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Path Planning of Wheel Loader type Robot for Scooping and Loading Operation by Genetic Algorithm

Toshinobu Takei†, Kentaro Ichikawa†, Kazuya Okawa⋆, Shigeru Sarata*, Takashi Tsubouchi*, Akira Torige†

***Abstract*— There is a demand of mining automation by heavy equipment in an open mine. Authors aim to automization of motion for wheel loader in scooping and loading operation. In this paper, we applied the optimization method by Genetic Algorithm to the path planning for the wheel loader on scooping and loading operation. We showed the quasi-optimized path and demonstrated by the miniature wheel loader robot.**

I. INTRODUCTION

There is a demand of mining automation by heavy equipment [1] in an open mine. The Automation makes economic advantage for mining company, because it is able to increase a working time as cutting down labor costs. Mining process in stope is roughly divided into cutting and carrying process. In the carrying process, wheel loader is mainly used to transport a cluster of cut ores from gathering space of cut ores into cargo space of a truck. The truck carries them and put into shaft of a mine. Authors aim to automation of the operation of wheel loader for the carrying task. We work to generate a path automatically for the wheel loader from the gathering space of the ores to the track and control the wheel loader to follow the path.

Several works on the automation for the wheel loader are already reported in [1]—[10] by the group “Yamazumi” in Japan. Demonstration of scoop and loading to a truck by the realistic autonomous wheel Loader in an open mine is reported in [7]. A path planning method for the wheel loader used in [7] is suggested in [2] and they called a shape of the path as “V-shape”. In paper [9], they proposed a method by which they generate a V-shape path on representative point in the front bucket of the wheel loader. The idea comes from the observation of the real path generated by human operator of the wheel loader. A nonlinear control method of articulated steering type vehicle is proposed and result with applied the method to the wheel loader type robot is reported in paper [11]. Though there are some method of path planning, those path in those works is not enough to work in realistic environment, because it is longer than a path generated by a human driver of realistic wheel loader. There is need for more optimal path and the generation method.

In this work, we apply an optimization method of automatic car parking path generation and control in [12] to the wheel loader for the path planning. In the method, one of the discrete motions of the wheel loader in a short period are treated as one vector which represent a movement from start point to end point in three degree space of x,y position and θ angle. In the space, an optimal path is generated Genetic Algorithm (GA) to serialize several kinds of vectors which represent those discrete motions of the wheel loader, under satisfying some conditions of evaluation function. The method is seemed to be useful for path planning in the following point. When start and goal point change every turn, cost of calculations for the path planning is not be increased, because generated path for different goals before now are used for new goals. Wheel loader goes and returns between a various stone pit and a bed of a truck point, those points are different by turns, repeatedly for scooping and loading.

†T.Takei, K.Ichikawa, A.Torige are with the Department of Systems Design Engineering Faculty of Science and Technology, Seikei University, Japan. takei-t@st.seikei.ac.jp

⋆K.Okawa is with the Department of Machinery and Control Systems, Graduate School and Faculty of Engineering, Chiba University, Japan.

*S.Sarata and T.Tsubouchi are with the Department of Intelligent Interaction Technologies, Graduate School of Systems and Information Engineering, University of Tsukuba, Japan.

Fig. 1. Wheel loader in scooping and loading operation in an open mine

In this paper, we present how to apply the method of [12] to path planning for the wheel loader. Then, we shows the optimized path and motion in experiments by the realistic miniature type wheel loader which is shown in Fig.2, and the discussions on the effectiveness and problems of this method are added.

II. PROBLEM DEFINITION

A. Wheel Loader type miniature Robot

The realistic wheel loader in Fig.1 is WA900 of KOMATSU. Our target robot used in this work is one twentieth length of the realistic wheel loader. The robot used in this work is shown in Fig.2 and parameters are shown in TABLE I in Fig.3. The robot are composed of two parts, forward part and back part, and those parts are connected by rotational active joint which is controlled by a DC motor. A length from the joint and front wheel axis is same as a length from the rear wheel axis. The moving direction of the robot is changed by angle and the angular velocity of the controlled joint. The angular velocity are limited in ±30 deg/sec and

Fig. 2. A wheel loader type miniature robot "Yamazumi4". The physical parameters are defined as same as proportion of the realistic wheel loader.

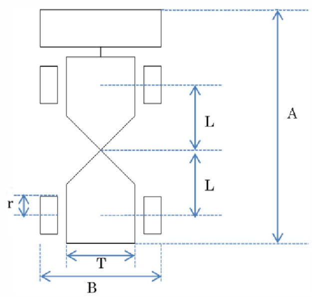

Fig. 3. Model of the wheel loader type miniature robot "Yamazumi4"

the angle is limited in ± 40 deg, the same as the realistic robot.

The characteristic of this wheel loader type robot is to have differential gear to absorb the slip caused by a difference of rotation of the right and left side wheels in forward and backward body. Translational velocity is controlled by one motor in the robot. The translational velocity is limited in 20 cm/sec. The rotation of the motor is divided into the rotation of front and back wheels equally. When the joint is kept to be constant in moving, the moving track of the front and the rear body are same, its means that the shape of the track is a part of a circle. When the robot moves both with translational velocity and with the angular velocity of the joints, the moving track becomes a similar shape of clothoid curve. The robot can perform stationary steering motion, but it is not used in the operation. The constraints considered for path planning are defined from those physical conditions of the robot.

TABLE I

PARAMETERS IN MODEL OF THE WHEEL LOADER ROBOT IN FIG.3

signal	meaning	value [mm]
A	length of body	600
B	width	300
T	tread	255
L	length between joint to axis of wheel	140
r	radius of wheel	60
l_1	length of arm	250

B. Path for the scooping and loading

In a general open mine space, a truck is set near the mine. After scooping by the wheel loader, it moves to the truck for loading the mine. The wheel loader can't move directly with straight pass to the truck, so, the wheel loader goes back in steering the joint in the body and stops in one term, then goes forward to the truck in steering its body. The number of times of changing from backward to forward motion is usually one time. The work of scooping and loading is repeated till to fill up the bed of the truck by the wheel loader. A sketch drawing of positional relationships between a truck, wheel loader and mineral ores are shown in Fig.4. The truck is placed away around the distance of 1 length-size of the wheel loader from the wheel loader. In this paper, the scooping position in the mine and load position of the truck, those are start and goal position, are given in advance.

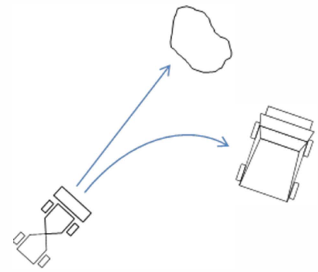

Fig. 4. Sketch drawing of a positional relationship between a truck, wheel loader and mineral ores

C. Path planning

The shape of the pass for the wheel loader is assumed to be composed from straight line, clothoid curve and circle line. The straight line is track of motion with straight steering angle. The circle is track of motion with fixed steer. The clothoid curve is track of motion in changing the angle between front and rear body for steering motion. One of the pass is shown in Fig.5, the wheel loader goes back from a to d and goes forward from e to f. Section from a to b is clothoid curve in counter clockwise rotation, from b to c is clothoid curve in clock wise rotation. The section from c to d is straight line, from d to e is clothoid curve in clock wise rotation, and from e to f is circle line. Thus, the pass planning for the wheel loader is what should be select and serialize those three kinds of line and in order in two dimensional surfaces.

The position x, y and posture θ which represents posture direction not a steering angle of the wheel loader is represented one point in three dimensional configuration space. One motion in one term is treated as a vector in the space. Our problem is to find a quasi-optimal solution for the pass by combination of the discrete vectors from start point to goal point in the three configuration space. In this work, at the goal point, we don't care the steering angle and only consider the posture of the wheel loader. In fact, the goal point is set a little front of the mining point and the steering angle is set to be straight after reaching the point.

In order to search quasi-optimal answer on the pass of the wheel loader, the method [12] using GA is applied. In the method, one vector i which represent one kind of basic

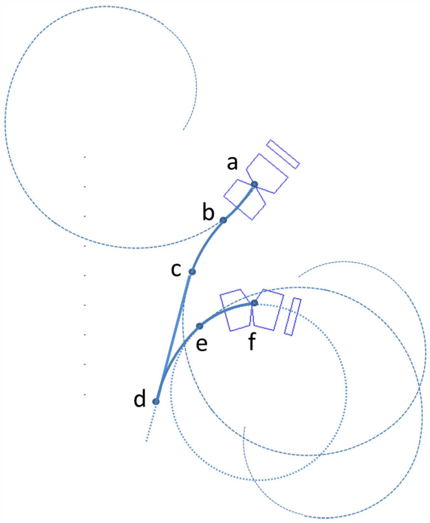

Fig. 5. One path constructed with combination of straight line, arc and clothoid curve

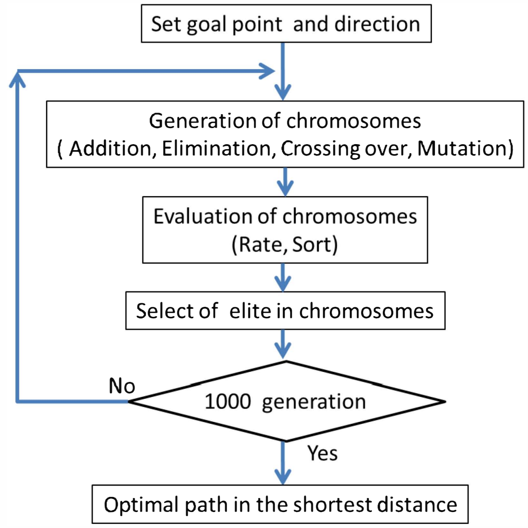

Fig. 6. A flow chart of the algorithm

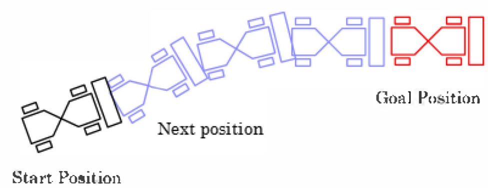

Fig. 7. Serialized basic motion in a path

motion in one term in the configuration space is treated as one kind of chromosomes. One path from start to goal is generated by the serialized composition of the combination of the basic chromosomes, and the path is treated as a gene. Many kinds of genes are generated from some kinds of chromosomes. When there are 26 types-kinds of basic chromosomes, if we consider n-th generation of the genes, then 26^n types of genes are exit. It takes much times to search all combinations, so, we use the method to declare the time of search for the quasi-optimal path.

For evaluation of the quasi-optimal path, the following conditions are used. Amount of the odometry of the motion in a two-dimensional plane, distance between the arrival point of generated path and goal point in three dimensional spaces, and the number of change of the direction of travel from back to forward is one time.

III. Path planning method

A. Procedure of algorithm in generation of motion queue

In simple genetic algorithm, length of chromosomes is fixed and crossover and mutation are done. In our method, the length of the chromosomes is not constant. The each length of chromosomes becomes to be various by the operations of adding and elimination. The length of chromosomes represents the total number of the motion from the start and goal point, and the length of the optimal pass is not known in advance. Through it may be considered to prepare a constant number for a lot of motions (genes) in the chromosomes, it take much time to search an optimal path represented by chromosomes in the large space.

The procedure of proposed method is following. We prepare 100 types chromosomes which show each path from start to goal. The path indicate serial motions queue which tell how the wheel loader gets to the goal from the start in Fig.7. One chromosome includes genes which show motions of wheel loader in one term. 100 type's chromosomes are equivalent 100 different kinds of path.

Length of those chromosomes is 0 at start point in initial condition. Optimal path is searched with adding several motions as one gene from the start point like breadth-first search. At every generation, adding, elimination, mutation, crossing over of genes are operated randomly to those chromosomes. As the result, the lengths of the chromosomes are various. Then, all of those chromosomes including elite chromosomes are scored and evaluated by using of performance function and constraint conditions. Chromosomes are sorted in order of high score (or low score) and some chromosomes which have high score are selected as elite chromosomes to be reserved at next generation. Elite chromosomes are not applied to adding, elimination, mutation, and crossing over. The above operations are done with 1000 generations, which means 1000 times loop in program. Then, path which leads to the nearest point of the goal are selected as an optimal path. A flow chart of this procedure of the algorithm is shown in Fig.6.

B. Generation of serial line of genes for the motion

1) Representation of genes: One gene in the line code of genes is represented a number which indicates one basic motion of the wheel loader. Line codes are generated to place the number of basic motion in a certain order. It is note that genes are not treated as binary digits. One line composed by genes represents motions of one path from the start point to goal point in three spaces. The example of the line for a motion is shown in Fig.8.

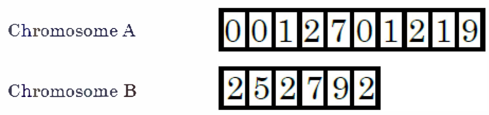

Fig. 8. Example of Chromosome with permutation encoding

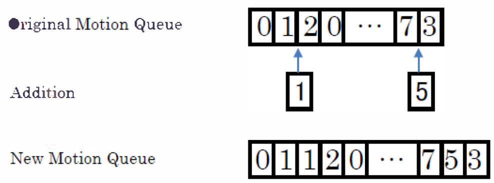

Fig. 9. Example of addition of the queue of the genes

2) *Addition and deletion:* This operation is operated to search a path from around of the start point. A number of sums in motion of the line queue to goal point from start point are unknown, so we add or delete the chromosome repeatedly in fixed number of generation. One example of the operation of adding queue of chromosome is shown in Fig.9. The number of place where one chromosome is added is selected randomly in the queue line. The number of the length of generated queue line by this operation is increase or decrease with the new chromosome. Adding new chromosome, the chromosome is selected in the basic motion which is limited by the kinematics.

3) *Mutation and crossing over:* To make less local answer, different two genes are selected randomly in the element motions, and two genes selected randomly in the queue line are exchanged to the two genes in the element motions. All the numbers of motions in the queue line after this operation is same as before.

The purpose of the operation of crossing over is to leave queue lines with good score to next generation and to generate many queue lines with the good score. In this work, one point-crossing over is used. Tow queue lines selected randomly are crossed over at random order position in the two queue lines. Examples of Mutation and crossing over are showing in Fig.10 and Fig.11.

4) *Selection, evaluation and end condition:* Scores are given to each the queue line by giving sum of the score of evaluation function (1) and number of change of moving direction from back to forward or the reverse. In evaluation, those discrete motions in the queue line are converted to continuous motions by using the kinematic equations in III-C.

$$score = \frac{x_{Goal} - x_{queue}}{x_{allow}} + \frac{y_{Goal} - y_{queue}}{y_{allow}} + \frac{\theta_{Goal} - \theta_{queue}}{\theta_{allow}} \quad (1)$$

where, $x_{Goal}, y_{Goal}, \theta_{Goal}$ represent the position and direction of the goal, $x_{queue}, y_{queue}, \theta_{queue}$ represent a position and direction of all the motion of the queue line. Those differences on x,y, and θ are normalized by operation of (1) on tolerance errors.

The queue lines are sorted according to the rated score in order to select the queue lines for the cross over operation.

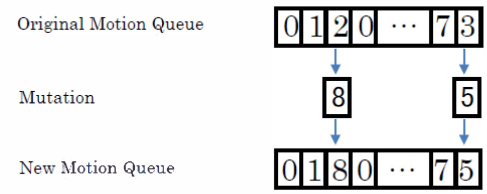

Fig. 10. Example of mutation

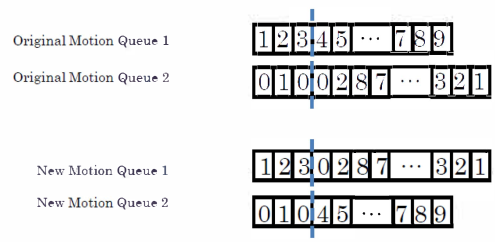

Fig. 11. Example of crossing over

The queue lines rated highly(in this case is small) are selected and some queue lines with low rated score are deleted. When there are queue with high score, the several queue lines in the high score ones are inherited as keeping its condition.

Repetitive operation in this algorithm ends with in given number of generation. When an operation is done to a queue line and the rated score of the queue is small, the operation is deleted, then the wheel loader with motion by the queue line stops at some position and direction.

C. Kinematic model and basic motion of wheel loader

The kinematics model is shown in Fig.12 and the representative point which indicate the position of the wheel loader is P which is called imaginary point in this paper. Parameters and letters used in Fig.12 are shown in Table.II. Then, angular velocity (w) of the vehicle is given as $w = v/R$ and the radius of the circle which is the trajectory of the wheel loader is given (2) then w become (3).

$$R = \frac{l}{\tan\frac{\phi}{2}} \quad (2)$$

$$w = \frac{v \times \tan\frac{\phi}{2}}{l} \quad (3)$$

When the wheel loader is the position and posture of P_k, the next ones are represented as following

$$P_{k+1} = P_k + \begin{bmatrix} v_k \cos(\theta_k) \\ v_k \sin(\theta_k) \\ w_k \end{bmatrix} \delta t \quad (4)$$

Where, δt is period of sampling time. Then, the position and the posture direction are calculated as following by using

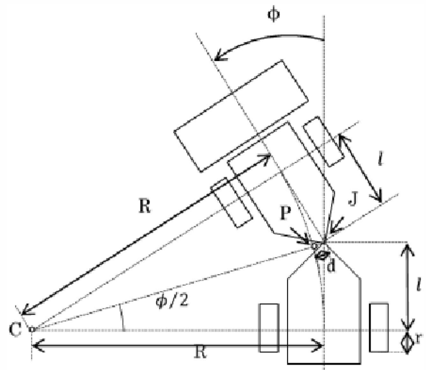

Fig. 12. Kinematics of wheel loader

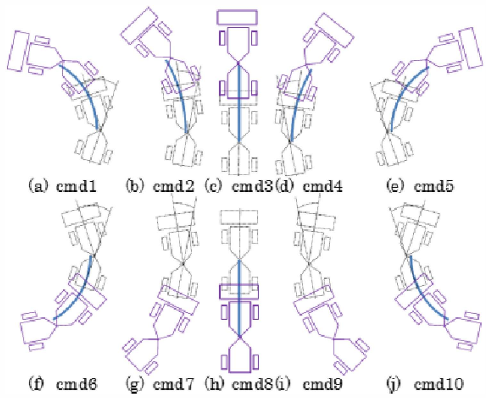

Fig. 13. Basic motion of wheel loader

odometry and steering angle.

$$\theta = \int_0^t w(x)dx + \theta(t_0) \quad (5)$$

$$x(t) = \int_0^t v(x)\cos(\theta)dx + x(t_0) \quad (6)$$

$$y(t) = \int_0^t v(x)\sin(\theta)dx + y(t_0) \quad (7)$$

Where, $x(t_0), y(t_0), \theta(t_0)$ are initial values.

The motion range of the joint in the body of the wheel loader is divided into some direction. A basic motion of the wheel loader is calculated as the wheel loader move on the each direction to a given distance away from present position and posture. The number of those basic motions are twice as number as those directions, because there are forward and back motions. An example of those basic motions are shown in Fig.13, the direction are $(30, 10, 0, -10, -30)$. Those genes and path are generated by the adding operation with select motions randomly in those basic motions. When those motions are serialized and evaluated the path, the position and posture are calculated by (5)(6)(7).

IV. Experiment

A. Preparation

Parameters for GA are defined as following, maximum length of the genes is 30, number of the generation is 1000, and number of the kinds of the genes is 100. Allowable

TABLE II

Parameters in model of the wheel loader robot in Fig.12

Symbol	Content
ϕ	Angle of steering
l	Length between front wheel axis to rear wheel axis
r	Radius of wheel
R	Radius of rotary motion
C	Center of curvature
J	Joint between front and rear body
d	Length between center of imaginary point and center of body
P	Position of imaginary point and posture on the whole body
v	Translational velocity
w	Angular velocity on whole body

error for evaluation function (1) are defined as 50[mm] on X axis, 30[mm] on Y axis, 1[deg] on θ. We shows results of experiment when the start position is (0, 0, 50) and goal-position is (0, -800, 0). In this case, distance of straight line from start and goal is 800[mm], and the posture at the goal is 50 [deg] and start point is 0 [deg]. Experiments are performed in room floor. The length from goal and start is near one tenth of realistic length usually used in mining field and the length is about same with length of miniature wheel loader.

In addition operation in secIII-B.2, a basic motion is selected randomly from only the range of directions that the wheel loader can reach to the angle in the time of the motion. For example, when a length of the motion is 200[mm], maximum translational velocity is 200[mm/sec], then, the maximum range that wheel loader can change in one motion is 30[deg] because the maximum angular velocity is 300[mm/sec]. The limit of the steering angle is ±30[deg]. If the steering angle is at 25[deg] now, basic motion is selected from between -5[deg] and 25[deg], and added as next motion. When the next motion is same with now-motion, the wheel loader keeps the angle in motion. The range to select basic motion in adding operation is change according to the length of the basic motion.

B. Results

We implemented the algorithm and found some quasi-optimal path for the miniature wheel loader robot. We gave to the robot the sequential motion on the quasi-optimal path and demonstrated the motion on quasi-optimal path by the robot. Two results of experiments in case of 30 [mm/sec] translational velocities and in 200[mm/sec] are shown in Fig.15 and Fig.16. In the experiment in Fig.15, angles for the basic motions are form -30[deg] to 30[deg] by 5[deg] and the length of one basic motion is 50[mm]. Then, there are 30 basic motions in the he sequential motion for quasi-optimal path, so the length of the path is 1500 [mm]. The errors between the reference goal and realistic position of the last motion in the path were 10.5[mm] on x, 13.5[mm] on y, 2.0[deg] on θ.

In the experiment in Fig.16, angles for the basic motions are form -30[deg] to 30[deg] by 5[deg] and the length of one basic motion is 200[mm]. Then, there are 11 basic motions in the he sequential motion for quasi-optimal path, so the length of the path is 2200 [mm]. The errors between the reference goal and realistic position of the last motion in the path were 30.6[mm] on x, 20.5[mm] on y, 2.1[deg] on θ.

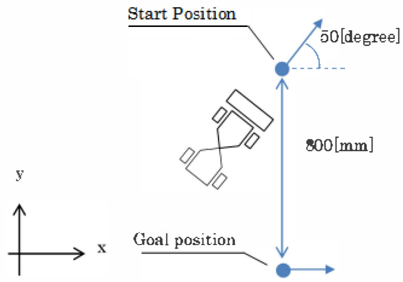

Fig. 14. Start and Goal position and direction in an experiment

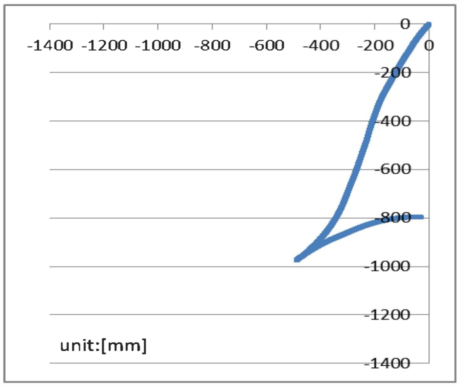

Fig. 15. Blue line is truck of representative point of the robot with quasi-optimal path on 30[mm] translational velocity

We searched the quasi-optimal path on various length parameters of basic motion from 50[mm] to 35[mm] by 5[mm] and various intervals of the steering angle from 5[deg] to 10[deg], for various translational velocity form 50[mm/sec] to 200[mm/sec]. The quasi-optimal paths on the same velocity with various those parameters were almost same shape and distance. The velocity is bigger, the distance of quasi-optimal path was longer. The robot could move in accordance with plan of quasi-optimal path in those experiments.

C. Discussion

We compare the path generated by the optimized method in this work and a path called "V-Shape" made by a method reported in [2]—[10]. The path of V-shape is composed of straight line and two clothoid curves. We made a path by the method of V-shape on the start and goal point defined already, then, the length of the path was 2465[mm] with 100[mm/sec] translational velocity. On the same condition, a path generated by GA is 2000[mm], the path by our method is 465[mm] shorter than the path of V-Shape. Time of repeated motion in the work will be reduced especially.

For the future work, we will tackle the following program. It will take 20 [sec] for the calculation to define one optimized path, so it will better to reduce the time. In realistic field, there are various conditions of the surface of the ground, so, it will need to consider the various friction of the ground. It would need to be clear the relation between representation-space of the genes and realistic motion, and parameters on GA needs to be optimized.

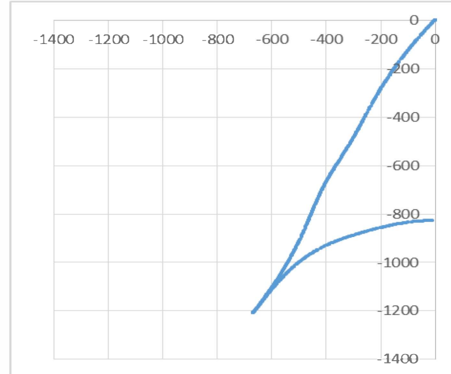

Fig. 16. Blue line is truck of representative point of the robot with quasi-optimal path on 200[mm] translational velocity

V. Conclusion

In this paper, we applied the optimization method to the path planning for the wheel loader on scooping and loading operation. We showed the quasi-optimized path and demonstrated by the miniature wheel loader robot. Owing to this method, we could generate shorter path than the method for V-shape [8][9]. Now, we tackle to confirm our method from theoretical view.

References

[1] Sarata,S.: "Model-based Task planning for Loading Operation in Mining", Proc. 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp.439-446, 2001

[2] Weerakamhaeng, Y.: "Path Generation for Articulated Steering Type Vehicle using Symmetrical Clothoid", Proc. IEEE International Conf. on Industrial Technology, B1-4, 2002

[3] Sarata, S. et al: "Trajectory Arrangement of Bucket Motion of Wheel Loader", Proc. International Symposium on Automation and Robotics in Construction, pp.135-140, 2003

[4] Sarata, S. et al ; "Approach Path Generation to Scooping Position for Wheel Loader", Proc. IEEE International Conference on Robotics and Automation, pp.1821-1826, 2005

[5] Shigeru Sarata, Yossewee Weeramhaeng and Takashi Tsubouchi: "Planning of scooping position and approach path for loading operation by wheel loader" 22nd International Symposium on Automation and Robotics in Construction, ISARC 2005 - September 11-14, 2005

[6] Shigeru Sarata,Yossewee Weeramhaeng,Akira Horiguchi,Takashi Tsubouchi; "V Shape Path Generation for Loading Operation by Wheel Loader", Field and Service Robotics, Springer Tracts in Advanced Robotics Volume 25, 2006, pp 591-602

[7] S.Sarata, N.Koyachi, and K.Sugawara: "Field Test of Autonomous Loading Operation by Wheel Loader", Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems, pp.2661-2666, 2008.

[8] S. Sarata, N. Koyachi, T. Tsubouchi, "Shorter path planning for loading operation by wheel loader", Proceedings of Mine Planning and Equipment Selection (MPES 2009), 2009.

[9] S. Sarata, N. Koyachi, T. Tsubouchi, "Improved path planning method for autonomous loading operation by wheel loader", Proceedings of International Symposium on Automation and Robotics in Construction (ISARC 2010), 2010

[10] S. Sarata, N. Koyachi, "Path Planning and Position Control for Autonomous Loading Operation by Wheel Loader", Proceedings of International Symposium on Mine Planning and Equipment Selection (MPES 2010), 2010

[11] N.Shiroma: "Nonlinear Straight Path Tracking Control for an Articulated Steering Type Vehicle", ICROS-SICE International Joint Conference 2009(ICCAS-SICE 2009)

[12] K.Okawa: "Path Planning and Consecutive Operation Based on Discrete Acquired Date for Auto Parking System", Journal of Robotics Society of Japan, Vol.29 No.4, pp.376-383, 2011, in Japanese