AUTOMATIC SYSTEM FOR BOULDER BREAKAGE BY USING FORCE SENSORS AND IMAGE PROCESSING

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Abstract: In this study, the automatic system for boulder breakage by using force sensors and image processing is investigated. In order to carry out the full automation of the boulder breakage, the following three subtasks have to be automated: 1)detection of the boulder, 2)control of the chisel to move to the boulder and 3)carrying out the boulder breakage. In this paper, the algorithm to automate the 3) task was proposed. The control algorithm was constructed by using the features from the signals of force sensors and ones from image processing. It was confirmed through the experiments that the algorithm proposed here worked well.

Keywords: Robotics, Boulder breakage, Image processing, Force sensor, Breaker

1 INTRODUCTION

In Japan, most limestone quarries utilize the vertical shaft to deliver rocks into a crusher as shown in Figure1. That is, rocks, usually carried by a dump truck from the working face to the vertical shaft, are dropped into the vertical shaft and fed to the crusher. However, over-size boulders delivered to the crusher may cause damage. Therefore, a grizzly bar is usually placed above the crusher to catch the boulders. These boulders will then be broken by a hydraulic breaker. However, as the working environment in the breaking room is not a favorable one for workers because of dust and machine vibration, some quarries utilize a remote controlled breaking system which enables the operators to work in a clean environment. But, this requires skill to operate the hydraulic breaker to avoid blockage. Therefore, recently, automation of the task of boulder breakage has received considerable attention.

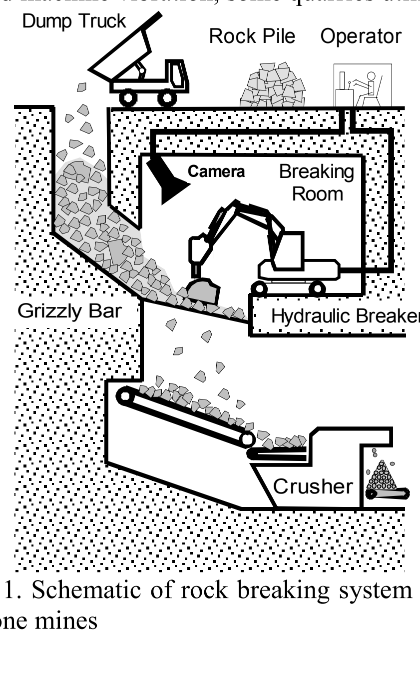


Figure 1. Schematic of rock breaking system used in limestone mines

In order to automate the detection and breakage of boulders, an intelligent work robot is necessary. This robot is required to have the ability to recognize the working environment and to perform the task autonomously because the position of the boulder varies and the shape of the boulder is not uniform (Corke et al. 1997[1], Takahashi and Sano 1997[2], Takahashi and Sano 1997[3]).

Figure 2 shows the automatic system for the detection and breakage of boulders proposed in this study. This system will be used not only in the limestone quarries but also in the tunnel construction site. This process consists of the following three steps:

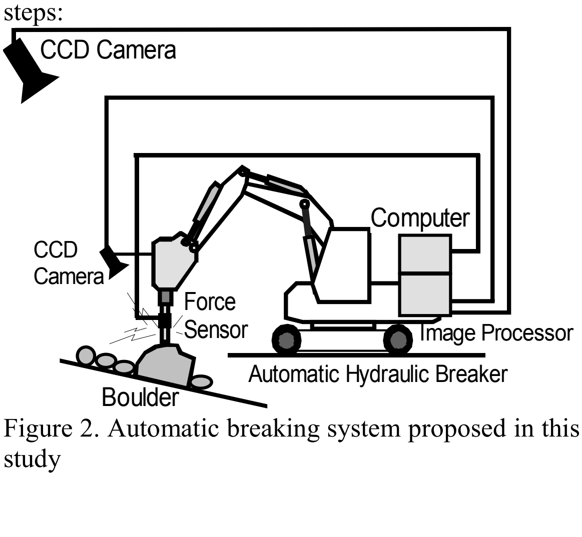


Figure 2. Automatic breaking system proposed in this study

1) Automatic detection of a boulder by image processing.
2) Measurement of the boulder position and control of the breaker tip (chisel) to move to the surface of the boulder.
3) Carrying out the breaking task by impacting the boulder.

Corke et al.(1997)[1] investigated the application of stereo-vision for the three-dimensional assessment of boulders on the grizzly bar. It is well known that stereo-vision is an useful technique to obtain three-dimensional information of an object. But, recognition of the boulders is necessary before any three-dimensional assessments can be performed. The authors have already investigated the image processing system to detect the boulders and measuring system of boulder position by using the CCD camera and laser spot (Takahashi and Sano 1997[2], Takahashi and Sano 1997[3], Takahashi and Sano 1999[4]). After a boulder is broken in task 3), the machine must be terminated immediately because powerless impacts would ruin the machine. That is, in order to achieve the automation of task 3), an algorithm to recognize boulder breakage is required. The authors tried to construct the algorithm to judge the boulder breakage by using force sensors (Takahashi and Monden, 1999[5]). However, the rate of success of judgment was about 80% and it was pointed out that sensor fusion technique would be necessary in order to increase the reliability.

Therefore, the objective of this study is to propose a system that is able to detect the breakage of boulders using the force sensors and image processing.

2 OBTAINING THE INFORMATION FROM FORCE AND VISION SENSORS

2.1 Experimental apparatus

Figure 3 shows the schematic diagram of the experimental apparatus used in this study. Strain gauges were used as the force sensors and they were attached beside of the chisel of the hydraulic breaker. Furthermore, two CCD cameras were used as the vision sensors. CCD camera 1 is used to detect the position of the boulder and fixed on the frame of the experimental apparatus. CCD camera 2 is an onboard camera and is attached beside the breaker. Therefore, this camera is movable with the breaker. In this experiment, firstly, the position of the boulder is obtained by processing the image from the CCD camera 1. Based on the information obtained from above mentioned image processing, the chisel of the hydraulic breaker is controlled to move to the surface of the boulder. After the chisel moves to the boulder, then the image of boulder is obtained by the CCD camera 2, and this image is processed to detect the information of the boulder breakage after impacting.

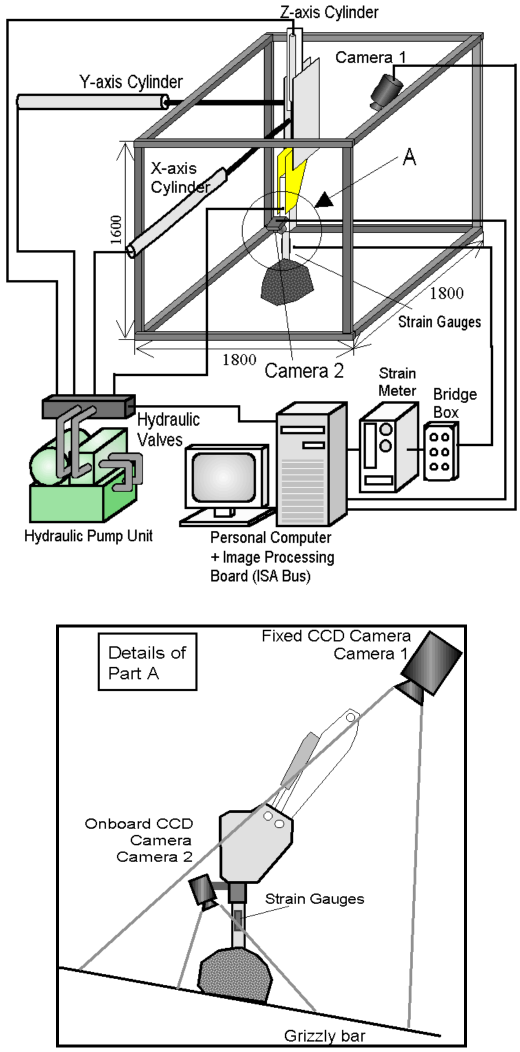


Figure 3. Schematic diagram of experimental apparatus

In this experiment, an actual hydraulic breaker was used. The tip of the chisel was flat and the diameter of the chisel was 40mm. As the actual hydraulic breaker was heavy(75kg), three hydraulic cylinders were used to control the breaker movement. The area of hydraulic breaker movement was 1000mm(X-axis)*1000mm(Y-axis) *600mm(Z-axis).

Figure 4 shows the schematic diagram of the measurement system. Impacting frequency was

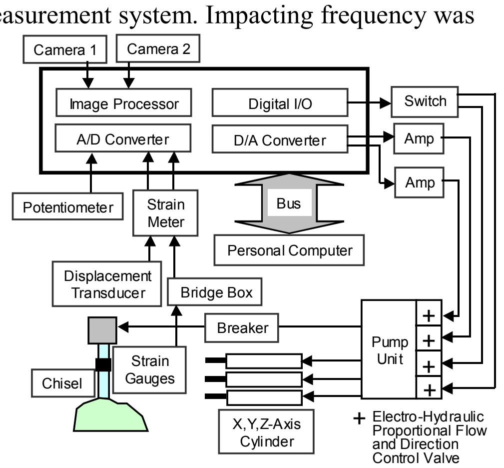


Figure 4. Schematic diagram of measurement system

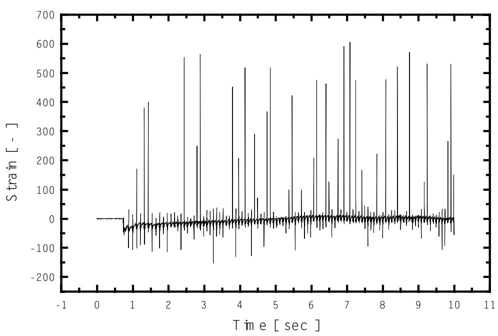
variable within the range of 700-1300[bpm] by changing the flow rate of the pump unit. In this experiment, impacting frequency was set at 1000 [bpm]. The image processing board used in this experiment was IP-2000 manufactured by HITACHI Co.Ltd. in Japan. The analog image is converted into digital image of 512*512 pixels. Each pixel has 256 gray level intensities.

In this experiment, after the position of the boulder is detected, the chisel is controlled to move to the position of the boulder. When the chisel reaches to the surface of the boulder, the chisel pushes the boulder. Then, the strain is set to be zero and the impacting is given to the boulder by the hydraulic hammer of the machine. Total impacting time was set to be 10 seconds because long time impacting may cause damage of the hydraulic breaker. That is, impacting is stopped after 10 seconds even if the boulder is not broken.

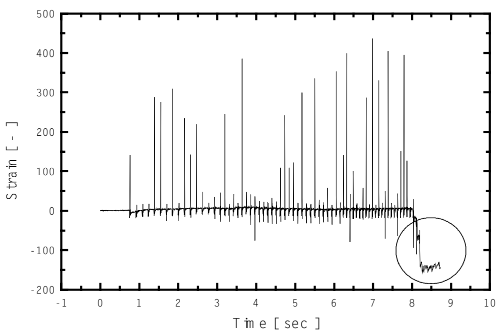
The rock samples were Andesite and Limestone, and the approximate size of these rocks was 350mm.

2.2 Examples of the measurement results

Figure 5 shows an example of the strain data while impacting the boulder by the hydraulic breaker. Figure 5(a) and (b) show the strain data in the case of unsuccessful and successful breakage, respectively. Sampling frequency of the strain data was 200Hz. Large spikes of the strain can be seen in the strain data, which correspond to the impacting the boulder.



(a) unsuccessful breakage

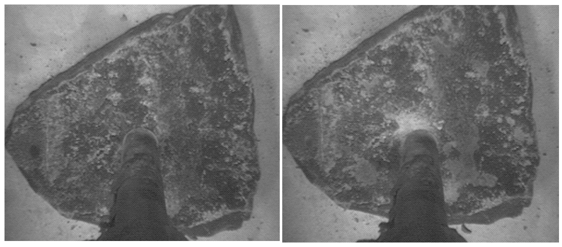


(b) successful breakage

Figure 5. Examples of the strain data while impacting the boulder by the hydraulic breaker

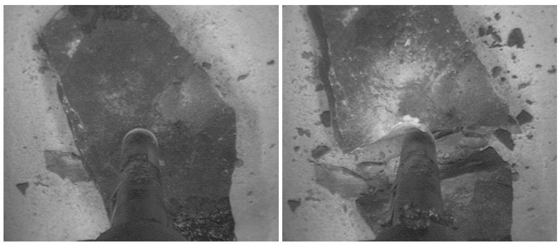
In the case of unsuccessful breakage, significant change of the strain data is not observed. On the other hand, in the case of successful breakage, strain data decreased rapidly at the boulder breakage, and after the boulder is broken, no spikes of the strain are observed (refer to the circle in (b)). Therefore, it can be considered that the difference of the feature in the strain data will be used to construct the intelligent judgment system of boulder breakage.

Figure 6(a) and (b) show the example of the image in the case of unsuccessful and successful breakage of the boulder, respectively. It is clear that the image after the boulder is broken is much different from the image before impacting the boulder. Therefore, the correlation between two images will give useful information for the intelligent judgment system of the boulder breakage.



Before impacting After impacting

(a) Image of unsuccessful breakage of the boulder



Before impacting After impacting

(b) Image of successful breakage of the boulder

Figure 6. Examples of the image in the case of unsuccessful and successful breakage of the boulder

3 ALGORITHM OF JUDGMENT SYSTEM FOR BOULDER BREAKAGE

As mentioned above, after the chisel pushes the boulder, the strain is set to be zero, and then impacting is given to the boulder. When the boulder is broken, as the chisel usually goes downward rapidly, the strain stored in the chisel is released. Therefore, large negative strain is observed at the boulder breakage. Furthermore, the significant difference between the strain wave in unsuccessful and successful breakage is that the spikes are not observed after the boulder is broken. Therefore, it is inferred that the rate of strain change will be almost zero after boulder breakage. In this study, the rate of strain change is defined as follows:

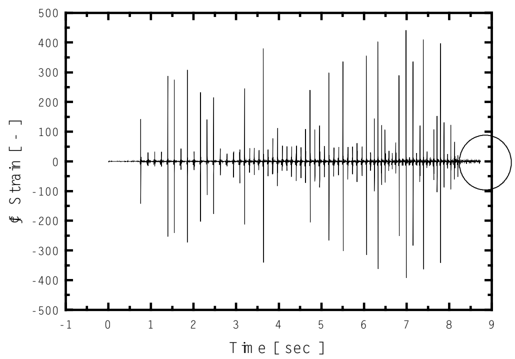
$$\Delta S = S_i - S_{i-1} \tag{1}$$

S_i and S_{i-1} are strains at t=i and t=i-1, respectively. In this experiment, as the sampling frequency was 200Hz. Therefore, the time interval of t=i and t=i-1 is 1/200[sec.]. Figure 7 shows an example of the rate of strain change in unsuccessful and successful breakage. In the case of successful breakage, no spikes are observed in a certain time after the breakage (refer to the circle in (b)). So, the following algorithm was constructed:

"If the following both conditions are satisfied, then it is judged that the boulder is broken:
1) Rate of strain change ΔS is successively less than the threshold value, ε_b over a certain time interval ΔT, which will be determined by the impacting frequency.
2) The large negative strain is smaller than the threshold value, S_m."

The threshold value ε_b and S_m were determined by trial and error method and they were 15 and -80, respectively.

(a) Unsuccessful breakage

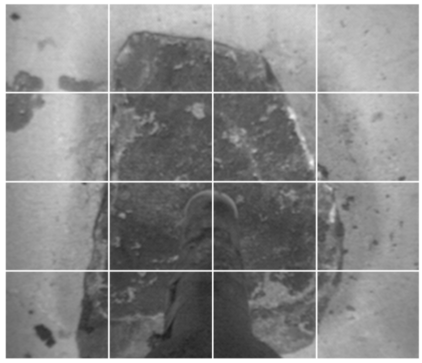


(b) Successful breakage

Figure 7. An example of the rate of strain change in unsuccessful and successful breakage

The next, in order to detect the difference between two images before and after impacting, the standardized cross correlation function was used. This function is generally used in template matching and is given by

Before impacting



After impacting

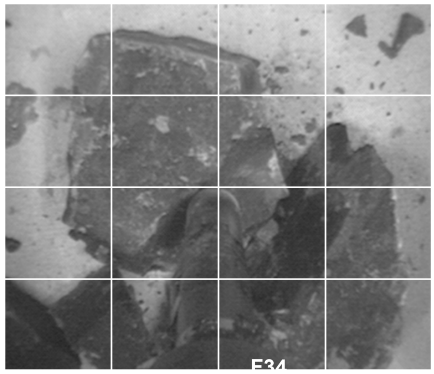


Figure 8. An example of template and target image

$$\sigma(x,y)=\frac{\sum_i\sum_j\{F(i,j)\cdot A(i-x,j-y)\}}{\sqrt{\sum\sum F^2(i,j)\cdot\sqrt{\sum\sum A^2(i-x,j-y)}}} \qquad (2)$$

Here, A(i,j) and F(i,j) are template image and target image for template matching, respectively. If two images are perfectly the same, then σ becomes unity. Usually it needs a long time to carry out template matching. Therefore, in order to reduce the calculation time, the image is divided into 16 areas as shown in Figure 8 and cross correlation function of each area is calculated from the next equation.

$$\sigma=\frac{\sum_i\sum_j\{F(i,j)\cdot A(i,j)\}}{\sqrt{\sum\sum F^2(i,j)\cdot\sqrt{\sum\sum A^2(i,j)}}} \qquad (3)$$

Then 16 values of the function are obtained.

By the way, it can be seen from Figure 6(b) that the change of the image is large in the outer area of the image because broken fragments scattered by impacting. Therefore, if the weight of the outer area is set to be large, it can be considered that correlation function will be more sensitive. So, the cross correlation function of the whole image was calculated from the next equation.

$$\sigma_s=w_b\begin{pmatrix}\sigma_{11}+\sigma_{12}+\sigma_{13}+\sigma_{14}+\sigma_{21}+\sigma_{24}+\sigma_{31}+\\ \sigma_{34}+\sigma_{41}+\sigma_{22}+\sigma_{43}+\sigma_{44}\end{pmatrix}$$
$$+\sigma_{22}+\sigma_{23}+\sigma_{32}+\sigma_{33}$$

$$\sigma=\frac{\sigma_s}{12w_b+4} \qquad (4)$$

In the case of successful breakage, cross correlation function will be small. So, the following algorithm was constructed:

"If the cross correlation function calculated from Eq.(3) is less than the threshold value, σ_i, then it is judged that the boulder is broken."

The weighted value, w_b and threshold value, σ_i were determined by trial and error method and they were 3 and 0.5, respectively.

4 RESULTS OF CONTROL EXPERIMENT

The first, several experiments were carried out. The following fact was confirmed through these experiments: When the boulder was broken largely, the large negative strains were obtained at the boulder breakage as shown in Figure 5(b). In this case, the algorithm based on the force sensor worked well. However, some boulders were not broken largely, and broken fragments of rocks still remained in the original position after the boulder was broken. In this case, as large negative strains were not obtained, the algorithm was not able to judge the boulder breakage and the breaker continued impacting in spite of boulder breakage. Figure 9 shows a photograph in this case, and Figure 10 shows the strain data corresponding to Figure 9. As shown Figure 9, the boulder was surely broken. However, as rock fragment exists under the chisel. This means that the chisel is supported by the rock fragment, and in this case, large negative strains were not observed as shown in Figure 10.

Figure 9. A photograph of boulder breakage in case of the existence of the rock fragment under the chisel

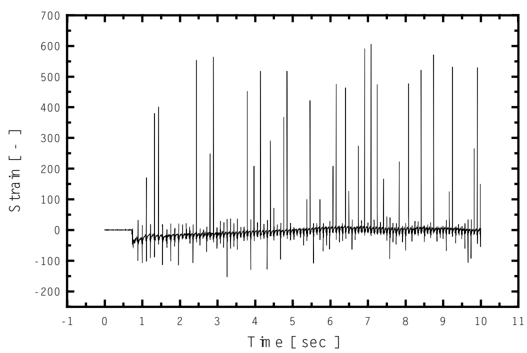
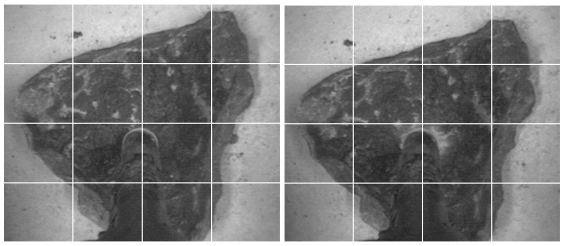
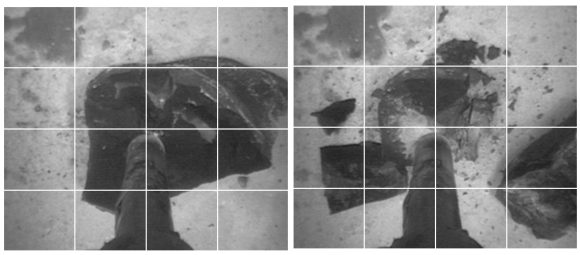


Figure 10. Strain data while impacting the boulder by the hydraulic breaker in the case of Figure 9

Figure 11(a) and (b) show the results of image processing in the case of unsuccessful and successful breakage. Figure 11(b) is the image in the case of Figure 9. As mentioned above, the algorithm based on the force sensors judged that the boulder was not broken for both cases. If the cross correlation function is calculated, it can distinguish successful and unsuccessful breakage. In the case of Figure 11(a), the cross correlation function is 0.752, on the other hand, it is 0.387 for Figure 11(b) and it is much smaller than 0.752. By analyzing 50 results of breakage, the threshold value for the cross correlation function was determined to be 0.5 by trial and error method. The processing time was within 1 second and it can be considered that this processing time is small enough to control the hydraulic breaker.



(a) σ=0.752



(b) σ=0.387

Figure 11. Results of image processing in the case of unsuccessful and successful breakage

As mentioned above, it was found from the analysis of the experimental results that if the algorithm based on the force sensor judges that the boulder is broken, then the boulder is surely broken. No error was observed. That is, the judgment is perfect. However, sometimes the algorithm judges that the boulder is not broken, in spite that the broken is surely broken. The algorithm based on the force sensor is able to judge the boulder breakage real time. This is a great advantage. Therefore, in this study, finally the following is proposed.

1) The first, the algorithm based on the force sensor judges the boulder breakage.

2) If the algorithm judges that the boulder is broken, then breaking task is stopped.

3) If the algorithm judges that the boulder is not broken after 10 seconds impacting, the algorithm

based on the vision sensor confirms the breakage.

4) If the algorithm based on the vision sensor judges that the boulder is broken, then the breaking task is stopped.

5) If the algorithm based on the vision sensor judges that the boulder is not broken, then continue impacting for more 10 seconds.

The experiments of detecting the boulder breakage were carried out by using the final algorithm proposed above. The results are shown in Table 1.

Run No.	Exp.	Judgment by Force Sensor	Judgment by Vision Sensor σ		Result of judgment by the algorithm	Remarks
01	□	□			□	S
02	□	□			□	S
03	□	×	□	0.387	□	S
04	□	□			□	S
05	□	□			□	S
06	□	□			□	S
07	□	□			□	S
08	×	×	×	0.739	×	S
09	□	□			□	S
10	□	□			□	S
11	□	□			□	S
12	□	□			□	S
13	□	□			□	S
14	□	□			□	S
15	□	□			□	S
16	□	□			□	S
17	□	□			□	S
18	□	□			□	S
19	×	×	×	0.769	×	S
20	□	□			□	S
21	□	×	□	0.451	□	S
22	□	□			□	S
23	□	□			□	S
24	□	□			□	S
25	×	×	×	0.78	×	S
26	□	□			□	F
27	×	×	×	0.554	×	S
28	□	×	□	0.411	□	S
29	□	□			□	S
30	×	×	×	0.645	×	S
31	□	□			□	S
32	×	×	×	0.738	×	S
33	□	□			□	S
34	×	×	×	0.752	×	S
35	×	×	×	0.545	×	S
36	□	□			□	S
37	×	×	×	0.605	×	S
38	×	×	×	0.747	×	S
39	×	×	×	0.847	×	S
40	×	×	×	0.749	×	S
41	□	□			□	S
42	□	□			□	S
43	□	×	□	0.422	□	S
44	□	□			□	S
45	□	□			□	S

Table 1 Results of the experiment of detecting the boulder breakage

Circle: Successful breakage, Cross: Unsuccessful breakage, Black triangle: Boulder was shifted while impacting., S: Success of judgment, F: Failure of judgment, The threshold value of σ is 0.5.

45 experiments were carried out, but only one misjudgment was occurred. The rate of success was 98%. Only misjudgment was occurred when the boulder was shifted while impacting the boulder. In this case, as the boulder moved from the chisel, the large negative strain was obtained and no spikes were observed in ΔT. Therefore, the algorithm based on the force sensor judged that the boulder was broken in spite of unsuccessful breakage. Therefore, further modification is needed in this algorithm, but the rate of success was 98% and it is considered that the algorithm proposed here works quite well.

5 CONCLUSIONS

In this study, an intelligent judgment system of detecting the boulder breakage was proposed by using the force sensors and vision sensors. The advantage of the force sensor is that real time judgment is possible. Therefore, the first judgment of boulder breakage was carried out by using force sensors. If the algorithm based on the force sensor judges that the boulder is broken, the breaking task is stopped because the possibility of misjudgment is extremely low. If the algorithm based on the force sensor judges that the boulder is not broken, the algorithm based on the vision sensor was used to judge the breakage. It was confirmed through the experiments that the algorithm proposed here works quite well.

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