Detection of Underground Obstacles by Using Vision and Force for Excavation

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Abstract

A new method for detecting underground obstacles, such as water pipes and power transmission cables, during excavation works is proposed in this paper. The studied method is based on the concept of sensor fusion and incorporates of visual information and force sensor data. The resistive force which acts on the bucket of an excavator, during excavation, is closely related to the changes in the shape of the ground caused by the excavator. During an excavation process, when the bucket of the excavator comes close to some underground obstacles or touches them, the relationship between the resistive force and the changes in the shape of the ground varies. So, using the sensed resistive forces and the visual data of the changes in the shape of the ground, an excavator robot can detect if the bucket is getting close to some underground obstacles or touches them. Fig.1 shows the image of our proposed method.

1. Introduction

As we use more construction machines in the construction sites than before, the demand for some autonomous or intelligent construction machines is increasing; for higher safety and more productivity of workers and higher efficiency of the system. In the construction sites, excavators are widely used for many purposes, such as digging the ground, carrying blocks, and hoisting heavy objects. To control an excavator a skillful operator is needed, because he/she must control four valves using two control levers in

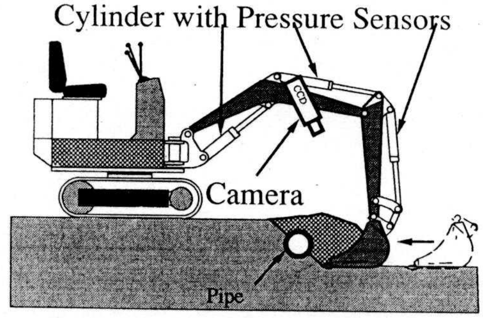

Figure 1: Detection of Underground Obstacles Using Vision and Force

coordination with each other. To overcome the problem of shortage of skilled operators, there has been some researches on developing an automatic excavator and increasing its maneuverability[1],[2].

Using an excavator, we sometimes remove soil around pipes or dig the ground where some stones have been buried. When we remove soil around the buried pipes, we must avoid any strong collision between the bucket and the pipes. Also, when we dig the ground with some stones buried in, it is not desirable that the bucket collides with the stones frequently, which results in decreasing the system efficiency. For these reasons, in order to dig the ground by an autonomous excavator, it is important to know the position of the underground obstacles and detect any contact between the bucket and them.

Ground penetrating radar is used to know the position of underground obstacles. Herman and Singh have developed an autonomous system, which equipped with the bucket with a ground penetrating radar antenna, for the retrieval of buried objects [3]. Since the measured data of the ground penetrating radar are influenced by the soil moisture, cavity, and some other properties of soil. Then, to utilize the measured data of an ground penetrating radar much experiences are needed. Therefore, it seems that autonomous ground excavation by using only ground penetrating radar is difficult.

When a robot moves around obstacles and doesn't know their precise position, it is required to use some contact information of the robot's body and the obstacles. When the robot is moving freely, sense of touch and force sensory data can be used for detecting contact between a robot's body and obstacles. K. Kosuge et al. proposed a system in that force sensory data is used to detect contact between the bucket and objects buried in the ground[4]. But, since a resistive force from soil acts on the bucket during excavation, it is difficult to detect robot-object contact by using only the sense of touch or force. So we proposed to use vision and force data together to detect if the bucket whether approaching or touching underground obstacles or not.

2. Method to Judge the State of Excavation

In the proposed method, to detect if the bucket is approaching or touching underground obstacles, the following informations are used.

- Resistive force acting on the bucket
- A change in the shape of the ground during excavation

The relationship between the bucket and underground obstacles, when they approach or touch each other, can be categorized as:

- When the bucket approaches or touches obstacles which are small or buried in a deep position.
- When the bucket approaches or touches obstacles which are big and buried in a shallow position.

2.1 Detection of approach and contact of the bucket to obstacles which are small or buried in a shallow position

Fig.2 shows the side view of the soil which dug by the bucket and a blade. The soil failure surface is formed from the end of the blade. The dug soil is accumulated between the blade and the soil failure surface, and the dug soil between the blade and the soil failure surface rises as the blade progresses in the ground. Other than the failure surface

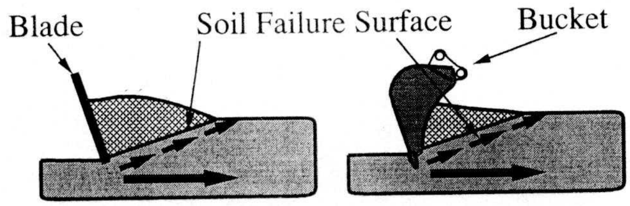

Figure 2: Excavation with a Blade and a Bucket

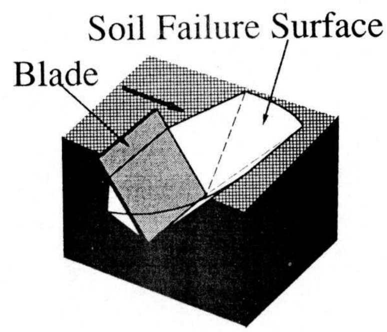

Figure 3: Three Dimensional Form of a Soil Failure Zone

shown in Fig.2, soil failure surfaces are formed on two sides of the blade also. Fig.3 shows the shape of a three dimensional soil failure zone. The shape of soil failure zone, when the soil is dug by the bucket, is similar to the one formed using a blade. The shape of a soil failure zone is closely related to the resistive force which acts on the bucket. Edward Mckyes proposed a three dimensional model for calculating resistive force, shown in Fig.4. Based on his model, the resistive force (P) can be calculated as:

$$\begin{aligned} P = & \left\{ \gamma g d^2 \frac{r}{2d}\left[1+\frac{2s}{3w}\right] \right. \\ & + cd\left[1+\cot\beta\cot(\beta+\phi)\right]\left[1+\frac{s}{w}\right] \\ & \left. + qd\frac{r}{d}\left[1+\frac{s}{w}\right] + c_a d\left[1-\cot\alpha\cot(\beta+\phi)\right] \right\} w \\ & \Big/ \left\{\cos(\alpha+\delta)+\sin(\alpha+\delta)\cot(\beta+\phi)\right\} \end{aligned} \quad (1)$$

where c is soil cohesion, c_a is soil-tool cohesion, g is gravitational constant, q is surcharge pressure on the soil surface, γ is soil density, δ is soil-tool friction angle, and ϕ is internal friction angle of the soil[5].

If the soil failure zone intersects with a small obstacle, as shown in Fig.5 (b), or the bucket touches an obstacle in a deep position, depicted in Fig.5(c), the resistive force is bigger than that when the bucket digs the ground where nothing is buried in. As it is shown in the above equation, the change of the resistive force depends on the physical parameter of soil and the shape of the ground. Then, using mere force data, detecting approach or contact of the bucket to obstacle would be possible only when the changes in

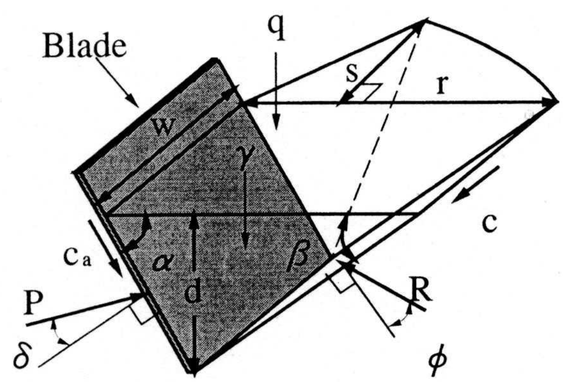

Figure 4: Three Dimensional Soil Failure Model

the resistive force is quit big. Therefore, using only force sensory data would be impractical when the underground object is a fragile one (like a pipe).

The shape of the soil failure zone isn't affected by a small object, shown in Fig.5(b), or an object buried in a deep position (Fig.5(c)). The cross line of the soil failure surface and the surface of the ground can be seen because the soil rises. Therefore the parameters of the shape of the soil failure zone; r, s, d, α, and β; and the surcharge pressure on the soil, q, are obtained by visual sensing. During excavation, the parameters of soil; c, c_a, γ, δ, and ϕ; can be estimated using the resistive force, measured by the force sensor, and the shape of the soil failure zone can be measured by the visual sensor. The resistive force can be calculated from (1) using the parameters of the shape of the soil failure zone measured by the visual sensor and estimated parameters of soil.

The resistive force estimated using vision data is almost equal to that measured data by a force sensor, when a bucket digs the ground where nothing is buried in. On the other hand, when the soil failure zone intersect with a small obstacle or the bucket touches the obstacle buried in a deep position, the resistive force measured by a force sensor is increased. But this increase in the force data can not be detected using visual information. This is due to the fact that, in this cases, the existence of the object does not affect the shape of the soil failure zone.

Therefore, approach or contact of the bucket to obstacles can be detected when the estimated resistive force, using visual data, is different from the resistive force measured by the force sensor.

2.2 Detection of approach and contact of the bucket to big obstacles buried in a shallow position

When the bucket approaches big obstacles buried in a shallow position, as shown in Fig.5(d), the resistive force acting on the bucket, measured by a force sensor, increases. At this time, since progress on the soil failure surface is obstructed with the obstacle, the inclination of soil failure surface, which is β in Fig.4, increases. In this case, the resistive force calculated from (1) increases too, and the difference between the calculated resistive force and the measured force by force sensor may be too small to detect approach and contact of the bucket to obstacles. The inclination of soil failure surface, which is β in

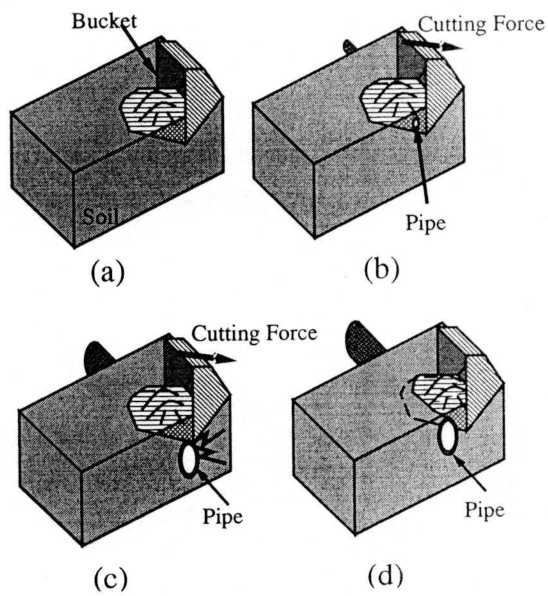

Figure 5: Approach and Contact of the Bucket to an Obstacle

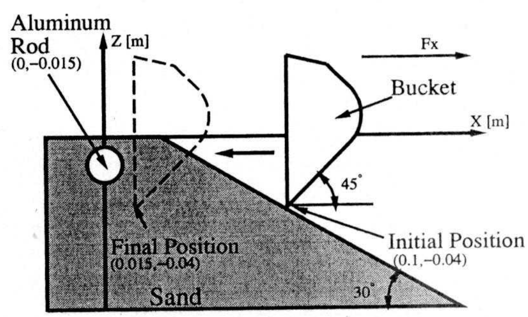

Figure 6: Digging Experiment

Fig.4, takes the value by which N_γ in (2) is minimized [5].

$$N\_\gamma = \frac{r}{2d}(1+\frac{2s}{3w})/\{\cos(\alpha+\delta)+\sin(\alpha+\delta)\cot(\beta+\phi)\} \quad (2)$$

The bucket is considered to approach or contact to big obstacle buried in a shallow position, when β measured by vision differs from β which minimizes N_γ.

3. Digging Experiments

3.1 Experiment method and the system

To confirm the effectiveness of our proposed method, two excavating experiments, when an obstacle was buried and wasn't, were executed. In these experiments the robot, on which a bucket was installed, dug the bank (schematically shown in Fig.6) that was made of dry sand. Fig.7 shows the robot used in the experiments. The resistive force acting on the bucket was measured with a six-axis force sensor, which was installed between the

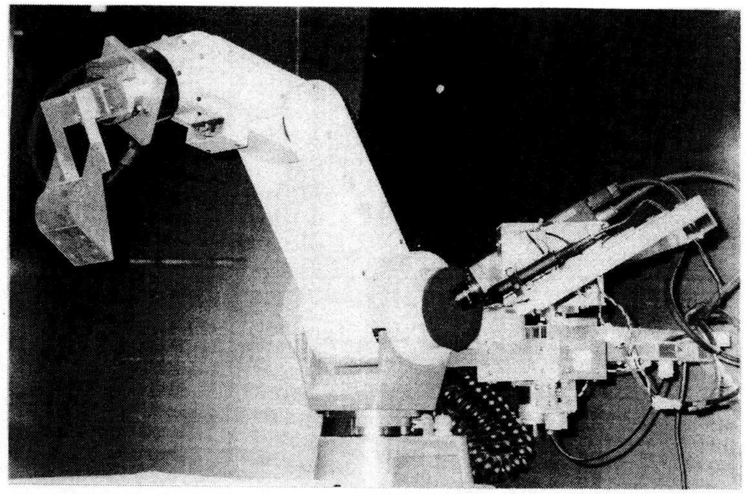

Figure 7: The Robot System

bucket and the robot arm. To detect the shape of the ground, a slit laser projector and a CCD camera were fixed on the mount which had two degrees of freedom. This mount was installed on side of the robot. The shape of the ground was measured by moving the vision system after digging. The aluminum rod of 10mm radius was put in the bank with its center at 15mm depth as an obstacle. The target position of the bucket was set where the bucket didn't contact with the obstacle.

3.2 Experiment Results

Figs.8-10 show the measured results of the shape of the ground. After digging, the rising height of the surface doesn't almost change whether an obstacle is buried in or not. Compared to the case when the obstacle isn't buried, parameter r (in Fig.4) is 2cm shorter when the obstacle is put in the sand.

3.3 Comparison of the measured and the estimated resistive forces

The resistive force is estimated from the change in the shape of the ground. The resistive force of the crescents at the sides of the blade (Fig.4) isn't included in the calculations, because the shape of the crescents isn't clear. The soil parameters are assumed as: $c = 0[kPa]$, $c_a = 0[kPa]$, $\delta = 23[deg]$, and $\phi = 35[deg]$. The value of γ is measured before doing the experiments. Fig.11 shows the measured resistive force by using a force sensor and the estimated resistive one, which are calculated using visual data, when the bucket approaches the obstacle most. When an obstacle is buried, as the bucket comes closer to the obstacle the bigger the resistive force becomes. On the other hand, the resistive force estimated by vision isn't affected by the existence of an obstacle. The estimated resistive force by using vision is different from measured resistive force by using a force sensor.

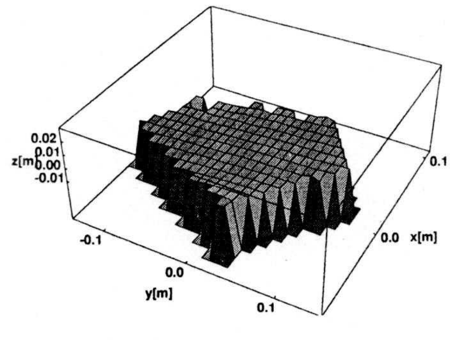

Figure 8: The Shape of the Ground before Excavation

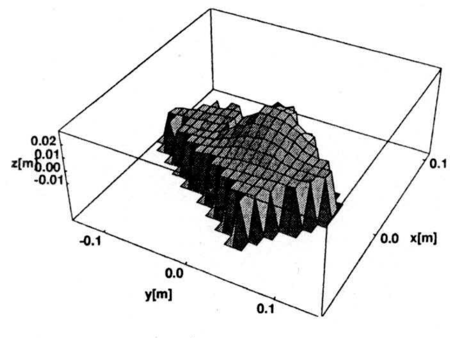

Figure 9: The Shape of the Ground after Excavation when an Obstacle is not Buried

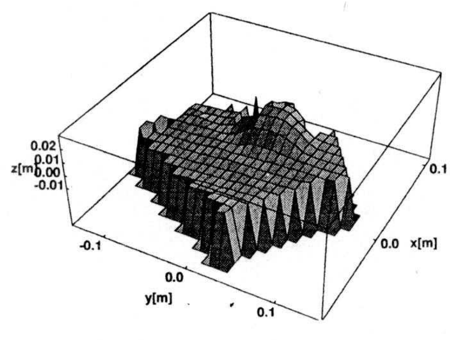

Figure 10: The Shape of the Ground after Excavation when an Obstacle is Buried

Mckyes' model doesn't consider the resistive force acting on the sides of the bucket. In one experiment, the resistive force when the resistive force of two sides of the digging blade is dominant and there is no obstacle in the ground, is measured. This force is added to the estimated resistive force, when an obstacle is buried. The resulting force is shown in Fig.11.

When an obstacle isn't buried and the resistive force acting on the sides of the bucket isn't considered, the estimated resistive force is about 50% of the measured one. But, if the resistive force acting on the sides of the bucket is added, the estimated resistive force is about 70% of the measured resistive force.

If an obstacle is not buried in the ground, the estimated resistive force and the mea-

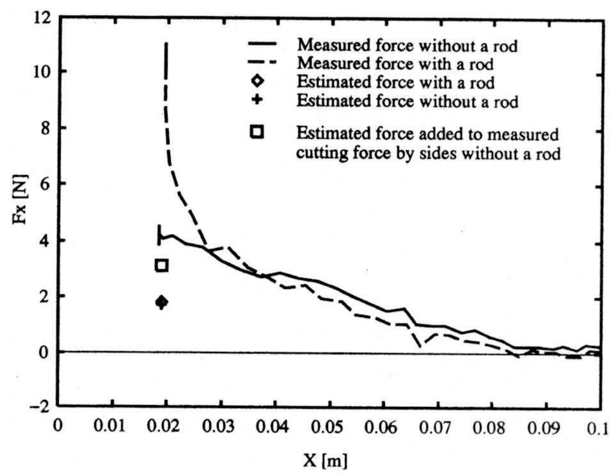

Figure 11: Measured Resistive Force and Estimated Resistive Force

sured one are relatively close to each other. But, in presence of the obstacle, the estimated resistive force and the measured force are quite different. Therefore, as stated before, it is possible to detect contact and approach of the bucket to obstacles by comparing the estimated resistive force and the measured one.

4. Conclusion

In this report, using visual and force sensory data, a new method for detecting approach and contact of the bucket to underground obstacles during excavation is proposed. Also, the effectiveness of studied method was confirmed by the experiments. Moreover, to improve the sensitivity of detection, resistive force acting on the sides of the bucket must be included in the model of the bucket applied in this study.

Acknowledgments

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References

[1] E. Nakano, et al., "Development of an Advanced Way of Improvement of the Maneuverability of a Backhoe Machine," 9th Int. Symp. on Automation and Robotics in Construction, pp.215-222, 1992.

[2] D. Seward, D. Bradley, R. Bracewell, "The Development of Research Models for Automatic Excavation," 5th Int. Symp. on Robotics in Construction, pp.703-708, 1988.

[3] H. Herman, S. Singh, "First Results in Autonomous Retrieval of Buried Objects," Automation in Construction, No.4, pp.111-123, 1995.

[4] K. Kosuge, et al., "Robot Force Control for Construction Work of Subterranean Line," Proc. of 13th Annual Conf. of RSJ, pp.719-720, 1995.

[5] E. Mckyes: "Soil Cutting and Tillage," Elsevier Science Publishers B.V. (1985).