

# Development of Autonomous System for Loading Operation by Wheel Loader

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**Abstract:** An outline of the developed system for autonomous loading operation by wheel loader will be described. The system consists of three sub-systems: (1) Environment measuring and modeling, (2) Planning and (3) Motion control. The environment measuring sub-system measures 3D shape of the environment by stereo-vision system. The shape of the pile is converted into the environment models. The planning sub-system determines the position and direction of scooping on the pile based on the environment models. It generates the V shape path between the scooping point and the loading point as well. The motion control sub-system controls actuators on the loader based on the reference values from the planning sub-system in traveling on the V shape. However the motion of the bucket at scooping is controlled based on the resistance force applied on the bucket during scooping motion. The developed system is installed on an experimental small size scale model in lab and on a real wheel loader in the experimental field.

**Keywords:** loading operation, autonomous system, V-shape path, scooping, wheel loader

## 1. INTRODUCTION

Earth moving operation is a basic task in fields of construction, mining and so on. The worksites in construction include irregularly shaped materials such as piles of sand, soil, and fragmented rock that change shape and position as operations progress. The unmanned systems in these fields should be intelligent systems with the capability to decide their actions based on the changing conditions at worksites. Construction is one of major fields for intelligent system applications. The authors have been working on Yamazumi project for development of autonomous system in such environment. The main targets of the project are the loading operation by wheel loader, the breaking operation for large locks and the crawler motion control.

In this paper, an outline of the developed system for autonomous loading operation by wheel loader is described. The wheel loader (Front end loader, "loader" hereinafter) is widely used for loading of materials in these fields. The loader has a large bucket at the front end and four wheels. The main functions of the vehicle are scooping with the bucket and freely maneuver with the large wheels. The developed system consists of sub-systems:

- (1) Environment measuring and modeling,
- (2) Planning and
- (3) Motion control.

The developed system is installed on an experimental small size scale model in lab and on a real wheel loader in the experimental field.

## 2. LOADING OPERATION AND PLANNING

The most common path between the scooping and loading positions is "V Shape" path including a switchback in the middle of the path as shown in Fig.1. One cycle of the loading operation is composed of following actions:

- (a) Scooping,

- (a-b-c) Traveling to the dump truck,

- (c) Loading and

- (c-b-a) Traveling to the scooping position.

The loading operation is carried out by the repetition of this cycle

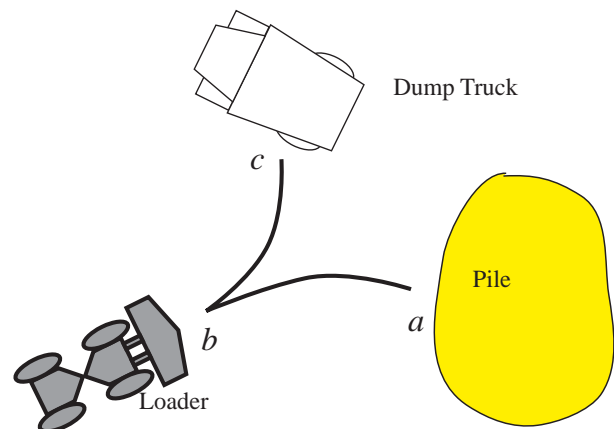


Fig.1 V shape loading method

Path planning for one cycle of loading includes planning of (1) Scooping position, (2) Scooping direction and (3) V shape path. The scooping position and the direction are determined based on the shape of the pile. V shape path is formed based on the scooping point and the loading point by the procedure described later.

Fig.2 shows the schematic diagram of the actions of loading operation in time series. *S* is scooping, *VL* is traveling from the scooping position to the loading position, *L* is loading to the dump truck and *VS* is traveling from the loading position to the scooping position. The suffix *n* represents that the action is in *n*th cycle. Let's consider planning of *n*th cycle. Because the shape of the pile was

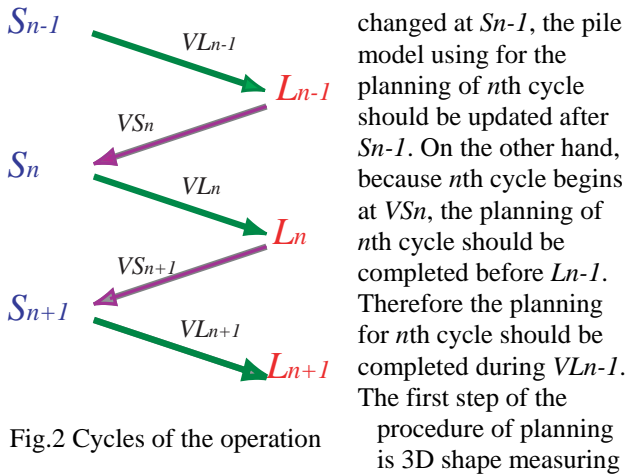


Fig.2 Cycles of the operation

immediately after  $S_{n-1}$  then the pile model is updated, and then the path planning is performed.

**3. SUB-SYSTEMS OF AUTONOMOUS SYSTEM**

**3.1 Environment measuring and modeling**

The first step of the procedure of the planning for one cycle is the shape measurement and update of the pile model. The shape of the pile can be measured by a stereo-vision system with two CCD cameras. The result of

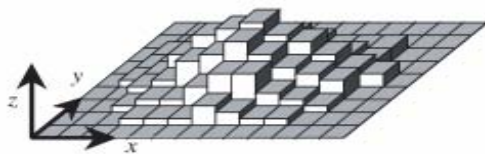


Fig.3 Column model

the measurement is converted into the pile model. The column model is a useful system for estimating the interaction between the bucket and piled material. Though simple in structure, the model can represent the shape of the pile, as well as changes in both shape and volume. Fig. 3 shows the structure of the column model. The working area is tessellated into sections, each forming the base of a column. The height of each column represents the height of the pile at that position. The sizes of the sections and unit of height have no relation to the particle or fragment diameter of the material making up the pile.[1]

As describing later, the scooping direction and the scooped volume estimation during scooping are obtained through processing the column model of the pile.

**3.2 Planning**

The major function of the planning sub-system is V-Shape path planning. Path planning for one cycle of loading includes planning of (1) Scooping position, (2) Scooping direction and (3) V-shape path. The scooping position and the direction are determined based on the shape of the pile. V-shape path is formed based on the scooping point and the loading point.

The scooping direction should be normal to the slope of the pile. If the scooping direction is far from perpendicular, as shown in Fig.4(b), the resistance force around the centre

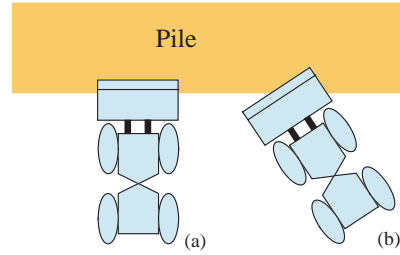


Fig.4 Scooping direction

line of the bucket is asymmetrical, imposing undesirable stress on the bucket link mechanism. The unbalance of the resistance force imposed on the bucket is estimated by estimating the

resistance force at each point on tip of the bucket using the column model and bucket trajectory model (Fig.5). The scooping direction with the least unbalance of resistance force should be selected to obtain the proper scooping motion.

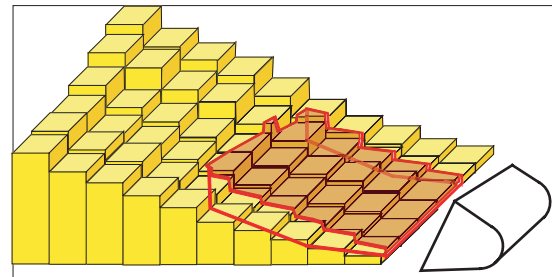


Fig.5 Column model and Bucket trajectory model

It is easy and effective to generate a path from the given initial position to the final position by combination of path elements such as straight line and curve. As the curve elements, "Clothoid" is employed in the path planning of the developing system. Curvature of clothoid is proportional to the length of the path. If the curvature is changed as shown in Fig.6(a), the path becomes the same clothoid joined in reverse direction: "clothoid pair[2]" (Fig.6(b)). At both of the end of clothoid pair, curvature is zero therefore the curve can be connected to straight lines with continuously.

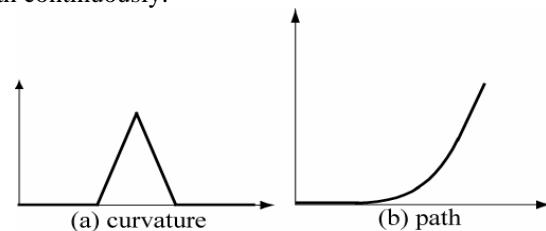


Fig.6 Clothoid pair

The steering mechanism of wheel loader is an articulate steering system of the type shown in Fig.7. The body of the loader is separated into a front part and a rear part connected by a center pin. The angle around the centre pin is controlled by hydraulic cylinders. The placement of the front and rear

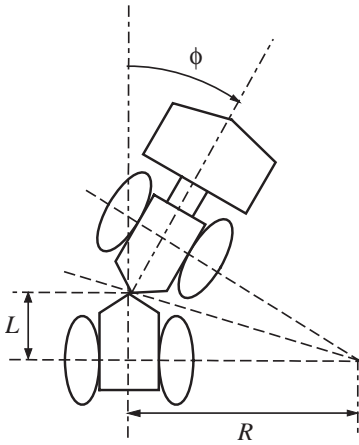


Fig.7 Articulate steering system

axles at equal distances from the centre pin ensures that the front and rear wheels travel over the same path, conferring high mobility on off-road surfaces such as mud or soft soil. Let  $\phi$  be the articulate angle,  $L$  be the distance from the centre pin to the front or rear axle,  $R$  be the radius of curvature, and  $\kappa$  be the curvature. The relations between the foregoing are as

follows:

$$L = R \tan(\phi / 2) \tag{1}$$

$$\kappa = 1 / R = 2 \tan(\phi / 2) / L \tag{2}$$

When  $\phi$  is small, curvature  $\kappa$  is proportional to  $\phi$  linearly. The operational range of the articulate angle is about 40 degrees. The relation between  $\kappa$  and  $\phi$  is almost linear in this range.

V shape path from the given initial position to the final position can be easily formed by a combination of straight line elements and curve elements. In the proposed method for path planning, we define ‘‘Symmetrical Pseudo-Clothoid’’ (SPC) as the curve elements. If the steering angle  $\phi$  changes as shown in Fig.8(a), the path becomes the same curves joined in reverse directions (Fig. (b)). The curves are almost same as clothoid pair with the error described in (2). Given that the curvature is zero at both ends of SPC, the curve can be connected to straight lines or other SPC with continuously.

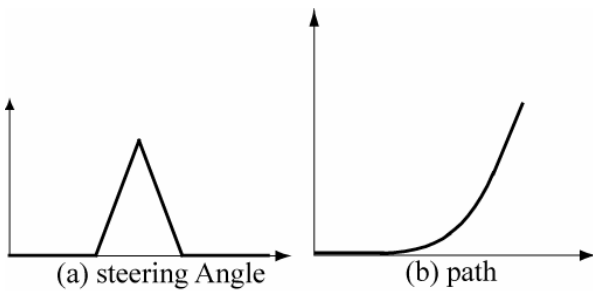


Fig.8 Symmetrical Pseud-Clothoid

V shape path is formed by the combination of two SPC and three straight lines as shown in Fig.9. Red curves and blue lines represent SPC and straight line segments respectively in Fig.9. To simplify the procedure of numerical solution, the sharpness of SPC which is ratio between travel length and steering angle, is limited to several values. The curve segments with two SPC are determined by directions at the scooping point, the loading

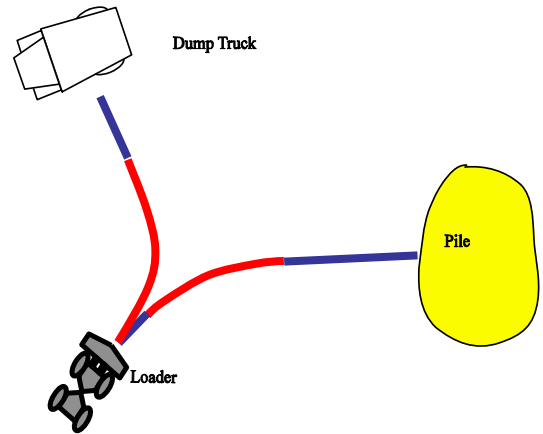


Fig.9 Combination of elements

point and the switchback point. The lengths of three line segments are obtained by an optimization[3][4].

For convenient of explanation, it is supposed that the initial position of loader is on the origin of coordinate system and direction of the loader is positive direction of x axis as shown in Fig.10. The grey zone in Fig.10 is the area that can be reached via the combination of straight line  $l1$ , PSC  $c1$ , straight line  $l2$ , PSC  $c2$ , and straight line  $l3$ . The directions of straight lines  $l1$ ,  $l2$  and  $l3$  are the directions of the loader at the initial position, at the end of  $c1$ , and at the final position, respectively. The loading operation with V shape path requires that the loader should move backwards on  $l1$  and  $c1$ , move forwards on  $c2$  and  $l3$ , therefore  $l1$  should be negative and  $l3$  should be positive value. The path planning proceeds in the following steps. As shown in Fig.10, Let  $P_s$  be the scooping position,  $\theta_s$  be direction at

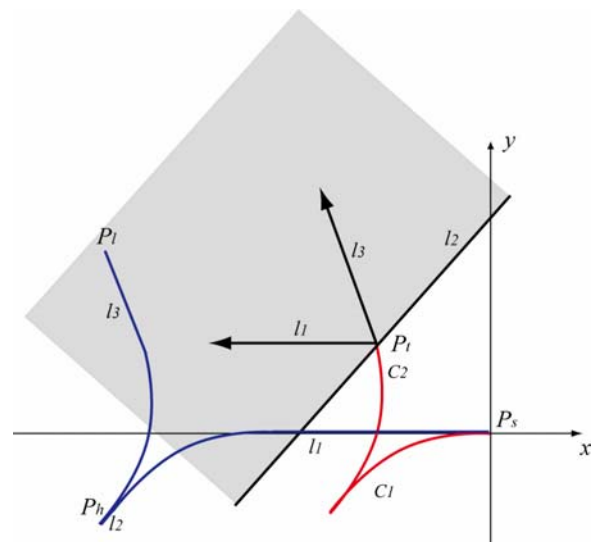


Fig.10 Procedure of path planning

that position,  $P1$  be the loading position,  $\theta_l$  be direction at that position and  $\theta_h$  be direction at  $Ph$ : the switch back point.  $\theta_h$  takes value between  $\theta_s$  and  $\theta_l$ . The final path consists of  $l1 - c1 - l2 - c2 - l3$  in this order, however  $c1 - c2$  is determined in the first step and  $l1$ ,  $l2$  and  $l3$  are determined in the second step. At

the first step, set  $k$  at a certain value and calculate  $c1$  for  $\theta h - \theta s$  at the end of  $c1$ . Next, calculate  $c2$  for  $\theta e - \theta h$  in the same manner and connect  $c1$  and  $c2$  in direction  $\theta h$ . In the second step, generate the path  $l1 - l2 - l3$  between the end point of  $c1 - c2$ : Pt and the scooping point  $Pl$  with optimization on length of  $l1 - l2 - l3$ .

### 3.3 Bucket motion control at scooping motion

In ordinary scooping, the bucket motion consists of three phases as shown in Fig.11. At the beginning of scooping, the bucket is placed on the ground. The base of bucket is kept horizontally. The bucket penetrates into the pile with advancing of the body by wheel revolution in Phase 1(A-B). In Phase 2(B-C), the tip of bucket moves upward along a line or a curve with arm lift and increasing of the tilt angle of bucket. When the bucket is filled up with the pile, the bucket moves upward almost vertically in Phase 3(C-D). Determination of transfer from Phase 1 to Phase 2 and appropriate arrangement of bucket path are significant for effective scooping.

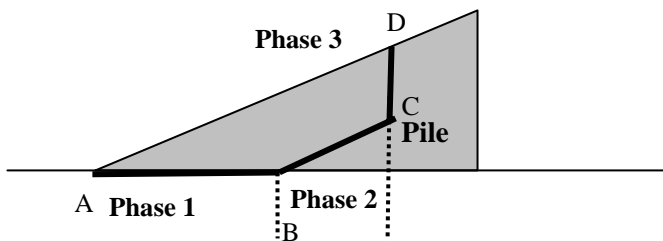


Fig.11 Phases in Scooping Motion

A large amount of resistance force is applied on the bucket during scooping motion. The resistance force consists of several elements of force and the relation between the bucket motion and the resistance force is complex[5]. A simplified model of the relation is used for the estimation of the resistance force. As shown in Fig.12, a virtual plane is assumed between materials inside and

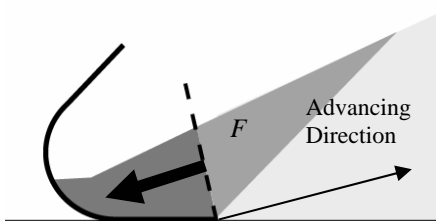


Fig.12 Virtual Plane between Inside and Outside

outside of the bucket. It is supposed that the force from the materials outside of the bucket acts in normal direction to this virtual plane. By advancing of the bucket, the virtual plane pushes material outside of the bucket. Required force for the bucket movement is greater than  $F$  which is the force

acting on the virtual plane.  $F$  is formularized by passive pressure of Coulomb theory. Direction of the virtual plane is normal to advancing direction of the bucket. Therefore magnitude of  $F$  is function of the advancing direction. Fig.13 shows magnitude of  $F$  in each advancing directions. [6]

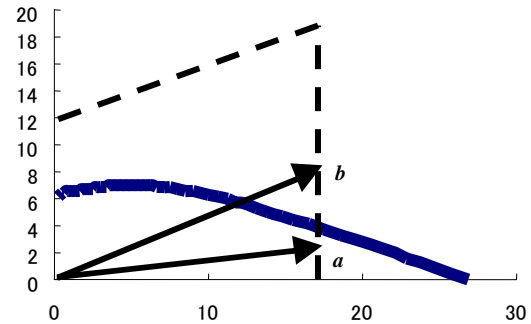


Fig.13 Resistance Force and Operational Force

Blue line is the total required force for advancing of the bucket in corresponding directions. Dotted lines represent the operational force of the bucket. If the bucket moves in direction  $a$ , magnitude of the resistance force exceeds the operational force. Therefore the bucket cannot move in this direction. If the bucket moves in direction  $b$ , the operational force is greater than the resistance force and the bucket can move in this direction. The direction for intersection of the resistance force and the operational force is the lower limit of the advancing direction. The consideration shows that the magnitude of the resistance force has a close relation to the advancing direction of the bucket. The less resistance force appears for the upper advancing direction of scooping motion.

Rules for trajectory arrangement of the bucket motion are as follows;

Phase 1: Penetrate the bucket in the pile horizontally until horizontal element of the resistance force reaches setting value.

Phase 2: If horizontal element of the resistance force exceed setting threshold, arrange advancing direction of the bucket upward. The arranged angle is proportional to exceeding value of the resistance force from the threshold. If scooped volume reaches setting value, transfer Phase from 2 to 3.

Phase 3: Move the bucket upward vertically to complete scooping motion.

The scooped volume estimation is obtained during scooping with the column model and bucket trajectory model as shown in Fig.5.

## 4. EXPERIMENTAL RESULTS

### 4.1 Experiments with small model

The proposed method described above was installed and evaluated using experimental model called YAMAZUMI-2(YZ-2.Fig14) and the pile of fragmented granite. YZ-2 has same structure and function of a wheel

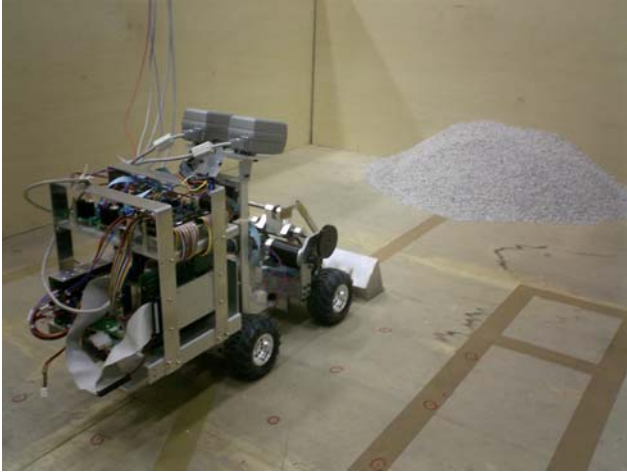


Fig.14 Experimental Model YZ-2

loader. The length between the front axel and the rear axel is 270mm and width of bucket is 250mm. Size of the experimental pile is about 1000mm in width and 300mm in height. Particle size of the pile is 5mm. Two CCD cameras are attached to YZ-2 for shape measuring of the pile by a stereo-vision system. The length of the base line of the cameras is 100mm. The resolution of image is 640X480. Fig.15(a) is image of the pile by CCD camera. The shape of the pile was obtained by applying the correlation method on the images. The column model of the experimental pile is shown in Fig.15(b). Size of the basement of column is 5x5mm and the column model consists of 300x300 columns. The column model can represent 1500 x 1500 mm area in the experimental field.

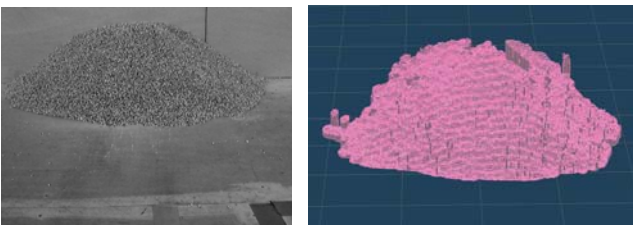


Fig.15 (a) Image of Pile (b) Column Model

Fig.16 shows the result of the experiment. Curves in Fig.16 are traces of YZ-2. Brown bold curve represents the edge of the pile and pale green square represents the vessel of dump truck. Red curve represents  $VL_{n-1}$ . The image of the pile after  $S_{n-1}$  is taken at red dot on  $VL_{n-1}$ . During traveling on  $VL_{n-1}$ , the planning for  $n$ th cycle is proceeded. The next scooping position  $S_n$  is set at bleu dot on the edge of the pile. The scooping direction is determined based on the estimation of unbalance of the resistance force. Blue and green curve in Fig.16 represent V shape path for  $n$ th cycle  $VS_n$  and  $VL_n$ . They are overlapped each other.

4.2 Field test with real loader

The proposed system is installed and evaluated on the experimental loader YAMAZUMI-4 in the test field (Fig.17). The size of YZ-4 is 7m in length and 2.5m in width

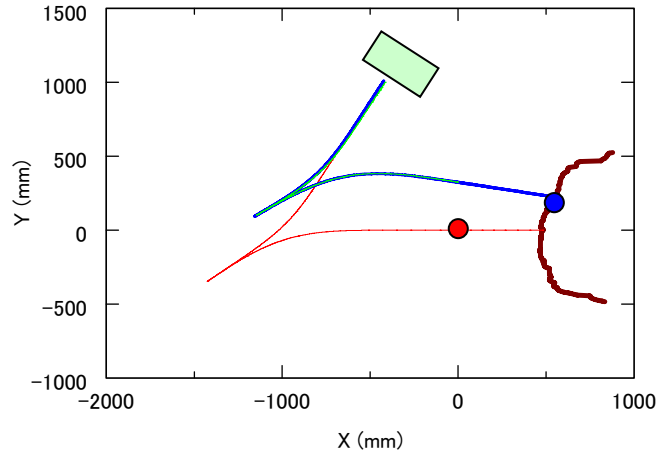


Fig.16 V-shape path of  $n-1$ th and  $n$ th cycle



Fig.17 Experimental loader YZ-4 and dump truck at the test site



Fig.18 Sensors on YZ-4

of the bucket. The capacity of the bucket is  $1.3\text{m}^3$ . The structure of the control system including the controller for actuators, PC and sensors is almost same as YZ-2.

YZ-4 has sensor systems including GPS and two Laser range finders which are not installed on the small size experimental model YZ-2 (Fig.18). Two GPS antennas are attached on both side of the body. The GPS system provides the position of YZ-4 in the global coordinate system as well as the direction of heading.

Fig.19 shows a example of the results of V-shape path traveling by YZ-4. The start position is (-152, -25) and the end position is (-166, -34) in a local coordinate system on the test site. The directions at each position are 3 degree and -87 degree respectively. The planned path consists of two PSC and three straight lines as described in the previous section. The total length of the path is about 50m.

Red line represents the trace of GPS positioning. Dotted line represents the planned path. The traces of the GPS positioning and the planned path agree with each other. Thin blue line represents the trace by dead reckoning based on revolution of the wheels and the steering angle.

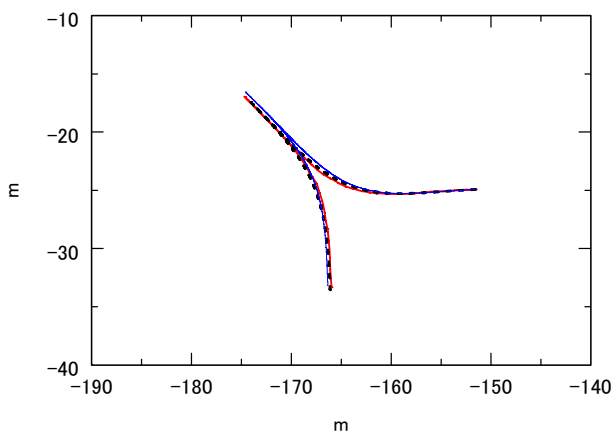


Fig.19 Trace of V-shape path

In this example of traveling, the velocity of YZ-4 is 2.2 m/sec. The position error at the end of the path is less than 0.4m in y-axis direction. Because path trucking by GPS positioning is not employed in this case, more precise trace is expected by using GPS positioning data.

The other sub-systems and functions such as the stereo-vision system, the modeling of environment, the planning and the bucket motion control are installed and tested. YZ-4 shows good performance at preliminary tests for those functions.

## 5. CONCLUSIONS

An autonomous system for loading operation by wheel loader is proposed. The developed system consists of following sub-systems:

- (1) Environment measuring and modeling,
- (2) Planning and
- (3) Motion control.

The system has capability of planning and motion control in changing conditions of the environment. The performance of the system is evaluated with the small experimental model. The results the experiments show that the system works very well. The developed system and methods with the small model are equipped and installed on the real size experimental loader. The performance of the system on real size model is evaluated at the test site.

The developed system could be applied to other operations in construction fields as the main structure of autonomous or unmanned systems.

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