Object Recognition Based on Boundary Description

Y. Huang and J.C. Trinder

Abstract

Three-dimensional (3D) object recognition is a difficult and yet important problem in computer vision. It is a necessary step in many industrial applications, such as the identification of industrial parts and the automation of the manufacturing process, and it is essential for intelligent robots equipped with powerful visual feedback systems. In this paper, a procedure is described to recognize 3D objects, using model-based recognition techniques. Objects in the scene are reconstructed by digital photogrammetry, while models in the database are generated by a CAD system. They are all described in a boundary representation. A detailed comparison between the potential matching graphs of a model and the object determines the identification of the sensed object, and its position and orientation.

Introduction

Digital photogrammetric procedures of machine vision are being investigated for their application in a flexible manufacturing system (FMS). Flexible manufacturing enables multiple products to be fabricated on a single assembly line under computer program control. The system is managed by work transfer robots which are required to recognize objects, as they pass along the assembly line, and to determine the next appropriate action that should be taken on them. For the recognition of objects, it is necessary to extract visible features from multiple digital images of the object by image analysis procedures. These features form the basis of the reconstruction of the objects in terms of three-dimensional (3D) geometric primitives. This representation of the object is then compared against entities in a model database, which contains a description of each object the system is required to recognize.

The development of such model-based recognition techniques has occupied the attention of many researchers in the computer vision community for years (Besl and Jain, 1985; Chin and Dyer, 1986; Brady *et al.*, 1988; Fan, 1990; Flynn and Jain, 1991). Many machine vision systems developed so far have been based on range images which contain direct 3D properties of objects. Using range images, the ambiguities of the feature interpretation which usually occurred in an intensity image, such as shadows, surface markings, or illumination, are eliminated. However, an intensity-based vision system is still acceptable not only because of its relevance to biological vision but also because of the robustness of passive sensing for industrial and other applications. There are a number of advantages in the use of an intensity imaging system, including (1) the intensity data is viewable by an operator and can reveal more than geometric information, e.g., color, texture, blemishes; (2) features such as edges and faces can be extracted from the object by image processing, provided that these features are apparent in the image; and (3) lighting can be varied to accentuate various elements in the object.

One problem of object recognition is related to the representation of models in a database and objects in scenes. The representation of models should be compatible with the description of the sensed object, so that the matching of elements from models and objects can be identical. One can match objects with models at many different levels of description with some tradeoffs. Lower levels of the descriptions, such as pixel and edge descriptions, are easier to compute, but they are not stable with respect to viewing directions. This makes it difficult to find correspondence between objects and models. Higher level descriptions such as volume description, on the other hand, maintain their invariance with respect to changes in environment, but the known algorithms to compute them are often weak and error prone (Fan, 1990). The appropriate level of description to be used for matching thus depends on the expected variations in the scenes and on the state-of-the-art in computing descriptions of models.

In this paper, a relational graph representation, in terms of object boundaries, is developed. The graphic representation is described by planar surfaces which are bounded by straight lines or regular curves. These surfaces are grouped in terms of their normal directions and are stored together with their areas and perimeters as matching elements. The topological relations between surfaces are constructed in terms of the center of each surface and the common edge of two surfaces.

The automatic procedure for a machine vision system for FMS includes three steps: (1) image processing techniques for the extraction of features on the industrial components and hence the three-dimensional measurements of these components; (2) representation of the three-dimensional objects in an efficient and convenient data structure; and (3) procedures for the recognition of the objects by comparing with models stored in the design database. Figure 1 illustrates a schema of the procedure by means of which objects in the scene can be reconstructed and recognized from digital stereo images.

Reconstruction of Objects

Images of industrial components are generally characterized by sharp discontinuities which represent features on the objects. In order to describe features by their boundaries and to use feature-based image matching in photogrammetry, it is necessary to extract linear features of the object from its edges, and to represent them in a suitable data structure such as straight lines and smooth curves. By matching these

School of Geomatic Engineering, University of New South Wales, Sydney, NSW 2052, Australia (J.Trinder@UNSW.edu.au).

Photogrammetric Engineering & Remote Sensing,
Vol. 65, No. 8, August 1999, pp. 915–921.

0099-1112/99/6508–915$3.00/0

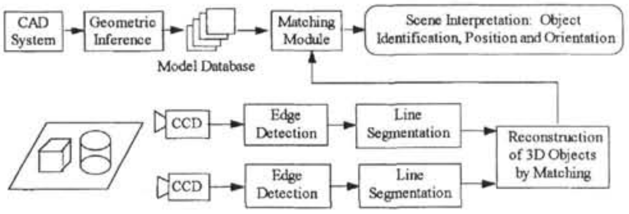

Figure 1. Components of an object recognition system.

geometric features in stereo images, the three-dimensional geometry of objects can be reconstructed.

Edge Detection

Edge detection is low level image processing, which serves to simplify the analysis of images by drastically reducing the amount of data to be processed, while at the same time preserving useful structural information in images. The edge detection method (Trinder and Huang, 1993) used in the research is based on a linear model which locates an edge point in the operator window with subpixel accuracy. Subpixel accuracy is necessary to ensure high quality measurement of objects for industrial monitoring and object recognition. The linear model comprises two aspects: one is to determine the peak of the intensity change in gradient direction, which is performed by the Förstner Operator (Förstner, 1987); the other is to limit the unstable edge location in the edge direction by the introduction of a linear constraint which passes through the window center and meets the edge at right angles.

To improve the accuracy of the edge location, an edge point is determined by a weighted average of points derived from both sides of the edge. Another implementation is to use a round operator window instead of a square window, so that the result will not be influenced by the difference of edge orientations, particularly near corners. The scattered edge points are then chained by following neighboring pixels, based on the minimum local distance. The direction of the edge chaining corresponds to the local direction of the edge, which is attached to each edge point as a primitive for the succeeding process. Figure 2b displays the edges detected from the image of an industrial component shown in Figure 2a. The edges can be located with a precision of 0.05 pixel, depending on their contrast. Generally, high contrast, which reduces the influence of noise, results in high precision of edge location.

Line Segmentation

In industrial environments, regular shapes such as ellipses and straight lines often occur as elements of object boundaries. In order to interpret objects in the scene, it is generally more relevant to present the boundaries of objects revealed in the images in geometric form, because simple geometric functions provide more reliable information and are easier to calculate.

The suitability of the approach of line segmentation developed in the research is demonstrated in Huang and Trinder (1994), based on the analysis of the local directions of edges. The local direction of an edge point is a one-dimensional value which clearly reflects the trend of the edge at the edge point, with respect to the next point. If a group of edge points contains the same trend in edge direction, it means that these edge points are of similar geometry. The method attempts not to find corners, but directly to find the basic components of straight lines or regular curves by assessing the local direction at the edge points along a complete edge. The principles of the line segmentation are that all edge points on a straight line should indicate approximately the same edge direction and that all edge points on a regular curve should indicate the same sign of the difference in direction.

The method starts with finding basic components of straight lines or regular curves by assessing the edge direction at the edge points along a whole edge. Straight lines or regular curves are then extended to their end points using geometric parameters determined by their components. Those lines with the same properties extracted from different edge sections can be merged in terms of their geometric similarity. In order to close boundaries of objects in image space, straight lines and open regular curves are linked at their terminal points. Finally, surface patches are generated by constrained chaining of the geometrical lines. Figure 3 illustrates the results of line segmentation.

Stereo Matching

Using two or more CCD cameras, 3D surfaces of an object can be constructed in an object coordinate system defined by the calibration process, by matching straight lines and ellipses. The reliability of the matching is confirmed by epipolar geometry, based on the camera orientation. The correspondence of a pair of straight lines in stereo images is determined by their terminals, which should satisfy the epipolar constraint. A 3D straight line is simply presented by 3D coordinates of its two terminals, using ray intersection.

To find the correspondence of regular curves, it is necessary to consider their size and location. An epipolar line, which is tangential to a given ellipse in one image, must be tangential to a matched ellipse in the other. This condition includes the basic requirement of the size and location of matched ellipses. The matched elements of an ellipse can be presented as a straight line with two tangent points as its ends as shown in Figure 4. In a similar manner to matching straight lines, the ellipses being matched should satisfy the

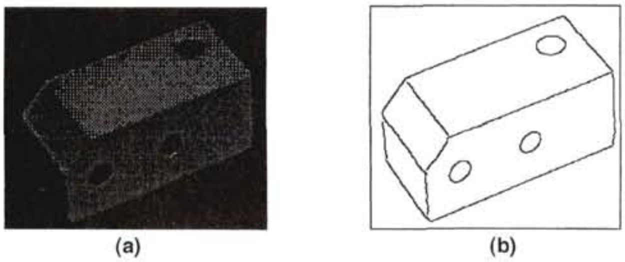
(a) (b)

Figure 2. (a) An image of a machine block. (b) Edges on the machine block.

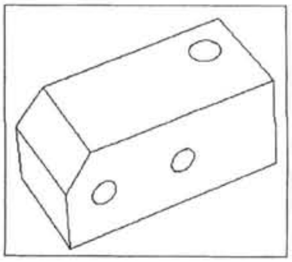

Figure 3. Results of line segmentation.

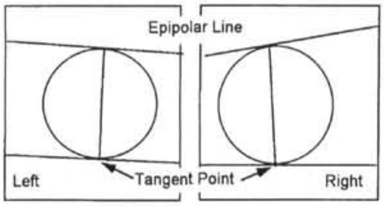

Figure 4. Process of matching ellipses in two images.

condition that their corresponding tangent points lie on the same epipolar line.

The calculation of 3D ellipses is based on the assumption that a special ellipse is an intersection of an object plane with a conic surface, whose apexes are at the projection center (Huang and Trinder, 1997). An ellipse in an image can also be referred to as the intersection of an image plane with the conic surface, as shown in Figure 5. The parameters of an ellipse on two different planes can be transformed, if the relations of the two planes are known. The determination of an ellipse in object space contains two aspects:

- One is to determine an object plane, which is determined by a few intersection points on the corresponding ellipses in the stereo images;
- The other is to establish the relation between image and object planes, which is established in terms of the camera orientation.

The ellipse on the image plane is then transformed onto the object plane. Therefore, a 3D ellipse can be described by a plane in object space and the 2D curve parameters on the plane.

Experiments have been conducted on an industrial component by following the procedure discussed above (Huang, 1996). Two cameras were set up horizontally and positioned about 0.5 m in front of the object of interest. A control frame with white balls fixed on it was first imaged, in order to obtain the parameters of camera orientation. The control frame was then replaced by an object, with dimension of about 103 by 50 by 67 mm, comprising 400 by 400 pixels in the image, with a pixel size in the object space of approximately 0.35 mm. Figure 6a illustrates a pair of stereo images which are processed by edge detection and line segmentation in Figure 6b. The two main polylines are matched by their terminal points based on their corresponding epipolar lines and transformed into object space, thus determining two surfaces (Figure 7). In Table 1, the dimensions of the object can be determined to an accuracy, expressed as an RMS of the difference between photogrammetric and direct measurement, of 0.13 mm or 0.37 pixel. The diameters of the circles in the object were determined to an accuracy of 0.07 mm or 0.2 pixel. In this example, only two images have been used and, hence, hidden surfaces cannot be measured. A complete measurement of the object could be achieved by acquiring and processing multiple images of the whole object.

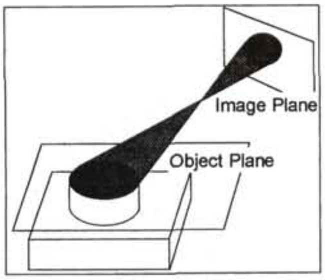

Figure 5. Intersection of a conic surface with planes.

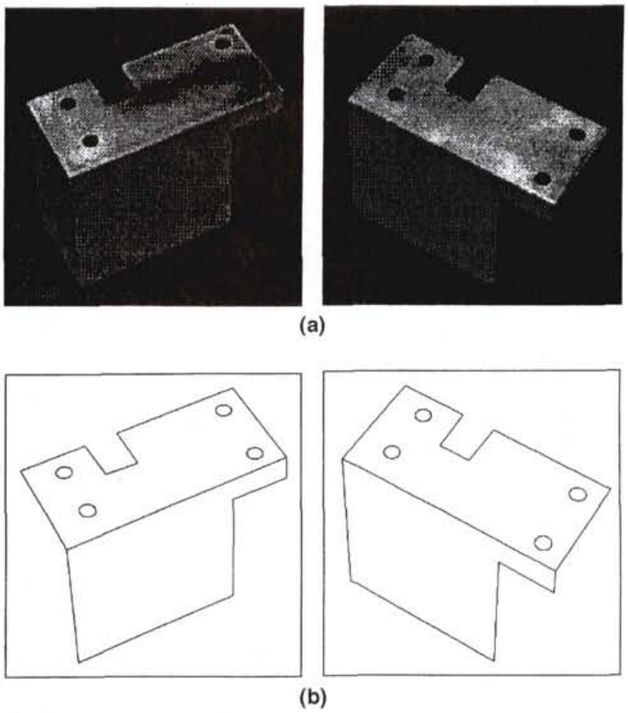

Figure 6. (a) Stereo images of an object. (b) Line segmentation of the edges of the object.

Generation of Models in the Database

In an industrial environment, CAD systems are usually used to design objects for the manufacturing task. Automatic gen-

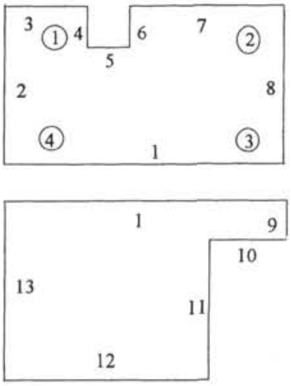

Figure 7. Top and front views of the object in Figure 6.

TABLE 1. RESULTS OF DIMENSION MEASUREMENTS OF THE OBJECT IN FIGURE 7.

		Measure (mm)	Difference (mm)
Lines	1	103.10	−0.08
	2	47.90	−0.13
	3	29.98	0.06
	5	14.84	−0.12
	7	57.00	0.05
	8	47.42	−0.20
	9	10.82	0.02
	12	77.22	−0.20
	13	66.58	−0.17
		RMS	0.130
Circles	1	6.90	−0.02
	2	6.90	−0.12
	3	6.90	−0.08
	4	6.90	−0.03
		RMS	0.074

eration of graphic code from the same object information used for design and manufacture would be an efficient, cost-effective approach. AutoCAD® is a general purpose computer aided design program for preparing two-dimensional drawings and three-dimensional models which can be output in the drawing interchanging format, DXF. CAD models serve as basic descriptions of object geometry. Inference procedures of various sorts are then applied to the CAD models to produce a graphic presentation in the database for object recognition.

CAD Output: The DXF Format

DXF files are standard ASCII text files, which can easily be submitted to other programs for specialized analysis. Because a DXF file is a complete representation of the drawing database, for the presentation of matching features, it is not necessary to use all information in the file. In the research, attention is concentrated on that portion of the DXF standard devoted to the description of 3D geometry. A DXF file is subdivided into four sections: headers, tables, blocks, and entities, which define the manner in which the data should be formed and drawn.

A DXF file is composed of many groups, each of which occupies two lines. The first line of a group is a code used to indicate its type and the general use. The second line is the group value, in a format specified by the group code. A program can easily read the value following a group code without knowing the particular use of this group in the file. A DXF file can also specify object geometry in terms of group entities such as lines, circles, arcs, and polylines. This basic geometry of models can be used to construct graphic presentations for object matching.

From CAD Models to Graphic Representation

An ideal 3D representation is unique and unambiguous, and has a rich set of representable parameters. The graphic database representation of models of manufactured objects used in this research is constructed by deriving a subset of the basic geometric entities from DXF files. The computational burden of graphic presentation is not incurred at object recognition time, because the transformation of CAD models to graphic presentations can be applied when a new model definition is created. Each model is handled separately, so that the addition of a model to the database does not change the representations of existing models.

Attributes of Geometric Primitives

The basic geometric elements of object boundaries are stored explicitly in the analytic format in the DXF file, in terms of lines, circles, and arcs.

(1) Line Segments: In the DXF specification, a line segment is characterized by a starting point and an ending point, whose coordinates are stored in the list of vertices. A *line* is presented as two numbers of vertex and length.

(2) Circular Arc: In the DXF file, a circular arc is specified in its own (arc-centred) coordinate system (x_a, y_a, z_a), in which the plane of the arc is parallel to the $x_a y_a$-plane, and displaced from it along the z_a axis. The direction of the z_a axis is related to the object coordinate system. The primitives of an arc contain its central coordinates, z axis direction, radius, start angle, and end angle. A circle is represented in a manner similar to an arc, without the start and end angles, while an ellipse is presented by 12 arcs which link smoothly at their ends. This system computes the major axis and minor axis of an ellipse from these symmetry arcs. The attributes for an ellipse are radius (an average of major axis and minor axis) and ratio (major axis divided by minor axis). These attributes are identical for circles, where the ratio is 1.0.

Planar Surfaces and Their Topology

The recognition system does not attempt to present objects in a complete way, but rather, dominant features are used for model matching. Planar surfaces and their relationships are chosen as the main features. They are generated from basic geometric elements of object boundaries, which are classified into two kinds: regular curves (circles and ellipses) and polygons. Each planar surface is presented by the normal direction (α, β, γ) of the plane, its central coordinates, and its bounded edges. A 3D regular curve for a planar patch is presented by 2D parameters projected on the plane, while a polygon is simply a group of straight lines. Additional primitives of a planar surface are radius and ratio for an ellipse or a circle, and perimeters and area for a polygon. Planar surfaces are grouped in terms of their normal directions, in order to establish their topological relationships. They are also related by their common edges and the distances between their central coordinates.

Graphical Presentation of a Model

The graphical presentation of an object derived from the DXF file can be created as shown in Figure 8, whose model corresponds to Figure 9. The representation of each object includes object name, orientation section, ellipse section, polygon section, line section, and vertical point section. The name **MODEL 1** stands for the first model in a database, following the four values which are maximum and minimum line lengths, and maximum and minimum circle or ellipse radii. Because objects are constructed to high accuracy, by comparing the dimensions of sensed objects and models, most models whose dimensions are beyond the range of object dimension can be ignored. The **DIRECTION** section contains the main orientations of planar surfaces, each of which includes the list of ellipses and polygons. The **ELEMENT_ELLIPSE** section lists all ellipses, in terms of elements of central coordinates, radius, and ratio. The direction of each ellipse is derived from the direction section. The **ELEMENT_POLYGON** section contains all polygons whose elements are central coordinates, perimeter, area, and the list of bounded lines. The **ELEMENT_LINE** section lists all lines where the first two numbers are vertices, and next numbers are polygons. The final element is the length of a line. The **ELEMENT_VETP** section lists the coordinates of all vertices.

Model Matching

Matching between an object in the scene and the models in the database is performed by a detailed comparison between their graphic representations. A sensed object is represented in the same way as the models in the database. Because the object in the images is only partly visible if only two images

```
MODEL 1
 113.52        9.9        3.80         3.11
DIRECTION 0               DIRECTION 1                DIRECTION 2
 0  1  0                   1  0  0                    0  0  1
ELLIPSE 8                 POLYGON 5                  POLYGON 4
 0  1  2  3  4  5  6  7    4  6  8  9  11 0  2  3    10
POLYGON 3                 ENDDIR 1                   ENDDIR 2
 1  5  7                   0                          0
ENDDIR 0
 0
ELEMENT_ELLIPSE 8
 0      -86.80     33.80  0.0         3.45 1

 ..............................
 7      -10.15       9.75         11.0         3.45 1
ELEMENT_POLYGON 12
 0        58.22      15.80  0.0     2028.25   194.0     4
         0   3   7   26

 ..............................
 11       72.70      33.25  9.8     1303.40   172.2     4
         0   3   7   26
ELEMENT_LINE 30
 0      0        1        0        1        30.5

 ..............................
 29     18       19       10       11       66.5
ELEMENT_VETP 28
 0      72.7     0.0      0.0

 ..............................
 27     10.15    11.0     9.75
ENDMOD 1
 0
```

Figure 8. Graphic representation and inferred quantities of bounded lines of the object in Figure 9.

are recorded, its description will not be complete. Therefore, the number of detected surfaces in an object will always be less than or equal to the number of surfaces in its corresponding model. The matching process contains two steps: the screener, in which most models unmatched to the given object are excluded, and the graph matcher, which performs a detailed comparison between the potential matching graphs and then computes the 3D transformation between them.

Screener

In principle, the number of models in the database may be large, and evaluating each pair to find possible correspondence would be prohibitively expensive. Instead, a simple comparison between the dimensions of a scene object and models enables the system to ignore most models whose sizes are different from the size of the object. There are two elements used for dimension comparison: length of lines and average radius of ellipses. Each model has its maximum and minimum lengths of straight lines and size of ellipse, if such features exist on the model. The size range of a sensed object should be within the range of a matched model, because the number of geometric features of an object is less than or equal to that of a corresponding model. Considering the errors in image processing, the possible range of model size is allowed to increase by 10 percent for the test. This process limits the candidates of the possible matched model in the next step to a very small number.

Graph Matcher

The graph matching procedure consists of finding the pairs of elements (in the object and model databases) forming the largest set of matching elements, consistent with a single rigid 3D transform. Grimson (1990) provided a comprehensive list of possible constraints for 3D edges, cylindrical features, and surface patches, some of which are used in the object recognition procedure. The process begins by finding all the possible pairs $<m, o>$ where m and o are the model and object surfaces, respectively. The geometric comparison of surfaces is dependent on the perimeter, the area, and the number of lines which bound a polygon, or radius and ratio when the surface is an ellipse. In measuring the similarity between m of the model and o of the scene object, the normalized measure of the difference is computed for each of the following properties:

- $d_{m,o}(1) = d(A_m, A_o)$, where A_m and A_o represent the surface area of a polygon in a model and an object, respectively.
- $d_{m,o}(2) = d(P_m, P_o)$, where P represents the perimeter of a polygon.
- $d_{m,o}(3) = d(R_m, R_o)$, where R represents the average radius of an ellipse.
- $d_{m,o}(4) = d(Rt_m, Rt_o)$, where Rt represents the ratio of major axis and minor axis of an ellipse.

A normalized measure between two elements t_1 and t_2 is defined as follows:

$$d(t_1, t_2) = \frac{|t_1 - t_2|}{\max(t_1, t_2)} . \qquad (1)$$

Thresholds are set for each of the differences to determine whether to accept or reject the match. One surface of an object may correspond to more than one surface of a model, as shown in Figure 6a, where the size of all circles are the same. Hence, one circle in an object may be found to correspond to eight circles in the model. If one surface of an object does not match any surface in a model, however, it will indicate that the model does not match with the object and the model is rejected. The process results in each surface of the sensed object having multiple corresponding candidates in a model. It is obvious that only one matching candidate is possible, if the object corresponds to the model. Therefore, multiple candidates must be reduced to a single candidate for each surface of an object. This process involves a compatibility constraint using topologic relations.

Topologic relationships exist among planar surfaces of a model or an object. If two pairs $<m_i, o_i>$ and $<m_j, o_j>$ satisfy similarity measures, respectively, the relation between m_i and m_j should be the same as that between o_i and o_j. Each time a pair of nodes $<m_j, o_j>$ is selected, it is compared to all the already matched pairs $<m_i, o_i>$ using a compatibility constraint. If this constraint is not satisfied, the chosen pair $<m_j, o_j>$ is discarded. The constraint contains the following relational checks:

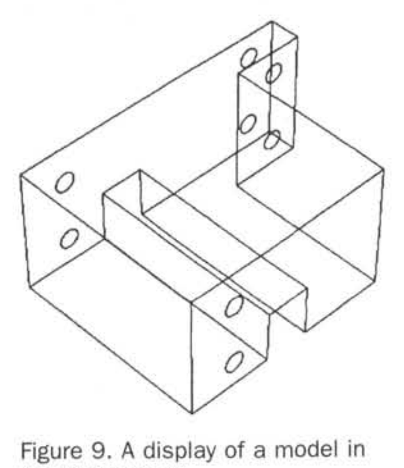

Figure 9. A display of a model in the CAD system.

- Orientation Relation (ξ1): Planar surfaces of a model or an object are grouped in terms of their normal directions. The angle between the orientations of two surfaces reflects their orientation relation. Let θ_m and θ_o denote the angles between the orientation of $<m_i, m_j>$ and $<o_i, o_j>$, and let $\Delta\theta = |\theta_m - \theta_o|$, then the pairs $<m_i, o_i>$ and $<m_j, o_j>$, are said to be ξ1 compatible if and only if $\Delta\theta$ is less than a certain user defined threshold.
- Proximity Relation (ξ2): Proximity relations summarize the distance between surface centers. Let L_m and L_o denote the distance between centroids of the surfaces m_i and m_j, and o_i and o_j, respectively, and let $\Delta L = |L_m - L_o|$, then the pairs $<m_i, o_i>$ and $<m_j, o_j>$ are said to be ξ2 compatible if and only if ΔL is less than a certain threshold. If two surfaces are polygons and adjacent (i.e., they share a common edge), an adjacent relation is checked between the two surfaces.

After all surface nodes of an object match with the model nodes and satisfy compatible constraints, a geometric transformation incorporating three translation and three rotation unknowns is calculated between the coordinate systems of a model and object, based on common nodes in model and object. Computing the geometric transformation between matched objects not only indicates how to bring the matched object and model into correspondence, but also helps to verify the matching process. The estimate of actual transform between model coordinate system and object coordinate system can be given by a set of vertices of the polygons. If all elements of the object after transformation are matched with the elements of a model, the object is considered to correspond to the model, and its position and orientation are determined.

Experiments

The system has been tested on several industrial components. The CAD models were constructed from physical prototypes whose dimensions were measured by hand. AutoCAD system designs of each model in terms of the data dimension were generated, and output in a DXF file. The geometric inferencing is then performed on models to create graphic representations which are stored in a model database. Figure 10 displays the models listed in the database.

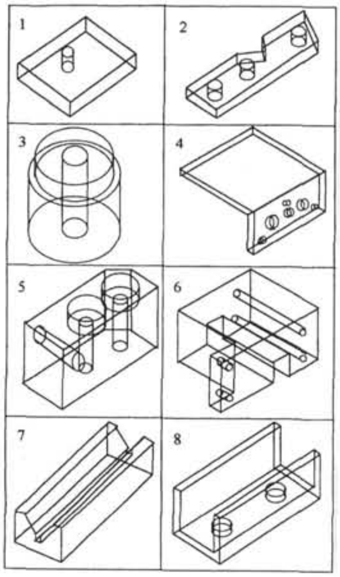

Figure 10. CAD models in the database.

A sensed object (Figure 6b) is constructed as discussed in the section on Reconstruction of Objects. The representation of the object is described in the same way as the models. The maximum and minimum of the line lengths in the object are 103 mm and 10.8 mm, and the maximum and minimum of the circle radius are both 7 mm. These four values are used to screen the models in the database and delete those whose ranges of dimension cannot cover the range of the object dimensions. In the database, only models 4 and 6 cover the dimension of the object, while the sizes of the other models are either too small or too large and are therefore ignored.

The graph searching process is then used to find the correspondence between the nodes in the object and the nodes in the model. Graph matching starts with one planar surface. Once one match is established, more matches can be added, if the resulting match meets the constraints of the node similarity and topologic relations. After all elements of the object are matched with those of a model, the object is transformed into the coordinate system of the model. Finally, not only the object is recognized as model 6, but also its position and orientation are determined.

Conclusion

This paper describes the elements of an automatic procedure for object measurement, positioning, orientation, and recognition. The digital photogrammetry system is data-driven in that no *a priori* scene knowledge is required. Descriptions of the objects are computed without prior knowledge about existing models. Object reconstruction reduces the image data to a few parameters of geometric functions, which are the most meaningful and reliable. Digital image processing methods developed in this research, based on the extraction of object features, have enabled the measurement of the objects to an accuracy of less than 0.5 pixel. Based on the graph matching procedure developed, it has been possible to match the measured object with the appropriate model successfully.

The system has been developed so far for the measurement and recognition of the industrial components with simple regular shapes and is designed for close-range applications. The processes of edge detection and line segmentation cannot correctly extract small detail features caused by complicated objects or occlusions. However, the method should be adaptable to more complex processes if multiple images are recorded and further procedures are developed for managing incomplete features in the images.

References

Besl, P.J., and R.C. Jain, 1985. Three-Dimensional Object Recognition, *ACM Comput. Surveys*, 17(1):75–145.

Brady, J., N. Nandhakumar, and J. Aggarwal, 1988. Recent Progress in the Recognition of Objects from Range Data, *Proc. 9th Int. Conf. Pattern Recognition*, pp. 85–92.

Chin, R.T., and C.R. Dyer, 1986. Model-Based Recognition in Robot Vision, *ACM Comput. Surveys*, 18(1):67–108.

Fan, T.J., 1990. *Describing and Recognizing 3-D Objects Using Surface Properties*, Springer-Verlag, Inc., New York.

Flynn, P.J., and A.K. Jain, 1991. CAD-Based Computer Vision: From CAD Models to Relational Graphs, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 13(2):114–132.

Förstner, W., 1987. A Fast Operator for Detection and Precise Location of Distinct Points, Corners and Centres of Circular Features, *ISPRS Intercommision Workshop on "Fast Processing of Photogrammetric Data,"* Interlaken, pp. 281–305.

Grimson, W.E.L., 1990. *Object Recognition by Computer: The Role of Geometric Constraints*, MIT Press, Cambridge, Massachusetts, 512 p.

Huang, Y., 1996. *A Digital Photogrammetry System for Industrial Mon-*

itoring, PhD thesis, The University of New South Wales, Australia, 161 p.

Huang, Y., and J.C. Trinder, 1994. A Feature-Based Approach to Reconstruction of 3D Objects from Digital Images, *International Archives of Photogrammetry and Remote Sensing*, 30(3):391–398.

———, 1997. Determination of a Spatial Ellipse from its 2D Geometric Parameters in Image Space, *Geomatics Research Australasia*, (66):77–92.

Trinder, J.C., and Y. Huang, 1993. Edge Detection with Sub-Pixel Accuracy for a Flexible Manufacturing System, *Videometrics II*, SPIE, 2067:151–161.

(Received 21 January 1997; revised 22 October 1998)

On behalf of the editors of *PE&RS*, we thank those reviewers listed below who have given their time and expertise to review the many manuscripts that are submitted to *PE&RS* each year. These reviewers represent the list of people who have reviewed manuscripts since January 1, 1999.

Hasan Abidin

David Alspaugh

Jon Arvik
Foundation Consulting Services

Chandra Bales
Earth Data Analysis Center

Walt Boge
Consultant

Paul Brooks

Andy Bruzewicz
U.S. Department of the Army

G. Bryan Bailey
USGS, EROS Data Center

Amy Budge
Earth Data Analysis Center

Howard Burrows
IBM

Jim Campbell
VPI & State University

Tina Carey
Cary & Associates

Jim Carr
University of Nevada Reno

Sky Chamard

Albert Chong
University of Otago

Jerry Coiner
RS & IS Company

Russell Congalton
University of New Hampshire

Merrill Conitz
University of Idaho

Doug Corr

Roger Crystal
Averstar, Inc.

Keith Cunningham

Rebecca Dodge
University of Texas at El Paso

Ian Dowman
University College London

Christine Fayad
United States Forest Services

Mark Finco

Tim Foresman
UMBC

Tom George
University of Alaska

Cliff Greve
SAIC

Armin Gruen
Institute of Geodesy &
Photogrammetry

Eberhard Guelch
University Bonn

Barry Haack
George Mason University

Ayman Habib
Ohio State University

Dale Hamby
GeoImage Technologies

Ray Harris
University College London

Bill Heidbreder
NIMA / TSS

Christian Heipke
University of Hannover

Floyd Henderson
SUNY Albany

George Hepner
University of Utah

Mike Hodgson
University of South Carolina

Roger Hoffer
Colorado State University

Dennis Hood
United States Geological Survey

Chuck Hutchinson
University of Arizona

Karsten Jacobsen
University Hannover

John Jensen
University of South Carolina

Amnon Krupnik
Technion – Israel Institute of
Technology

Tom Lillesand
Environ-Remote Sensing Center

Tom Loveland
United States Geological Survey

Nick Lunn
Canadian Wildlife Service

Tania Maria
Sausen Instituto Nacional de
Pesquisas Espaciais Divisao
de Sensoriamento Remoto

Stewart Marsh
University of Arizona

Ed Martinko
University of Kansas

George May
ITD

Helmut Mayer
Technical University Munich

Theo Moons
Katholieke Universitiet Leuven

Shunji Murai
University of Tokyo

Peter Murtha
University of British Columbia

Sunil Narumalani
University of Nebraska

Paul Neville
Earth Data Analysis Center

Maury Nyquist
United States Geological
Survey / BRD / CBI

Thierry Ranchin
Ecole des Mines de Paris

John Rehder
University of Tennessee

Rebecca Ritter
Washington State Dept. of
Natural Resources

Chuck Robinove
USGS (retired)

Stuart Robson
University of College London

Hugo Rogers
United States Department of
Agriculture / ARS

Ralph Root
United States Geological
Survey / BRD

Larry Rowan
National Center

Don Runquist
University of Nebraska – Lincoln

Vince Salomonson
NASA / Goddard Space
Flight Center

Bill Stone
National Geodetic Survey

James Taranik
University of Nevada Reno

John Trinder
University of New South Wales

Jim Vogelman

Ray Watts
United States Geological Survey

Steve Yool
University of Arizona