VALVE MEASUREMENT USING PHOTOGRAMMETRIC FEATURE MODELING

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ABSTRACT

The assessment of critical components in nuclear power plants is an important problem which presents some unique challenges. For photogrammetric processing, the difficulties relate to the lack of point features for use in a conventional bundle adjustment. Viewing angles can be unfavorable when looking inside a valve. Likewise illumination and reflections cause interpretability problems in the photographs. We have chosen to use feature modeling to address the lack of points. We have chosen mirror reflections and corresponding mathematical modeling to address the view angle problem. Current research is addressing the illumination and interpretation problems. Results to date relating to implementing the desired mathematical models has been successful. Experimental results in actually producing valve measurements have so far exhibited unacceptable discrepancies compared to manual measurements. These discrepancies are being investigated.

1 INTRODUCTION

In 1989 the NRC, Nuclear Regulatory Commission (USA), issued Generic Letter (GL) 89-10, *Safety-Related Motor-Operated Valve Testing and Surveillance.* This required that each nuclear utility develop a program to ensure that the switch settings on all safety-related motor-operated valves (MOV) are selected, set, and maintained in such a way as to ensure that the MOV will operate under the design basis conditions. GL 89-10 recommends that, when practicable, all safety-related MOV's be tested in-situ at design basis conditions to demonstrate their capability to function. In-situ testing at design basis conditions is difficult and not practicable in many cases.

The Electric Power Research Institute, EPRI, is currently conducting a comprehensive MOV research program (MOV Performance Prediction Program) with the objective of providing nuclear utilities with an analytical method of *predicting* MOV performance under design basis conditions. This program includes a combination of analysis and tests that address relevant aspects of valve and operator performance. The methodology developed by the EPRI MOV Performance Prediction Program will require information on gate valve internal design features, materials, and dimensions in order to predict valve performance.

These dimensional measurements of the valve internals are primarily made manually on the valve itself. This is done using scales, calipers, micrometers, and verniers. The problems associated with these measurement techniques are chiefly associated with the contamination hazard from close and prolonged contact with valve components. Personnel who have exceeded their limit for radiation exposure are no longer permitted to perform these tasks. Because of these problems with the manual measurement technique, it appeared that photogrammetry offered the possibility for reduction in both time and proximity compared to the manual method. Since only photographs would have to be taken at the valve location, with the actual measurement done later in a clean environment, this should reduce the time of exposure. Likewise, the excessive hand contact required by manual measurement should be reduced with most of the activity involved with the photography taking place at a distance of about one meter. Another advantage to using photogrammetry is that additional measurements can be made at a later time without going to or disrupting the plant to disassemble the valve. Also the photographs will provide a permanent, archival record for comparison with later inspections to determine if conditions are changing. There have also been some problems associated with reliability of the manual measurements. While photogrammetry does not necessarily enhance this reliability, it does offer the possibility for multiple observers to make duplicate or repeated sets of observations in any cases where discrepancies or unexpected results are obtained. Cost has also been suggested as a factor where photogrammetry may potentially provide an advantage. Certainly in other spheres, i.e. topographic mapping, antenna measurement, etc., photogrammetric techniques have been accepted as preferable in cost and performance to strictly manual techniques.

The desired accuracy of measurements for this purpose has been stated as 0.006 inches (0.15 mm). From larger distances, point accuracies have been reported as a fraction of the object distance in the range of 1 part in 20,000 to 1 part in 100,000. At a distance of one meter, 1 part in 20,000 would be 0.05 mm which is about one-third of the desired level. Thus it seems plausible that this technique might be usable for the proposed task. In many other close-range photogrammetric problems, the position determination is focused on discrete, well-defined points in space. For the present problem, however, the dimensions required are such things as distance between valve guide faces, radius of an edge on a beveled valve seat, etc. These features do not lend themselves well to traditional "pointwise" photogrammetric processing, and moreover there may be photo interpretation problems in locating the feature to be measured in cases of low contrast, poor illumination, specular reflections, or poor viewing angles.

Thus there is promise in this technique, but there are also some potential difficulties which may limit the accuracies attainable, compared to other point oriented measurement tasks.

2 FEATURE MODELING

In this application, as in many such instances in close-range photogrammetry, there is a distinct shortage of well-defined image points which would be usable for pass points or control points for spatial triangulation. On the other hand, there are numerous linear features which are visible in the images. In our case these linear features are either straight lines, circles, or low degree curves, all arbitrarily oriented in space. Photogrammetric condition equations for such linear features have been developed by Mulawa (1988, 1989) and applied by Sayed (1990).

In our case, these linear features are often the items of most interest in the dimensional analysis of motor-operated valves. One of the characteristics of observing linear features is that, for monoscopic measurements, one cannot obtain conjugate observations of the same point on the feature. There are generally no distinguishing or identifying characteristics of any single point on the feature. Fortunately with the above mentioned condition equations it is only necessary that an observed image point be on the feature, there is no requirement for conjugate points. In the case of straight linear features, the following condition equation would be written for each observation on each photograph.

$$\begin{vmatrix} p_x & p_y & p_z \\ b_x & b_y & b_z \\ lc_x & lc_y & lc_z \end{vmatrix} = 0 \tag{1}$$

In this equation $\mathbf{p}$ is the object space vector defined by the observed image point, $\mathbf{b}$ is a vector defining the object space components of the line of interest, and $\mathbf{lc}$ is the vector from the exposure station, $\mathbf{l}$, to the point, $\mathbf{c}$, on the line and closest to the origin. In the case of circular linear features, the following condition equation would be written for each observation on each photograph.

$$\left\| (\mathbf{l}-\mathbf{c}) - \frac{(\mathbf{l}-\mathbf{c})^t\mathbf{n}}{\mathbf{p}^t\mathbf{n}}\mathbf{p} \right\| = r \tag{2}$$

where $\mathbf{l}$ is the exposure station as before, $\mathbf{c}$ is the point at the center of the circle, $\mathbf{n}$ is the normal vector to the circle plane, $\mathbf{p}$ is the object space vector of the observed point, and r is the circle radius. A sample photograph showing a valve seat with the gate removed is shown in Figure 1. As evident in this photograph, the difficulty caused by the lack of well defined points is compounded by the unfavorable viewing angle. This viewing geometry is forced by the construction of the valve itself, not permitting views of the features of interest without substantial obliquity. In order to see these features more clearly, it was decided to introduce a first surface mirror into the valve. It can be positioned for optimum viewing of the upstream valve seat, then re-positioned for optimum viewing of the downstream valve seat. This is shown in Figure 2. To incorporate photogrammetric observations of reflected features into the bundle adjustment, a number of new capabilities had to be incorporated. (1) Equations were written to allow points on the mirror surface itself to be used to estimate the parameters of the reflecting plane. (2) Equations 1 and 2 were extended to permit observation of a reflected feature, carrying the parameters of the actual feature plus the mirror plane parameters. Previously published work which has included the photogrammetric processing of mirror reflected objects includes Benes (1969), Kratky (1974), and Torlegard (1975). The geometry which is necessary to develop the reflection equation is shown in Figures 3 and 4. The equation of the plane is,

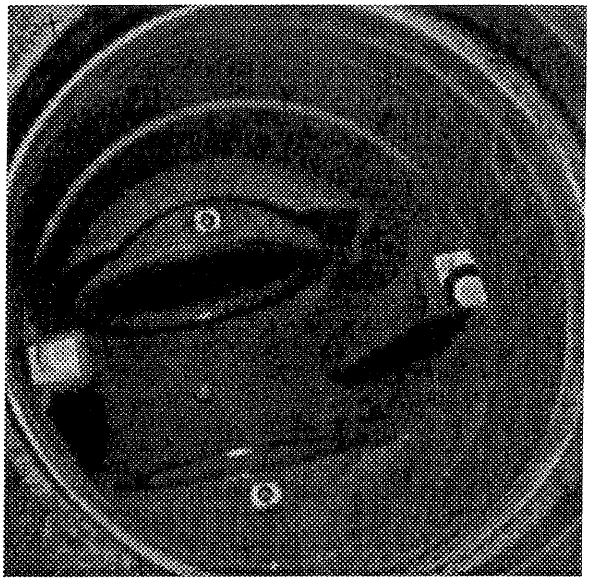

Figure 1: Valve seat

$$\mathbf{x}^t\mathbf{u} = \mathrm{d} \tag{3}$$

where $\mathbf{x}$ is any point in the plane, $\mathbf{u}$ is a unit vector normal to the plane, and d is the distance from the origin to the plane in the direction of $\mathbf{u}$. From Figure 4, where $\mathbf{x}_1$ is the point and $\mathbf{x}_2$ is the reflected position,

$$\mathbf{x} = \mathbf{x}_1 - \left[\left(\mathbf{x}_1{}^t\mathbf{u}\right)\mathbf{u} - \mathrm{d}\mathbf{u}\right] \tag{4}$$

and,

$$\mathbf{x} = \mathbf{x}_1 + \left(\mathrm{d} - \mathbf{x}_1{}^t\mathbf{u}\right)\mathbf{u} \tag{5}$$

$\mathbf{x}_2$ will be located at just twice the displacement from $\mathbf{x}_1$ to $\mathbf{x}$,

$$\mathbf{x}_2 = \mathbf{x}_1 + 2\left(\mathrm{d} - \mathbf{x}_1{}^t\mathbf{u}\right)\mathbf{u} \tag{6}$$

By taking differences of Equation 6 between two points and their reflected images, we obtain a means to write an expression for a reflected vector,

$$\mathbf{v}_2 = \mathbf{v}_1 - \left(2\mathbf{v}_1{}^t\mathbf{u}\right)\mathbf{u} \tag{7}$$

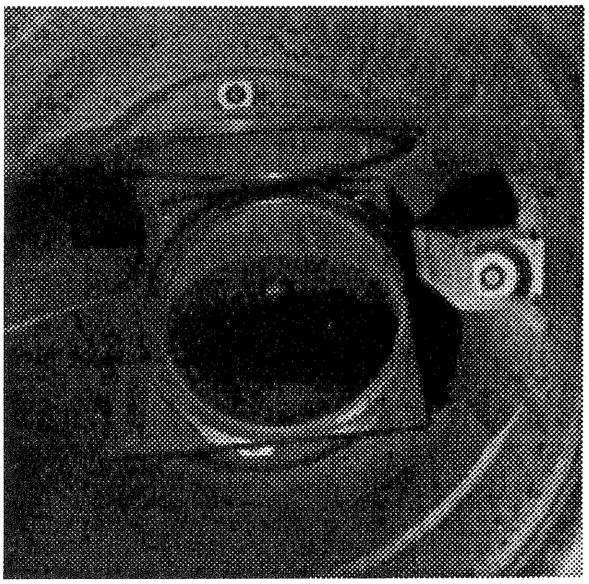

Figure 2: Valve seat via mirror reflection

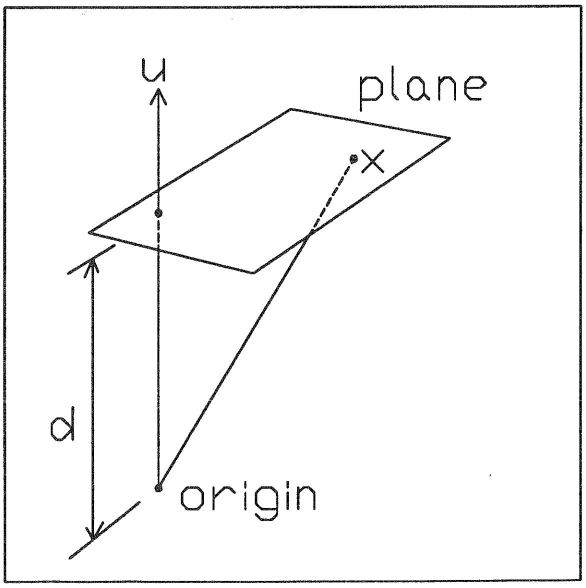

Figure 3: Plane

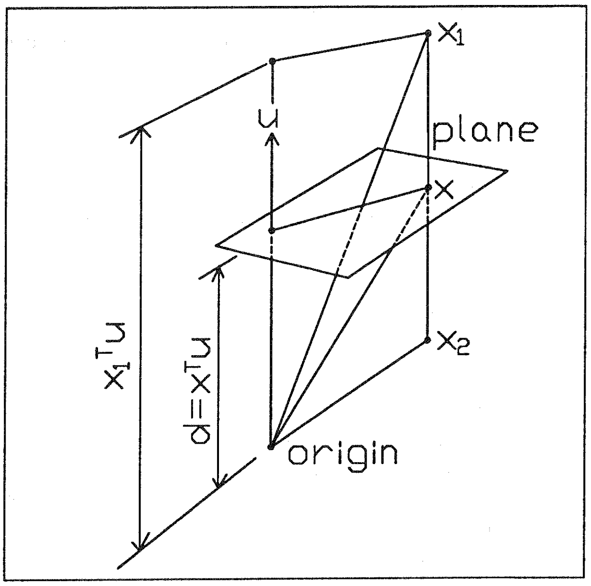

Figure 4: Geometry of reflected point

If points on a circle are observed in a mirror then Equation 3 may be rewritten as follows,

$$\left\| (\mathbf{l} - \mathbf{c}') - \frac{(\mathbf{l} - \mathbf{c}')^t \mathbf{n}'}{\mathbf{p}^t \mathbf{n}'} \mathbf{p} \right\| = r \qquad (8)$$

In this case $\mathbf{c}'$ is the reflected position of the actual circle center $\mathbf{c}$, and $\mathbf{n}'$ is the reflected image of the circle normal vector, $\mathbf{n}$. Note that since $\mathbf{c}'$ and $\mathbf{n}'$ are functions of $\mathbf{c}$, $\mathbf{n}$, and the mirror parameters, we are able to caarry the parameters of the actual (unreflected) features in the adjustment. This has the virtue that both *direct* and *reflected* observations of the same feature may be used, even in the same photograph. One cautionary note should be made for the circle condition equations. If the ray corresponding to the observation is nearly parallel with the circle plane (i.e. you are looking nearly edgewise at the circle), then the solution becomes ill-conditioned and numerically unstable. Such observations may actually provide a great deal of information, and it seems that a better solution would be to develop an alternative condition equation rather than eliminate that observation.

3 RESULTS

Table 1 shows some recent results comparing photogrammetrically determined dimensions against dimensions taken manually. These results do not seem consistent with the known capabilities of close-range photogrammetry. We feel that the cause of these discrepancies can be traced to several sources. First, the descriptions of some of the quantities to be measured are ambiguous, second, some of the physical features to be measured do not have uniquely defined edges and faces, and third, illumination inconsistency and specular reflections lead to uncertain interpretation by the operator about the location of some of the features. We have developed a number of strategies to address these difficulties.

Feature	*Photo.*	*Man.*	*Diff.*
B1	5.624	5.688	-0.064
B2	5.612	5.688	-0.076
B3	0.361	0.313	0.048
B4	0.345	0.313	0.032
B11	3.478	3.536	-0.058
B12	4.554	4.506	0.048
B14	5.175	5.199	-0.024
R3	1.000	1.000	0.000
R4	0.998	1.000	-0.002

Table 1: Comparison of Results (units in.)

4 CONCLUSIONS

Our results to date have not been consistent with expectations. One very important change which will be instituted in the next comparison will be that we will have the manual measurements taken with the involvement of someone from the photogrammetric team. This should insure that problems of feature description ambiguity and other "communication" problems are minimized. Additionally we plan to have the comparison measurement made by a coordinate measuring machine as another independent check. Nevertheless, the following recommendation was made by the management of mechanical and nuclear engineering at the Tennessee Valley Authority, "GL 89-10 requirements may result in periodic examination of valve internal surfaces for wear and other aging effects. Photogrammetry should be considered for documenting valve internal condition and trending wear of internal parts when manual measurement/inspection is not possible or practical because of dose rate or other reasons."

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