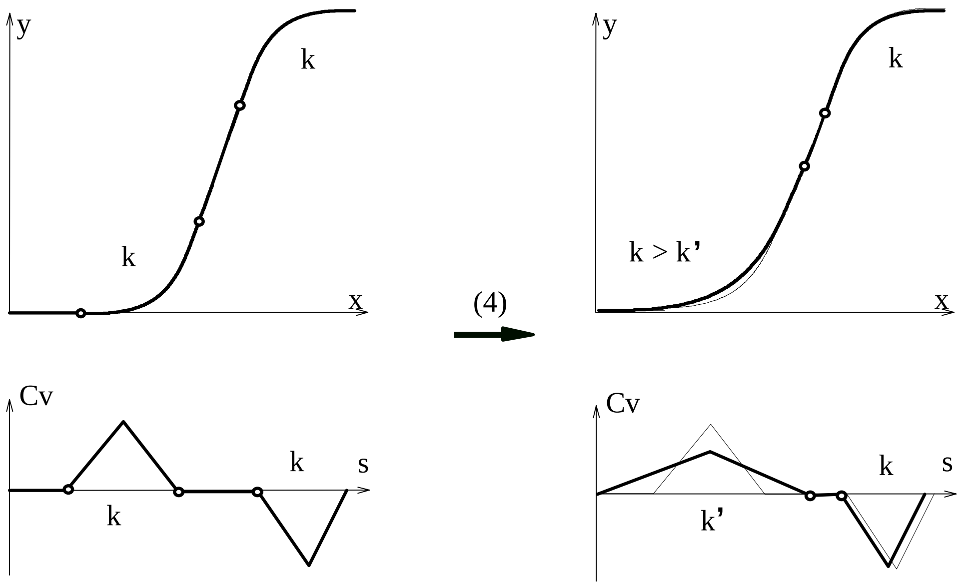

Fig.3 Regenerating the path to reduce the total length

(4) In regard to the path selected in step (3), if two straight lines that connect to the both ends of a clothoid pair have the same moving direction as the direction of the clothoid pair, the total movement length can become shorter with changing the sharpness k (See Figure 3).

MOTION PLANNING

In this section, the command value generation method is described. The command value parameterized by the length along the whole path consists of the steering angle and the velocity. Table 1 shows parameters obtained by the path generation.

Table 1 Parameters obtained by the path generation

	Fist Straight line	Fist clothoid pair	Second straight line	Second clothoid pair	Third Straight line
Segment No.	1	2	3	4	5
Length	s_1	$s_2 = (2\theta_2/ k_2)^{1/2}$	s_3	$s_4 = (2\theta_4/ k_4)^{1/2}$	s_5
Turning angle		θ_2		θ_4	
Sharpness	0	k_2	0	k_4	0
Moving direction	α_1	α_2	α_3	α_4	α_5
Turning direction		β_2		β_4	

The local curvature ${}^{LN}Cv$ at each point on the Nth segment is given by

$$ {}^{LN}Cv(r) = \frac{1}{2} \cdot k_N \cdot s_N - \left| k_N \cdot r - \frac{1}{2} \cdot k_N \cdot s_N \right| \tag{13} $$

Where, r_N indicates the length along the Nth segment. Using the length s along the whole path, r_N is given by

$$ r_N(s) = s - \sum_{m=1}^{N-1} s_m \qquad \left(0 \le r_N(s) \le s_N\right) \tag{14} $$

Then, the curvature Cv(s) at each point on the whole path is simply given by Eq. (15)

$$ Cv(s) = \beta_2 \cdot {}^{L2}Cv(r_2(s)) + \beta_4 \cdot {}^{L4}Cv(r_4(s)) \tag{15} $$

Furthermore, the velocity can be parameterized easily by the length s with using s_N and α_N, under the constraint that the velocity accelerates and decelerates at the constant rate and has a maximum and minimum speed. Figure 4 and Figure 5 show examples of the generated path and command values.

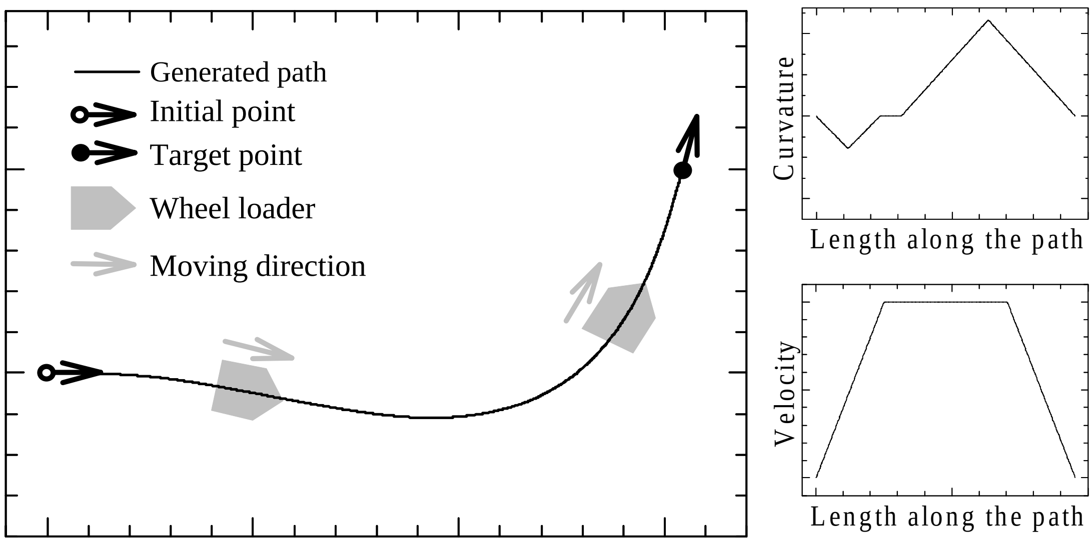

Fig. 4 Example of generated path and command value

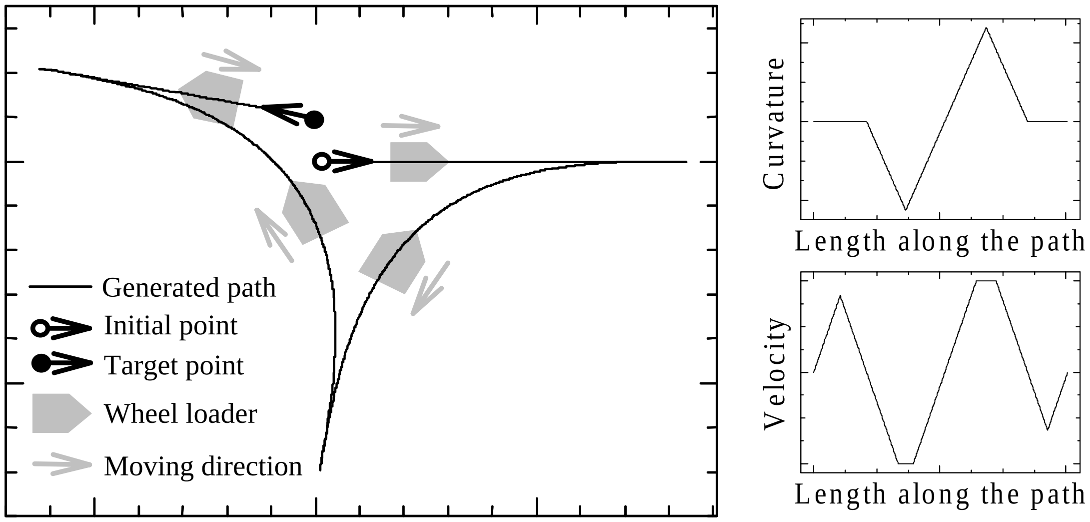

Fig. 5 Example of generated path including V-shape curve and command value

CONCLUSIONS

The path generation method to control the wheel loader autonomously in the limited narrow area and rough terrain was proposed. It was possible to interpolate between the initial point and the target point by using the smooth path which consists of the clothoid pair and the straight line segments. Furthermore, from the viewpoint of avoidance of rapid turning and narrow area, V-shape curve including forward path and backward path was generated. By using the path generation method proposed here, smooth path will be generated, and will be utilized for easy trajectory trucking control.

In the next step, we are intending to establish the control method to move accurately along the designed path with using the odometry and the vision system that recognize the working environment, and to carry out the experiment.

ACKNOWLEDGEMENT

This study is financially supported Limestone Association of Japan. The authors would like to appreciate their support.

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