MOTION CONTROL FOR BUCKET OF WHEEL LOADER BASED ON SHAPE OF PILE AND RESISTANCE FORCE

SARATA,Shigeru 1), OSUMI,Hisashi, HIRAI,Yusuke 2), MATSUSHIMA,Gen 3) and TSUBOUCHI,Takashi 4)

1) *National Institute for Advancing Industrial Science and Technology (AIST)*
Namiki 1-2-1, Tsukuba, Ibaraki, 305-8564 JAPAN E-mail: sarata-s@aist.go.jp
2) Chuo University 3) Citizen Watch Co., Ltd 4) University of Tsukuba

For autonomous scooping operation by wheel loader, a method for trajectory generation and motion control of bucket at scooping operation is proposed. Prior to scooping, three-dimensional shape of pile is measured by stereovision system with two CCD cameras. The initial trajectory model is modified according to the shape of pile. During scooping, the control values for the actuators are arranged based on the resistance force. The proposed method is implemented on the experimental model. The results show that the adequate bucket control is performed by the proposed method. For effective scooping, the desirable direction of advancing of the bucket is discussed.
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Keywords: Scooping operation, Wheel loader, Scooping trajectory, Bucket motion control, Column model, and Trajectory planning

1 INTRODUCTION

Wheel loader (front-end loader) is one of the major loading machines in fields of construction, mining, agriculture etc. For autonomous loading operation, several methods for bucket trajectory generation and motion control have been proposed. One of major method is similar to the computed torque method, which is used for control of serial link manipulators in assembling lines. In this method, the reference value for the control system is the estimation value of resistance force at the bucket based on soil-bucket interaction models [1][2].

This method might be a proper way in "Robotics", however, soil-bucket interaction models are based on estimated value of unknown factors such as bulk density, angle of internal friction etc. The mechanism of interaction between soil and bucket is not clear.

By contrast, the other major methods do not use any information on the pile. In these methods, bucket arm lift and tilt are controlled based on resistance force during scooping operation. Planning of bucket motion or planning of scooping path prior to scooping is not involved in the methods. In the scoop operation by human operator, scoop procedure is consist of several cycle of arm lift and bucket tilt alternately. A kind of sequence controller was installed and applied to scooping operation of gravel at asphalt plant [3]. The controller performed this cyclic bucket motion based on the resistance force.

Fuzzy controller was applied to simulation of bucket motion [4]. Controlling input for actuators are arranged based on horizontal and vertical element of the external force at the bucket through fuzzy rules.

In this paper, the method of bucket trajectory generation and motion control is proposed. Prior to scooping, the model of pile is formed by shape measurement. Planned trajectory is issued to the controller. During scooping, the direction of bucket is arranged based on resistance force at the bucket. The rules for trajectory arrangement are based on fuzzy logic. The proposed method is implemented on the experimental model. The results of the experiments and the desirable advancing directions of the bucket are discussed.

2 PILE MODEL AND BASIC PATH MODEL

In the laboratory experiment, The shape of scooping area on the sloop of pile is measured by stereovision system using two CCD cameras. Pile of gravel or fragmented rock has good texture on its surface for correlation method to generate three-dimensional shape. The shape of pile is represented by the column model as shown in Figure 1. Structure of the pile model is a set of columns. The working place is tessellated into sections, which are bases of columns.

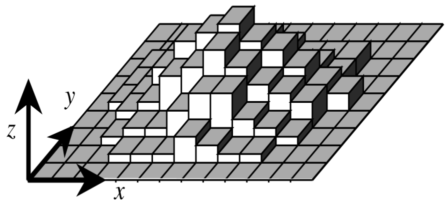


Figure 1. Column model

The height of column represents the height of pile at that position. The size of sections and the unit of height have no relation to size of particle of the pile. The column model can represent shape and volume as well as their changes.

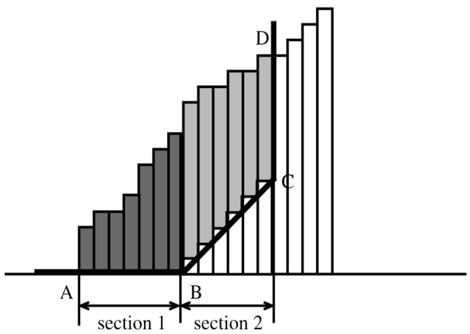


Figure 2. Column model and basic path model

From measured positions, shape model is formed by interpolation and/or extrapolation (Figure 2). Bold line in the figure represents the basic bucket path. The bucket path model is formed based on observations of bucket motion by experienced operators. The path consists of three sections. In the first section (A-B), the bucket is held on the ground and penetrates into pile horizontally. In second section (B-C), the bucket moves forward and upward. Third section (C-D) is final stage of the scooping.

In proposed method, penetration length of the first section is determined by advancing force of the loader. Scooping angle at the second section is selected to keep resistance force in proper range. Because the resistance force of bucket has relation to scooping depth, to keep proper resistance force may result proper scooping depth.

The swept area by the cutting edge can be considered to be scooped volume divided by width of the bucket. The scooped volume should not exceed the capacity of the bucket. The end position of scooping is determined by scooped area.

3 BUCKET TRAJECTORY ARRANGEMENT BASED ON RESISTANCE FORCE

3.1 Experimental model

The experimental model YAMAZUMI-2 (YZ-2) is a scale model of a wheel loader (Figure 3). YZ-2 has almost same mechanism of a wheel loader and 75 cm in length, 25cm in width. The wheels and bucket are driven by DC motors and controlled by on board computer. YZ-2 is self-contained system except DC power. Two motors are installed for bucket motion. One motor drives bucket arm lift and the other drives bucket tilt. The tilt motor is installed at base joint of the arm and connected to bucket through parallel link. Wheels and steering mechanism are driven by other motors. Electrical currents of the motors are measured for sensing generated torque at each joint of the mechanism

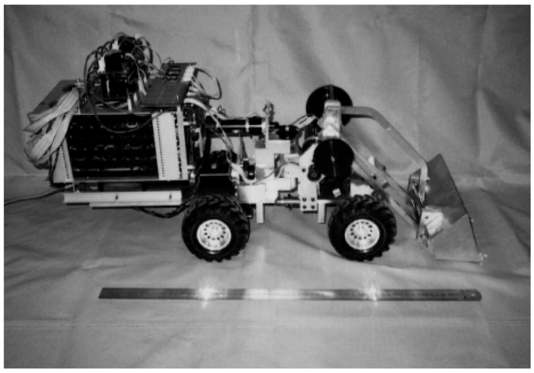


Figure 3. YAMAZUMI-2

3.2 Bucket link mechanism

The mechanism for bucket motion of wheel loader includes wheel drive and parallel linkage however it can be expressed by a model of three-link serial mechanism. In this model, wheel drive is represented by a prismatic actuator because the loader moves on straight line during scooping. The bucket position and configuration are changed by the combination of advancing distance of the body, arm lift angle and bucket tilt angle. The bucket motion mechanism can be described in simplified model in Figure 4.

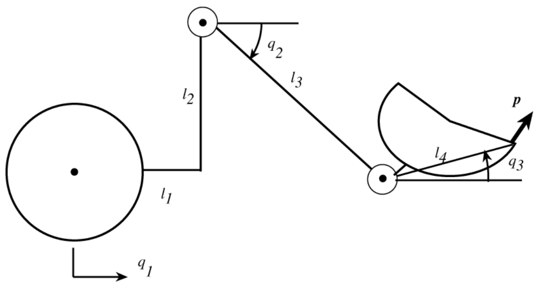


Figure 4. Bucket linkage model

The kinematics equations for the bucket motion are as follows:

$$p_x = q_1 + l_1 + l_3\cos(q_2) + l_4\cos(q_3 + \theta_b) \quad (1)$$
$$p_y = l_2 + l_3\sin(q_2) + l_4\sin(q_3 + \theta_b) \quad (2)$$
$$\theta_p = q_3 + \theta \quad (3)$$

where $\boldsymbol{p}=(p_x, p_y, \theta_p)^T$ is the position vector of bucket tip, $\boldsymbol{q}=(q_1, q_2, q_3)^T$ is the joint vector, q_1 is the advancing distance, q_2 is the angle of arm and q_3 is the angle of bucket tilt. θ_b is the offset angle between direction of l_4 and the bucket.

Matrix equation (4) is obtained by differentiating above equations. This equation describes relation between joint velocity and bucket velocity.

$$\dot{\boldsymbol{p}} = \boldsymbol{J}\dot{\boldsymbol{q}} \quad (4)$$

Where $\boldsymbol{p}$ is bucket velocity vector, $\boldsymbol{q}$ is joint velocity vector and $\boldsymbol{J}$ is Jacobian matrix.

Relation between force at the bucket and torque at each joint is described by the equation.

$$\boldsymbol{\tau} = \boldsymbol{J}^T\boldsymbol{f} \quad (5)$$

Where $\boldsymbol{J}^T$ is transposed matrix of Jacobian. $\boldsymbol{\tau}=(\tau_1, \tau_2, \tau_3)^T$ is the torque vector and each element is the torque at each joints respectively. $\boldsymbol{f}=(f_x, f_y, n_{xy})^T$ is the external force vector.

3.3 Control system

The control method for bucket motion is similar to that for industrial manipulators used in assembling applications. Each motor at the joint is controlled individually. Basic method of the control systems is PI control and the reference value is angular velocity of wheel, arm lift and bucket tilt.

If the planned trajectory of the bucket is given, reference velocity of the bucket at each position on the path can be specified. The reference angular velocity for each motor is obtained by solving the equation (4). Because the velocity of the bucket may be varied by interaction with piled ore, the reference angular velocity values issued to the control system are described with respect to the position of bucket but time.

4 PLANNING AND MODIFICATION OF BUCKET TRAJECTORY

Basically, bucket path is supposed to consist of three sections as mentioned previously. Planning of the bucket trajectory in the first and second section is based on external force at the bucket. For measurement of external force, measuring devices for electric current are installed at motors of each joint.

Moment of external force at the bucket can be negligible. The relation between external force and torque at each joint is obtained as equation (6) from (5).

$$\begin{pmatrix}\tau_1\\ \tau_2\\ \tau_3\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ -l_3\sin(q_2) & l_3\cos(q_2) & 0\\ l_4\sin(q_3+\theta_b) & l_4\cos(q_3+\theta_b) & 1\end{pmatrix}\begin{pmatrix}f_x\\ f_y\\ 0\end{pmatrix} \quad (6)$$

The torque at wheels has direct relation to horizontal element f_x of the external force. The torque at arm has relation to horizontal element f_x as well as vertical element f_y, and is affected by the angle of arm q_2.

In the first section of the path, penetration distance into the pile is determined based on torque at wheels. When the current of wheel drive motor reaches the setting value, the first section is finished and the planning phase is changed to phase for the second section.

In the second section, sloop angle of the pile is selected for the initial direction of bucket advancing. During scooping, the advancing direction is modified based on torque at the joints. Depth of the cutting edge and advancing velocity of the bucket have close relation to external force, however, it is difficult to formulized this relation because of many uncertain factors affect this relation. Fuzzy logic is applied to the modification of the bucket direction and velocity. Basic rules are follows;

If $\boldsymbol{\tau}$ is *large*, move the bucket *upward*.
If $\boldsymbol{\tau}$ is *small*, move the bucket *downward*.
If $\boldsymbol{\tau}$ is *very large*, move the bucket *slower*.

Scooped volume is obtained from resultant path and column model of the pile. When scooped volume reaches capacity of the bucket, final third section is initiated.

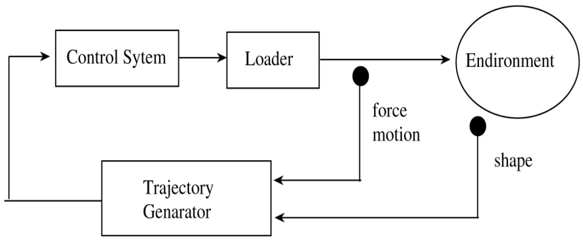


Figure 5. Trajectory generation and control system

Schematic diagram of the trajectory generation and control system is shown in figure 5.

5 EXPERIMENTAL RESULTS

The proposed method described previous sections for generation and modification of trajectory of the bucket is installed into experimental model YZ-2.

Figure 6 and 7 show results of the experiment of scooping by YZ-2 at steep slope and gentle slope respectively. In the experiments, the pile is crushed granite and the particle size is 5 mm.

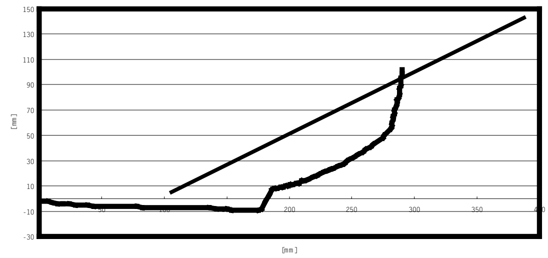
In figures (a), the path of the tip of bucket and the slope of pile are shown. Figures (b) show the electrical current of each motor, that is, the curves represent torque at each motor. In figures (b), black lines, gray lines and white lines represent the current of motors for the arm, the wheel and the tilt espectively, and the horizontal axes represent time.

The horizontal element of load at the bucket is mainly generated by torque at the wheel drive. When the current of wheel motor reaches a setting value, the first section is finished and transferred to the second section. Length of the first section of path at the steep slope is shorter than that of the path at the gentle slope.

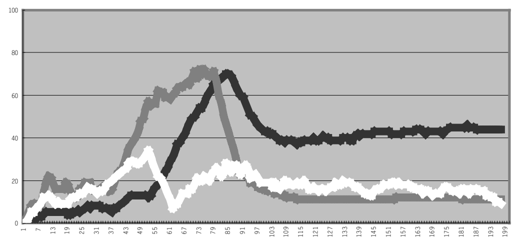
In the second section, both of the paths show that the bucket moves to follow surface of the pile to keep the depth in proper range.

As shown in figures (b), magnitude of current at each motor for the steep slope is larger than that of the gentle slope, however, the length of time for scooping at the steep slope is shorter than that of the gentle slope.

Results show that appropriate path is generated and motion of the bucket is controlled well. During scooping, the electrical current at each motor does not exceed the limit of the setting maximum value.

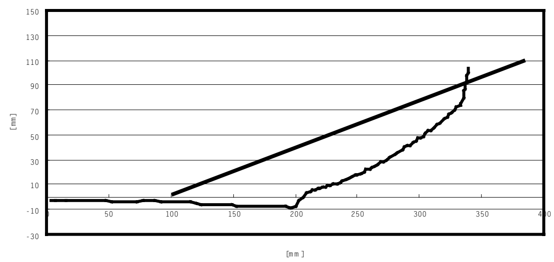


(a) the path of the tip of bucket

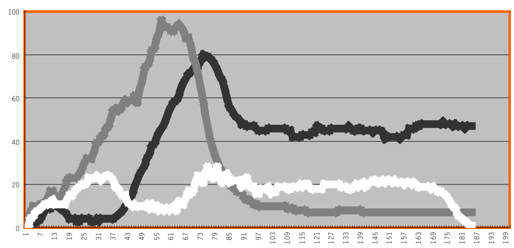


(b) the electrical current of each motor

Figure 6. Result of the experiment (steep slope)



(a) the path of the tip of bucket



(b) the electrical current of each motor

Figure 7. Result of the experiment (gentle slope)

6 CONSIDERATIONS ON ADVANCING DIRECTION OF THE BUCKET

Several analyses of resistance force at the bucket have been performed. Hemami[1] proposed that the resistance force is resolved in five elemental resistance forces as shown in Figure 8.

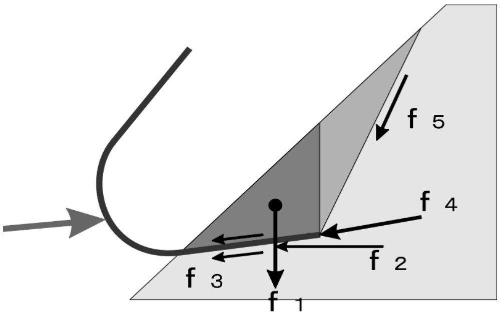


Figure 8. Resistance force

Summary definition of each element is as follows: f1 is weight of materials in the bucket. f2 is resistance force from materials against the advancing direction of the bucket. f3 is frictional force between materials and the bucket. f4 is resistance force of penetration on the cutting edge and side wall of the bucket. f5 is necessary force to move materials inside and above the bucket. This definition does not coincide with Hemami's definition precisely.

Magnitude of f1 is calculated from scooped volume of pile. In usual operation, f2 is not generated because advancing direction of the bucket tends to upward for scooping. Magnitude of f3, f4 and f5 is dominated by depth of pile at the cutting edge and advancing direction of the bucket.

Horizontal component F_x and vertical component F_y of resistance force are formulated in equations (7) and (8) respectively.

$$F_x = F_f \cos\theta_a + F_i \cos\kappa + P\cos\theta_a \quad (7)$$

$$F_y = F_f \sin\theta_a + F_i \sin\kappa + Mg + P\sin\theta_a \quad (8)$$

Where F_f is frictional force and F_i is resistance force of penetration. θ_a is advancing direction of the bucket. Other notations are shown in Figure 9. P is necessary force derived from Coulomb's theory.

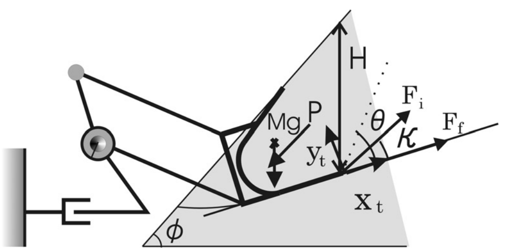


Figure 9. Forces on he bucket

In figure 10, dotted arrows represent magnitude of resistance force in each advancing direction of the bucket. The envelope is defined as "resistive force envelope". Generally, resistive force envelope has shape like an ellipsoid with horizontal apse line. It is inferable from equations (7) and (8). However below horizontal direction, resistance force might be very large because of effects of f2.

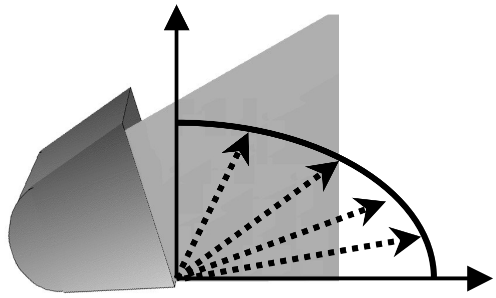


Figure 10. Resistance force Envelope

Manipulating force is resultant force of supplied force from the actuators at each joint through the linkage. Manipulating force is obtained from solutions of equation (5). It is a function of torque at each actuator as well as the configuration of bucket. If the maximum torque at each actuator is applied, envelope of manipulating force in each direction of advancing forms polygon as shown in Figure 11. Maximum value of horizontal component of manipulation force is equal to frictional force between wheels and the ground. Magnitude of vertical component is larger than that of horizontal component from characteristic of the bucket link mechanism.

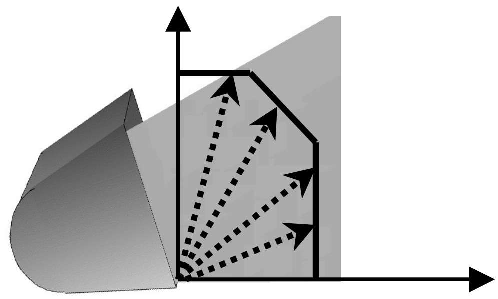


Figure 11. Manipulating force polygon

Figure 12 shows an example of a resistive force envelope and a manipulating force polygon. If the magnitude of resistive force envelope exceeds that of the manipulating force in certain direction, the bucket cannot advance in that direction. In this case, the bucket can move upward direction than the intersection of the envelope and the polygon.

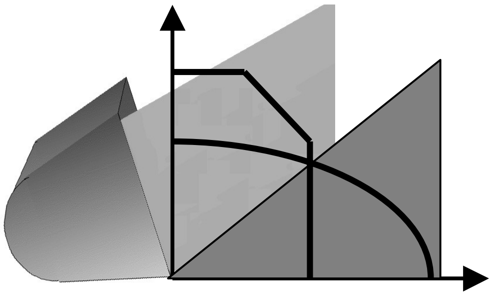


Figure 12. Resistive force envelope and manipulating force polygon

As shown in figure 13, in the beginning stage of scooping, because the depth of pile at the cutting edge is small. The intersection of the envelope (ellipse in dotted line) and the polygon locates lower position. Restricted range on advancing direction is narrower. In the latter stage, the depth of pile at the cutting edge becomes large and the resistive force envelope (ellipse in full line) exceeds the manipulating force in a certain range of direction. The intersection locates upper position than the beginning position. The restricted range is wider and the bucket can move upward direction.

For effective scooping, the bucket is required advancing in foreword direction. If the resistive force envelope exceeds the manipulating force, the direction to the intersection of the envelope and the polygon is the closest direction to horizontal advancing in movable range.

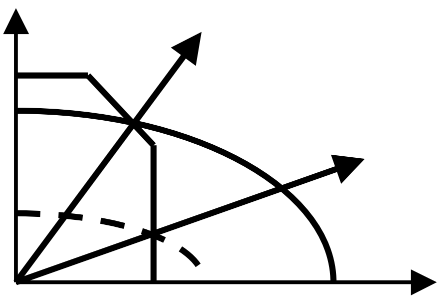


Figure 13. Intersections and advancing ranges

7 CONCLUSION

The method for motion control for bucket of wheel loader has been proposed. The initial reference trajectory is generated based on shape of the pile. During scooping, advancing direction is arranged based on resistance force at the bucket. Resistance force is decomposed into horizontal and vertical elements. Advancing direction is determined based on elements of resistance force through fuzzy reasoning. The control method is implemented on the experimental model. The results of the experiments show that the adequate bucket control is performed by the proposed method. For evaluation of control performance, resistance force envelope is defined. The intersection of the resistance force envelope and the operational force polygon indicates the desirable direction of advancing of the bucket.

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