Detection of Abnormal Movement of Industrial Robots Using Image Sequence

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Abstract—**In this paper, a monitoring system for industrial robots working in factories is proposed. This system automatically detects different movement from reference and immediately reports to the operator. It has the advantage that there is no need to receive any signal from the robot controller because it only observes with a simple camera such as CCD. For the detection method, Eigenspace Method is used which is excellent in compression of image data and calculation of the correlation among images. Parametric Eigenspace Method(PEM) is also used to detect abnormalities such as the speed of movement. Some experiments using 2-axis robot show the effectiveness of the proposed method.**

I. INTRODUCTION

It is important that faults of the elements and mistaken movements are surely detected to avoid the dangerous condition in various equipments including industrial robots. Artificial operation mistakes and abnormalities of input signal and controlled system have potentialities to cause a lot of damage to the surroundings including the human. For example, false movement of industrial robot brings about various accidents such as throwing the object out at fault.

Majority of the industrial robots in the world are operating in Japan, and many accidents to death relative to industrial robots are also happened in Japan[1].

It is needless to say that a high reliable system is required to keep the safety in industrial robots. Now, high reliable self fault diagnosis function is necessary, and CPU, I/O interface, power supply equipment and servo system are monitoring and detect faults in real time[2]. For example, in the current factories, the servo system and controller detect abnormalities such as overcurrent, overheating, excess of the error and settling time, and the system is stopped.

On the other hand, as an approach in analytical model, it has been shown that faults of the elements such as actuators and sensors can be detected using disturbance observer[3].

However, such systems depending on the robot itself don't have high reliability. For example, when the robot vibrates and its axis bends because of bellying up by large acceleration, the servo system and controller judge it normal though the end of robot don't move accurately. Thus, there are some abnormalities which cannot be detected by the current system. In addition, it is any longer impossible to detect abnormalities when sensors and actuators break down. Therefore, it has been recognized that a new abnormality detection system independent of the robot system itself is required.

In this paper, it is attempted for the first time to detect various abnormal movements of industrial robot by observing with a simple camera such as CCD and the detection method is proposed.

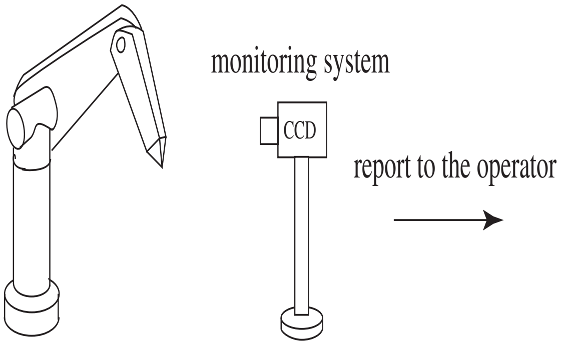


Fig. 1. Realization of a monitoring system for industrial robots

This system needn't receive any signal from the robot controller because it only observes with a camera. This system is independent of the robot.

It is required to realize a simple and nonexpensive system bacause there are many industrial robots in the factory. The proposed system only observing with a camera such as CCD meets the requirements.

II. ABNORMALITY DETECTION USING IMAGE SEQUENCE

A. Realization of a monitoring system

Monitoring system of industrial robot is realized as shown in Fig.1. A camera is set by the robot and the system reports to the operator as soon as it detects abnormal movement. The robot is supposed to repeat the teached movement.

This system has the following advantages:

1. We don't need to go about to observe the robots in the factory and are safe from danger.
2. We can grasp the situation early and exactly by the obtained image sequence when some accident occurs.
3. This system is inexpensive because a simple camera such as CCD is used.
4. There is no need to receive any signal from the robot

controller because it only observes with a camera. This system is independent of the robot.

5. It is easy to install to any industrial robots.

B. Classification of abnormalities detected with a camera

Abnormalities of industrial robots which can be detected by image information are classified as follows:

[Ab-I] Different movement from reference

If the robot moves differently from the teached trajectory, the system should judge it abnormal, for example, moving roundly without passing the teached square trajectory when it moves in high speed, and vibrating a little when it stops.

[Ab-II] Speed of movement

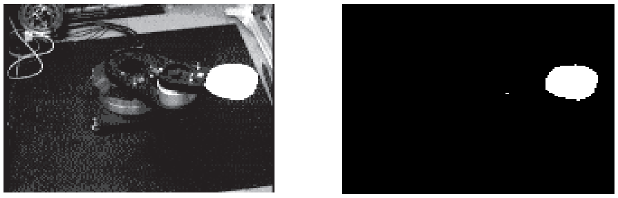
Even if the robot moves on the same trajectory as the reference, quicker or slower movements than reference including making a stop are abnormal.

[Ab-III] Pass partialy on the teached trajectory

It is abnormal when it moves partialy on the teached trajectory, for example coming in contact with the obstacle.

C. Extraction of the end of robot

It is difficult to extract the region of the robot manipulator by simple subtraction because the background image in the factory is very complicated. It can be tracked using optical flow and edge[4], however, computation time should be shorten as much as possible. Therefore, it is appropriate to attach a colored marker to the end of robot and extract it using color information. In this experiment, a white marker is attached and extracted by simple binarization as shown in Fig.2.



(a) Original image

(b) Extraction result by binarization

Fig. 2. Extraction of the end of robot

A monitoring system for aged people to detect his/her abnormal action and behavior using image sequence has been proposed[5]. By measuring the correlation among images using Eigenspace Method, abnormal action and the speed of action have been detected. In this study, abnormal movements of industrial robot are also detected based on this method.

III. LEARNING OF USUAL MOVEMENT

A. Eigenspace Method

The theory of Eigenspace Method applied to the image data is described[6][7]. An normalized image data at time t is represented as $\boldsymbol{y}(t)$. The covariance matrix of image data set $\boldsymbol{y}(t)$ is represented by

$$\boldsymbol{Q} = \sum_{t=1}^{T} (\boldsymbol{y}(t) - \boldsymbol{c})(\boldsymbol{y}(t) - \boldsymbol{c})^T \tag{1}$$

where $\boldsymbol{c}$ is the mean vector for $\boldsymbol{y}(t)$. k eigenvectors $\boldsymbol{e}_1, \boldsymbol{e}_2, \cdots, \boldsymbol{e}_k$ $(\lambda_1 \geq \cdots \geq \lambda_k \geq \cdots \geq \lambda_K)$ are determined by solving eigenvalue problem:

$$\lambda_j \boldsymbol{e}_j = \boldsymbol{Q}\boldsymbol{e}_j \tag{2}$$

The k-dimensional subspace spanned by these k eigenvectors corresponding to k large eigenvalues is called the eigenspace. By ignoring the small eigenvalues, dimension of the image data is reduced. The cumulative proportion of eigenvalues in equation (3) and the threshold generally set 0.8 or 0.9 determine the effective dimension.

$$W_k = \frac{\sum_{i=1}^{k} \lambda_i}{\sum_{i=1}^{K} \lambda_i} \geq T_s \tag{3}$$

Then, one image vector $\boldsymbol{y}(t)$ is projected onto the eigenspace by

$$\boldsymbol{z}(t) = [\boldsymbol{e}_1, \cdots, \boldsymbol{e}_k]^T (\boldsymbol{y}(t) - \boldsymbol{c}) \tag{4}$$

It has been proved that when two images $\boldsymbol{y}_m$, $\boldsymbol{y}_n$ are projected on the points in the eigenspace $\boldsymbol{g}_m$, $\boldsymbol{g}_n$, the distance between the two projection points $\|\boldsymbol{g}_m - \boldsymbol{g}_n\|$ is small if the correlation $\boldsymbol{y}_m^T \boldsymbol{y}_n$ is large[6]. Therefore, the closer the projections are in the eigenspace, the more highly correlated the images are. In addition, it is possible to compress the image data about four or five order because the image data is about 10000 $\sim$ 100000 dimension and the vector in the eigenspace is 3 or 4 dimension. Therefore, Eigenspace Method is very excellent in calculation of the correlation among images and compression of image data, and this method has been applied to face recognition[8] and jesture recognition[9].

In this study, it is considered that the images of abnormal movement different from reference has low correlation to the reference images, and they are detected using the distance among the projection points in the eigenspace.

B. Parametric Eigenspace Method(PEM)

An image can be mapped to a point in the eigenspace, therefore a sequential movement can be represented as a smooth locus in the eigenspace as shown in Fig.3. This is called Parametric Eigenspace Method(PEM). For example, the object's pose, the light source direction[6] and time[7] are selected as a parameter for object recognition and human motion analysis.

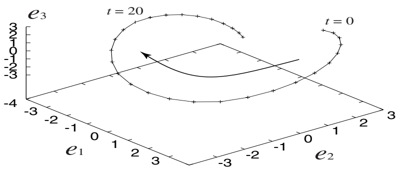
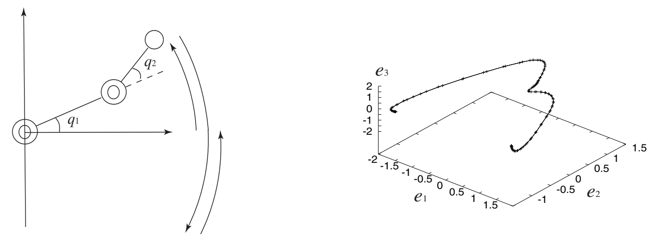


Fig. 3. Parametric Eigenspace Method

C. Representation of usual movement

In the learning stage, correct movement of the robot is represented as the set of projection points in the eigenspace. The eigenspace is constituted from the image set capturing the correct movement and the projection points are stored.

In this experiment, sinusoidal position reference is given to each joints of 2-axis robot and it moves like a pendulum as shown in Fig.4(a). Then, the eigenspace constituted from the obtained images is shown in Fig.4(b).



(a) Movement of the robot

(b) Projected points in the 3-dimensional eigenspace

Fig. 4. Learning of the normal movement

IV. DETECTION OF ABNORMAL MOVEMENT

A. Detection of abnormality I (Ab-I)

Different movement from reference can be considered that the images have low correlation to the reference images, therefore, the input image which is different from any reference images should be judged abnormal.

As discussed before, the closeness in the eigenspace represents the correlation among images, therefore, different movements from reference are detected as low correlation images by the distance in the eigenspace. The system computes the minimum distance d_1 between the projection points of the reference images $\boldsymbol{h}_i$ and the projection points of the input image $\boldsymbol{z}(t)$, and judges it abnormal if d_1 comes to be larger than a threshold d_{th}.

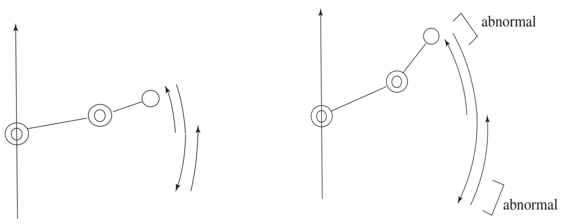
$$d_1^2 = \min_i \|\boldsymbol{z}(t) - \boldsymbol{h}_i\|^2 \quad (5)$$

$$d_1 > d_{th} \rightarrow \text{abnormal}$$

In this experiment, movements as shown in Fig.5 are used.

(Reference): Sinusoidal reference is given (Fig.5(a))

(Input): Double amplitude sinusoidal reference is given (Fig:5(b))

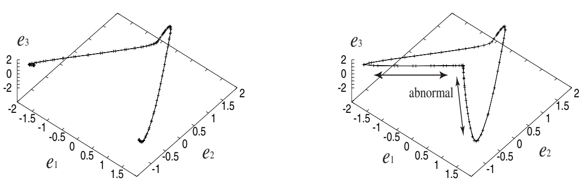


(a) Reference movement

(b) Input movement

Fig. 5. Experiment to detect abnormality I

Fig.6(b) shows the locus of the input image sequence projected onto the eigenspace constituted at the learning stage Fig.6(a). There are some projection points apart from the reference points.



(a) Reference points

(b) Input points

Fig. 6. Projected points in the 3-dimensional eigenspace

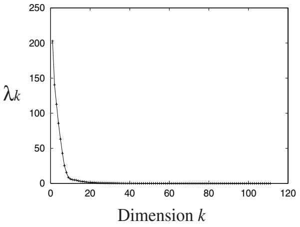


Fig. 7. Eigenvalues

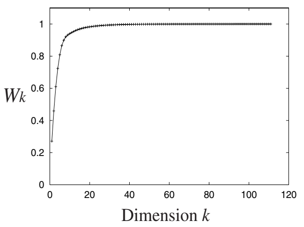
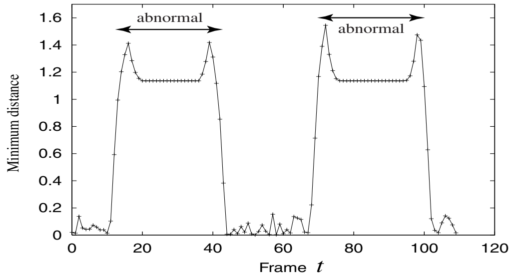
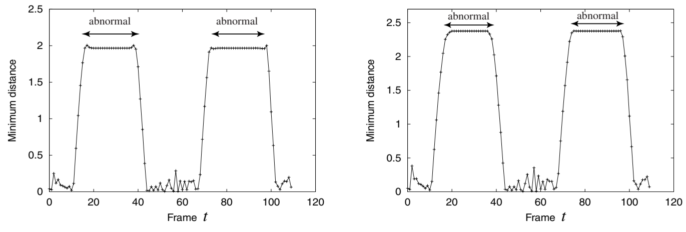


Fig. 8. Cumulative proportion of eigenvalue

Cumulative proportion of eigenvalue W_k are shown in Fig.8 and it is found that $W_7 = 0.9$. Fig.9(a)∼(c) show the minimum distances in the eigenspaces d_1 whose dimensions are 3, 5 and 7. d_1 comes to be large when the robot moves to the outside, therefore, they can be detected by the threshold, for example, $d_{th} = 0.5$ in 3-dimensional eigenspace. 3-dimensional eigenspace is enough to detect different movement.



(a) 3-dimension



(b) 5-dimension

(c) 7-dimension

Fig. 9. Minimum distances in the eigenspace d_1

B. Detection of abnormality II (Ab-II)

It is impossible to detect the speed of robot using the above method because equation (5) compares among the static images, therefore, the method to compare between image sequences is required. For this reason, using Parametric Eigenspace Method[7], the loci in the eigenspace are compared. The distance between the image sequences is defined as the distance between the loci in the eigenspace as shown in equation (6).

$$d_2^2 = \min_{a,b} \sum_{t=1}^{T} \|\boldsymbol{z}(t) - \boldsymbol{h}(at+b)\|^2 \tag{6}$$

$$\tilde{a} = \{\ a \mid \min_{a,b} \sum_{t=1}^{T} \|\boldsymbol{z}(t) - \boldsymbol{h}(at+b)\|^2 \} \tag{7}$$

where t is time, a is the time stretch factor, and b is the time shift factor. By introducing these two parameters a, b, reference locus $\boldsymbol{h}(t)$ closest to the projection locus of the input image sequence is searched. Then, it can be considered that the absolute value of $\tilde{a}$ represents the speed of movement and the sign of $\tilde{a}$ represents the direction of movement. That is,

if	$\tilde{a} < -1$,	opposite direction, quickly
if	$-1 \leq \tilde{a} < 0$,	opposite direction, slowly
if	$0 \leq \tilde{a} < 1$,	same direction, slowly
if	$1 \leq \tilde{a}$,	same direction, quickly

Here, a search by golden section, what is called Golden Section Method, is applied to the calculation of the equation (6). The right side of equation (6) is a function having two variable a, b.

$$f(a,b) = \sum_{t=1}^{T} \|\boldsymbol{z}(t) - \boldsymbol{h}(at+b)\|^2 \tag{8}$$

Fig.10 shows the graph of $f(a,b)$. It turns out that $f(a,b)$ is a unimodal function, therefore, 2-dimensional Golden Section Method can be used to search the minimum value of $f(a,b)$.

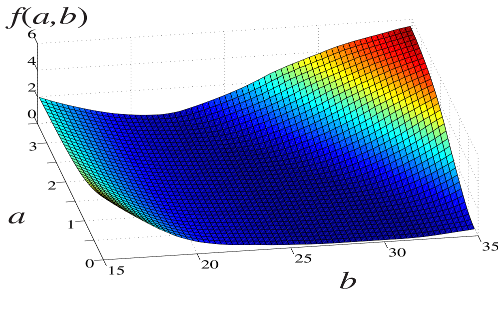


Fig. 10. $f(a,b)$

In the case of one variable function, search range is divided by the golden ratio and narrowed according to size of $f(u^k), f(v^k)$ as shown in Fig.11. Then, there is no need to compute $f(u^{k+1})$ because $v^k = u^{k+1}$.

In the case of two variable function, as shown in Fig.12, gradient of $f(a,b)$ at an initial points $\boldsymbol{g}_1$ and the minimum value of $f(a,b)$ in that direction are computed, and it becomes a new trial point $\boldsymbol{g}_2$. This operation is repeated.

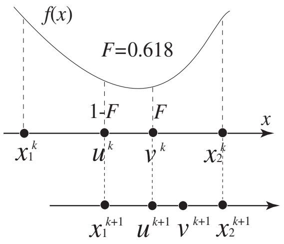


Fig. 11. Golden section method of one variable function

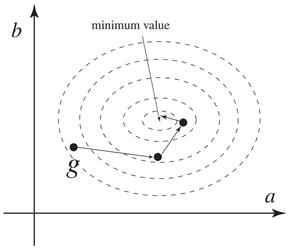


Fig. 12. Golden section method of two variable function

Algorithm of Golden Section Method for two variable function

Step1 Give an initial point $\boldsymbol{x}_1^1 = (a_1, b_1)^T$, and compute the gradient $\boldsymbol{g}$.

$$\begin{aligned}
\boldsymbol{g} &= \left.\frac{\partial f(\boldsymbol{x})}{\partial \boldsymbol{x}}\right|_{\boldsymbol{x}=\boldsymbol{x}_1^1} = \begin{pmatrix} \left.\frac{\partial f}{\partial a}\right|_{a=a_1} \\ \left.\frac{\partial f}{\partial b}\right|_{b=b_1} \end{pmatrix} \\
&= \begin{pmatrix} \frac{f(a_1+\Delta_a, b_1) - f(a_1-\Delta_a, b_1)}{2\Delta_a} \\ \frac{f(a_1, b_1+\Delta_b) - f(a_1, b_1-\Delta_b)}{\Delta_b} \end{pmatrix} \\
\boldsymbol{x}_2^1 &= (a_2, b_2)^T = \boldsymbol{x}_1^1 + \alpha_k \boldsymbol{g} \\
\boldsymbol{u}^1 &= \boldsymbol{x}_1^1 + (1-\gamma)\alpha_k \boldsymbol{g} \\
\boldsymbol{v}^1 &= \boldsymbol{x}_1^1 + \gamma \alpha_k \boldsymbol{g}
\end{aligned}$$

and compute $f(\boldsymbol{u}^1), f(\boldsymbol{v}^1)$, and let $k = 1$. $\gamma = 0.618\cdots$.

Step2 If $\|\boldsymbol{x}_2^k - \boldsymbol{x}_1^k\| < l_1$, compute $\boldsymbol{x}_{min} = \frac{\boldsymbol{x}_1^k + \boldsymbol{x}_2^k}{2}$, and go to Step5. If not, go to Step3.

Step3 If $f(\boldsymbol{u}^k) \geq f(\boldsymbol{v}^k)$, compute

$$\begin{aligned}
\boldsymbol{x}_1^{k+1} &= \boldsymbol{u}^k,\ \boldsymbol{x}_2^{k+1} = \boldsymbol{x}_2^k,\ \boldsymbol{u}^{k+1} = \boldsymbol{v}^k \\
\boldsymbol{v}^{k+1} &= \boldsymbol{x}_1^{k+1} + \gamma(\boldsymbol{x}_2^{k+1} - \boldsymbol{x}_1^{k+1}) \\
f(\boldsymbol{u}^{k+1}) &= f(\boldsymbol{v}^k)
\end{aligned}$$

and $f(\boldsymbol{v}^{k+1})$. If $f(\boldsymbol{u}^k) < f(\boldsymbol{v}^k)$, compute

$$\begin{aligned}
\boldsymbol{x}_1^{k+1} &= \boldsymbol{x}_1^k,\ \boldsymbol{x}_2^{k+1} = \boldsymbol{v}^k,\ \boldsymbol{v}^{k+1} = \boldsymbol{u}^k \\
\boldsymbol{u}^{k+1} &= \boldsymbol{x}_1^{k+1} + (1-\gamma)(\boldsymbol{x}_2^{k+1} - \boldsymbol{x}_1^{k+1}) \\
f(\boldsymbol{v}^{k+1}) &= f(\boldsymbol{u}^k)
\end{aligned}$$

and $f(\boldsymbol{u}^{k+1})$.

Step4 Let $k := k+1$, and go to Step2.

Step5 If $\|\boldsymbol{x}_{min} - \boldsymbol{x}_{min}^{old}\| > l_2$, $\boldsymbol{x}_{min}^{old} = \boldsymbol{x}_{min}$, and go to Step1. If not, let $\boldsymbol{x}_{min}$ be the minimum value and terminate the search.

In this experiment, $T = 5$ in equation (6), that is, every five frames of the input image sequence are compared with the reference locus in the eigenspace. Fig.13 shows the process searching the minimum value of $f(a,b)$ by Golden Section Method.

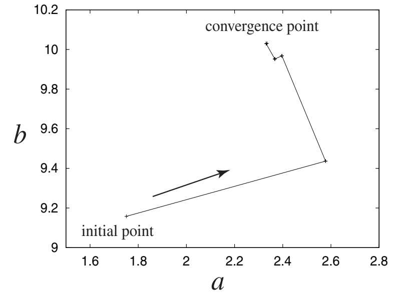


Fig. 13. Convergence to the minimum point

Previous calculation result $(\tilde{a}_{i-1}, \tilde{b}_{i-1})$ is used to determine the next initial point $\boldsymbol{x}_1^1 = (a_1, b_1)$.

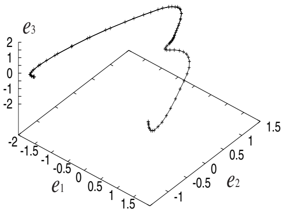
$$a_1 = \tilde{a}_{i-1} \tag{9}$$
$$b_1 = \tilde{b}_{i-1} + 5\tilde{a}_{i-1} \tag{10}$$

That is, reference locus closest to the next five frames is predicted based on the previous result.

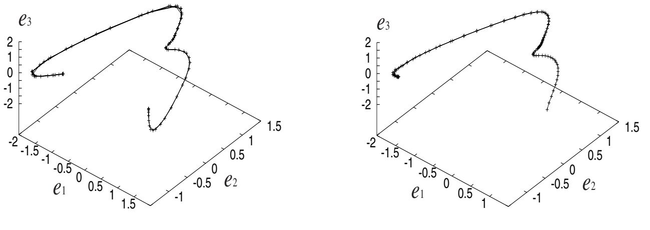
The eigenspace shown in Fig.4(b) is constituted at the learning stage, then, the following three patterns of image sequences are used.

(a) same speed as reference ($T = 24$[s] : normal)
(b) quicker than reference ($T = 12$[s] : abnormal)
(c) slower than reference ($T = 32$[s] : abnormal)

Fig.14(a)(b)(c) show the loci in the eigenspace of the above three input sequences projected onto the eigenspace shown in Fig.4(b). These are the almost same loci as the reference locus.



(a) Same speed as reference



(b) Quicker than reference (c) Slower than reference

Fig. 14. Projected locus of input image sequence

Calculation results of $\tilde{a}$ to each image sequence in 3-dimensional eigenspace are shown in Fig.15, which shows the quicker the robot moves, the larger $\tilde{a}$ is. It is found that the speed information of the robot is reflected on $\tilde{a}$. The system can detect abnormal speed by the threshold 0.75 and 1.25.

$\tilde{a}$ comes to zero at times because the robot stops at the turning points in short time. 3-dimensional eigenspace is enough to detect abnormal speed by comparing the loci on it.

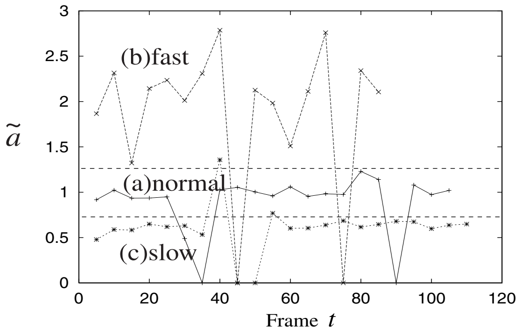
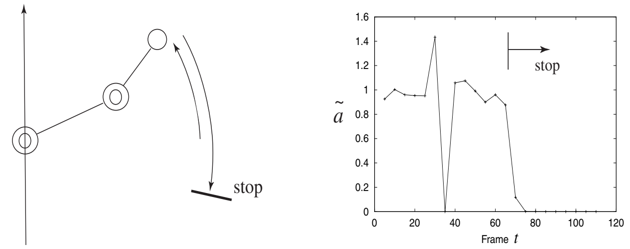


Fig. 15. $\tilde{a}$ for three input image sequences

Next, if the image sequence showing that the robot stops at time $t = 65$ is input, $\tilde{a}$ comes to zero as shown in Fig.16(b), therefore, the system can understand that the robot has stoped and judge it abnormal.



(a) Movement of robot (b) $\tilde{a}$

Fig. 16. Detection of stopping of robot

Using Golden Section Method, equation (6) is calculated in very short time. Calculation times of three search methods are compared as follows:

1. Search in the whole range with a, b changing : 120[s]
2. Search in the whole range limited to some extent based on the previous five frame result : 25[s]
3. Golden Section Method : 0.6[s]

C. Detection of abnormality III (Ab-III)

If the robot passes the teached trajectory partially, for example coming in contact with the obstacle, the system should judge it abnormal. Such abnormality cannot be detected by the above two method.

In the calculation of equation (6) using Golden Section Method, the locus closest to the next five frames is predicted based on the previous result as shown in Fig.17. Then, the search range of a is limited over zero by reason of the calculated amount. Therefore, it is considered that the distance between the loci d_2 comes to be large when the opposite direction locus is input.

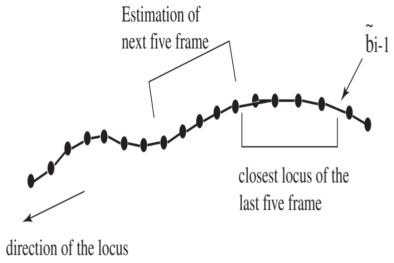
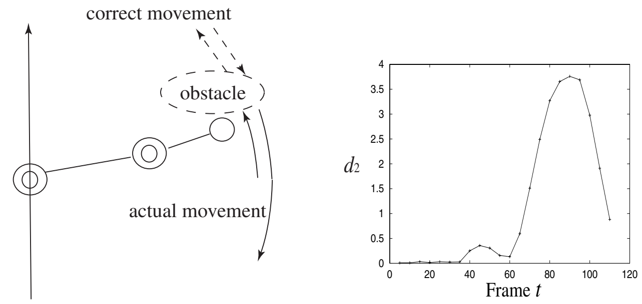


Fig. 17. Search of the closest locus

Fig.18(b) shows the calculation result of d_2 when the image sequence which the robot moves in the opposite direction from $t = 35$ is input. d_2 comes to be large from that time, and the system can judge it abnormal using a threshold. It is true that the movement in opposite direction can be detected also using the sign of $\tilde{a}$, but the above method is used by reason of the limitation of search range.



(a) Movement of the robot (b) d_2

Fig. 18. Detection of abnormality III

V. Conclusion

In this paper, the first attempt to realize a monitoring system of industrial robots to detect abnormal movement by observing with a camera has been done, and the detection method has been proposed. Some experiment results have shown the effectiveness of the proposed method.

It has been recognized that a new abnormality detection system independent of the robot system is required because there are some abnormalities which cannot be detected by the servo system and controller. The proposed monitoring system using only visual information is very useful. By using this monitoring system together with it, more reliable system can be realized.

For the detection method, Eigenspace Method was used which is excellent in compression of image data and calculation of the correlation among images. And, Parametric Eigenspace Method(PEM) was also used to detect abnormalities such as the speed of movement. In addition, Golden Section Method enabled to detect accurately in very short time.

When a marker attached to the end of robot cannot be taken in the image because of the angle of a camera, several markers should be attached to each joint. And, though a simple binalization was used to extract the marker in this experiment, color information should be also used to extract from the complicated background image in the factory. These are future problems.

This study is yet in a basic stage to the first attempt and there are many problems to be solved, however, some possibilities have been shown that abnormal movements of industrial robot can be detected to some extent using the proposed method.

The proposed system had been developed also for monitoring aged people[5], however, it can be applied to various systems, for example, observation of inpatients in hospital, traffic, and security monitoring in buildings and stores.

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