Order Number 1346719

Potential features for object identification by robots

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POTENTIAL FEATURES
FOR OBJECT IDENTIFICATION BY
ROBOTS

by

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A thesis Submitted to the faculty of the

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

In Partial Fulfillment of Requirements
For the Degree of

MASTER OF SCIENCE
WITH A MAJOR IN ELECTRICAL ENGINEERING

In the Graduate College

THE UNIVERSITY OF ARIZONA

1991

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Acknowledgement

I would like to thank all those who helped me to learn more. Special thanks to my advisor Dr. B. P. Zeigler. Dr. Zeigler's support and suggestions gave me the courage and motivation I needed to finish this thesis. I learnt a lot from him and other professors from Electrical and Computer Engineering department at University of Arizona. Dr. F. E. Cellier and Dr. J. W. Rozenblit have been always helpful. Dr. S. Risbud from the Material Science and Engineering department helped me to understand material properties and their possible use in Robotic object identification. The discussions with Dr. Risbud about NDE (Non Destructive Evaluation) techniques were a treasure of useful and extremely helpful information. His help and suggestions are greatly appreciated.

Thanks to all the students in the AI/NASA group at the Electrical and Computer Engineering Dept. Hessam Sarjoughian, Steve Lee, Sung Do Chi, and others have been very helpful.

I should not forget my family specially my wife Farzana whose moral support and patience helped me all along.

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ABSTRACT

Object identification is an important first step for all intelligent robotic manipulation of objects. Different approaches to object identification have been studied. A study on potential features of objects for Robotic object identification has been done. Three prime techniques of features extraction have been analyzed; these are Vision, Touch and Non Destructive evaluation of materials (NDE). The role of perceptual organization in aiding object identification is also discussed. A list of features has been obtained for each technique. Evaluation, based on cost of computation and accuracy of computation, of techniques for features extraction is presented. Some sample object identification systems have been designed using Classification Expert System Maker (CESM). Use of D-matrix (distiguishability matrix) is emphasized to get the optimal features set, which can be used to generate a classification tree. The classification tree can then be transferred into CESM knowledge base to obtain an expert system for object identification. A comprehensive multisensor system for object identification is proposed.

1.0 INTRODUCTION

Artificial Intelligence has created many interesting fields of research . Its applications are very diverse. One of the more interesting applications have been in the field of Robotics. The promise of Robotics is the Complete Automation. It will make every process more efficient and safer. Robots are getting more and more versatile. All applications of Robotics use some kind of manipulators. Hence the main function of a Robot is to manipulate objects. A robot can not intelligently manipulate objects without proper identification of objects. Robotic object identification is, therefore, the first step towards the fulfillment of the promise of Robotics.

1.1 Overview of Object Identification.

As mentioned earlier object identification is extremely necessary to make the best use of robots. Object identification has attracted lot of researchers. The task of object identification is a kind of data processing application. Most of object identification algorithms use two phases approach. The first phase is the training phase. In this phase data for an object is acquired through some sensor(s), which is saved in a storage area. The second phase is the actual recognition phase. Here, data is acquired from the object and that data is compared with the data saved in the storage area. Appropriate match between the sensed and stored data identifies an object. At high level all object identification algorithms are similar, and they are a type of pattern recognition. At low level and intermediate level the object identification algorithms can have many different classes. One big difference among different algorithms is the source of data. Another difference is the different ways of data processing. Yet another important way to differentiate among different object identification algorithms is the data representation.

1.2 Different approaches of object identification.

Three major factors responsible for differences in object identification approaches are:

1) Source of Object Data.
2) Methods of data processing.
3) Data Representation.

Sources of object data can be machine vision (2D or 3D), tactile sensors and material (electrical, thermal, mechanical and optical) properties sensors. NDE techniques are a big help in extracting material properties.

Methods of data processing are different kinds of image processing techniques. Most of these techniques were originally developed for visual image processing. They are now being adapted for other kind of data also, for example tactile image and Ultrasonar image.

Data representation could be the shape of objects or some simpler features. Since earlier approach to object identification was based on 2D vision alone, most of the earlier features were really features of the shape of the object. Later on as 3D vision got introduced, and tactile imaging was developed other features like height, thermoconductivity, thermodiffusivity etc. were tried as potential features for object identification.

1.3 Importance of Features.

Object identification has been a major topic of research by scientists all over the world. Main thrust of object identification research has been based on machine vision. In machine vision the main feature used for identification task has been the object shape. The common practice has been on the lines of pattern matching, and the pattern to be matched has been of course the shape of the object. This process is often quite time consuming and may not be favorable for domains which have a big number of different objects to work with. A lot of researchers realized the limitation of shape alone, and started looking for other simpler features e.g. size, perimeter, circularity, etc. These features could make the identification process a lot faster. After vision, tactile sensing has received the most attention for object identification task. Recently scientists have started using combination of vision and tactile sensing, which has a potential of giving better results than using either vision or tactile sensing alone. An even better approach is the inclusion of more sensors.

1.4 Overview of the thesis.

Chapter 2 starts with the discussion of machine vision. It talks about different level of machine vision. Some image processing techniques are discussed. It sheds some light on different kind of shape descriptors. Then it discusses 2D vision, and lists features that can be obtained using 2D vision techniques. 3D techniques are discussed after 2D techniques. The two major approaches to range imaging/finding are discussed. Features that can be extracted using 3D techniques follow the discussion of 3D vision.

Nonvisual techniques to extract features of objects are discussed in chapter 3. This chapter talks about touch and Non Destructive Evaluation (NDE) of material techniques. Perceptual organization is listed as a source of feature extraction. It is not a direct source; it could be based on vision, touch, or (possibly) NDE techniques. Both NDE and tactile imaging are discussed in detail. Different approaches for both techniques are mentioned.

Different sensors for touch are listed. A list of features is provided for each source (touch, NDE and perceptual organization).

Chapter 4 provides evaluations of vision, touch and NDE techniques based on cost of sensors, cost of computation required to extract a feature and accuracy of the computation. This chapter presents two tables of evaluation; one based on cost of computation and the other based on accuracy of computation. These tables are based on intuition and some guess work. They are provided to show their usefulness in the object recognition process in case of a multisensor system. If these tables have the accurate information based on experimental work then they become invaluable source of knowledge required for optimal object identification. From chapter 2 and chapter 3 one can easily see that most of the features can be obtained by either one of the sources discussed in these chapters. If we already have the two tables given in chapter 4 we can easily pick the best candidate. CESM (Classification Expert System Maker), which is discussed in chapter 5, has the ability to use cost (or some other criteria) to pick the best candidate.

CESM is an expert system shell developed at Simulation and AI lab at Electrical and Computer Engineering department of University of Arizona. Chapter 5 discusses CESM. It explains the main functions and components of CESM.

Three different approaches to object identification using a sample domain is discussed in Chapter 6. All these approaches were implemented using CESM. As it might become obvious from chapters 5 and 6; CESM makes system development very easy. First approach is based on 2D vision only. The second approach uses 3D vision and touch. The final approach is based on the features discussed in chapter 2 and chapter 3. Nine candidate features were picked to identify the objects in the sample domain. D-matrix (distiguishability matrix) was used to get optimal list of features. A classification tree was obtained using the optimal list of features. The classification tree was then converted into an entity structure to create a CESM knowledge base. This knowledge base was then compiled to get a rule base and hence an expert system for object identification was obtained. This last approach emphasizes the strength of the object identification system proposed in the final chapter of the thesis.

Chapter 7, the final chapter proposes a comprehensive multisensor system built on top of CESM. It is bi-phased. It uses one route when in learn mode and another when in recognition mode. Recognition mode is when learn mode is off. It uses d-matrix to optimize the features-set during learn mode.

The system is a generic approach to object identification and can be used for virtually any domain and environment. Some pseudo code is also provided.

2.0 VISUAL FEATURES

Visual features are obtained using machine vision. This chapter describes machine vision. It talks about 2D and 3D vision and lists some of the features mentioned in the literature which have applications in object identification.

2.1 Machine Vision.

Vision is probably the most important tool for human being. We perceive our world through vision. Through vision we are able to identify and recognize the objects around us. Naturally for robotic identification of objects most of the earlier work has been done using machine vision. Machine vision can be defined as the process of obtaining information about real world via image processing. Machine vision , which is also called computer vision, is basically image processing and the interpretation of images. Machine vision can be described at two basic levels :

a. Low Level Vision.

b. High Level Vision.

Low level vision is basically image processing. High level vision is symbolic processing of the output of the low level vision. Complete machine vision process could be a following sequence :

Object brightness --> Optical Image --> Digital Image --> (Low level) Processed Image --> (High Level) Symbolic Interpretation

Let us discuss each of the above steps. The first step, transformation of object brightness to optical image, is called image acquisition. Optical image is represented using pixels (picture elements). The second step, transformation of Optical image to digital image is called digitization or quantization. This step uses an Analog to Digital Converter to transfer brightness into grey levels (GLs). Grey levels are shades of grey. Typically eight bits are used to represent GLs so we can have 256 grey levels. Third step , low level processing, is an application of image processing techniques. The last transformation step (high level processing) blends with the low level processing. It is symbolic manipulation for example labelling and classification.

Let us further discuss Low level and High level processing. As mentioned earlier low level processing is contained within image processing. Image processing serve following functions :

a. Preprocessing of image before further processing

b. Enhancement for visual interpretation

c. Low-level machine vision

Preprocessing may consist of distortion removal, noise reduction, radiometric calibration etc. Enhancement for visual interpretation may contain contrast enhancement, edge enhancement etc. The third function which applies in our series of sequence mentioned above can include edge detection, segmentation, boundary finding, etc.

Distortion removal and radiometric calibration can be done by calibrating the sensor. Noise can be suppressed by using an appropriate smoothing filter. Candidate smoothing filters are low pass filter, moving conditional average filter and median filter [20,4,11,23,25,26,50,49].

Contrast enhancement can be done using low pass or high pass filter. Low pass filter will lower the contrast and high pass filter will increase the contrast.

Edge detection can be done using Parallel scanning methods or Sequential scanning methods. Parallel scanning methods consist of directional differentiation, mask operators, multichannel methods and thresholding the gradient picture [35].

Let's now discuss high level processing. High level processing may consist of geometrical processing and relational processing. Examples of Geometrical processing are : boundary tracking, shape description, and moments. Boundary tracking can be done using Papert's turtle algorithm. This algorithm can be described as below :

a. scan image until desired region pixel is found

b. go to the next pixel using one of the following rules :

Rule 1: If currently at region pixel, move to left neighbor.

Rule 2: If currently not at region pixel, move to right neighbor pixel.

c. if reached the starting pixel, stop.

Many shape descriptors have been proposed to describe shape. Chain code is an important and quite popular shape descriptor [19,44]. In this technique direction from one pixel to next is coded. Two types of operators are popular for chain code and other applications 4-connected and 8-connected. For chain coding 4-connected and 8-connected operators are given in Fig. 2.1. Fig. 2.2 illustrates the application of 8-connect chain code operator. If the initial pixel (x1,y1) in Fig. 2.2 is fixed then chain code provides completely unique description. In case of no fixed initial pixel chain code provides translation invariant description. By using derivative of chain code one can get rotation invariant description. Derivative of chain code is obtained by calculating the difference in the results of chain code in the connected pixels. For example in case of the object shown in Fig 2.2 with chain code of (1 0 0 1 1 2 0) the derivative is (-1 0 1 0 1 -2).

Fig 2.1 - 4-connected and 8-connected operators for chain code

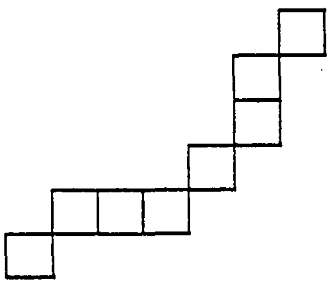

Fig 2.2 - An example of 8-connected operator

Another important shape descriptor is Fourier descriptor [20]. Fourier descriptors are represented as Fourier Series :

$$FD(S) = 1/P \quad [X(S) + jY(S)]e^{-jkw0s}\, dS$$

$w_0 = 2 * pi / P$

P = Period = Perimeter

S = arc length

k = frequency

If all fourier series terms are retained shape is described exactly. Alternately if the series is truncated the details are lost , yet retaining the basic shape. Fourier descriptors can be manipulated using the following principles:

1) To change size of image multiply Fourier Descriptor (FD) by a real constant.
2) To rotate the image by an angle theta, multiply FD by $e^{j\ theta}$.
3) To shift the origin multiply FD by $e^{j k T}$, where
   k = kth frequency , and
   T = fraction of period to shift ranging 0 to P.

Moments can also be used as shape descriptors [20]. The basic equation of moment of order p and q is :

$M_{pq} = \quad X^p Y^q f(x,y)\ dx\ dy$

For binary image f(x,y) = 1, and therefore the above equation can be reduced to :

$M_{pq} = \quad X^p Y^q\ dx\ dy$

Area can be easily found as M_{00} = double integral over dx dy . Simple moments are useful to extract image features but they are not invariant to translation, rotation, scale and contrast. Central moments are translation invariant; invariant; invariant moments are translation, scale and rotation invariant; and contrast invariant moment are translation, scale,rotation and contrast invariant. Table 2.1 gives the formulae for central, normalized central, invariant, and contrast invariant moments.

Table 2.1 Formulae for moments

Central Moments:

$$\mu_{pq} = \iint_R (x-\bar{x})^p (y-\bar{y})^q \, dx\,dy$$

$$\bar{x} = m_{10}/m_{00}$$

$$\bar{y} = m_{01}/m_{00}$$

$$m_{10} = \iint_R x \, dx\,dy$$

$$m_{01} = \iint_R y \, dx\,dy$$

(m upto order 3 in terms of m_{pq})

$$\mu_{00} = m_{00}; \; \mu_{10} = 0; \; \mu_{01} = 0$$

$$\mu_{20} = m_{20} - \bar{x} m_{10}$$
$$\mu_{02} = m_{02} - \bar{y} m_{01}$$
$$\mu_{11} = m_{11} - \bar{y} m_{10}$$
$$\mu_{30} = m_{30} - 3\bar{x} m_{20} + 2\bar{x} m_{10}$$
$$\mu_{12} = m_{2} - 2\bar{y} m_{11} - \bar{x} m_{02} + 2\bar{y}^2 m_{10}$$
$$\mu_{21} = m_{21} - 2\bar{x} m_{11} - \bar{y} m_{20} + 2\bar{x}^2 m_{01}$$
$$\mu_{03} = m_{03} - 3\bar{y} m_{02} + 2\bar{y}^2 m_{01}$$

Normalized Central Moments:

$$\eta_{pq} = \mu_{pq} / \mu_{00}^{r}$$

where $r = (p + q/2 + 1)$

Invariant Moments:

$$\phi_1 = \eta_{20} + \eta_{02}$$
$$\phi_2 = (\eta_{20} - \eta_{02}) + 4\eta_{11}^2$$
$$\phi_3 = (\eta_{30} - 3\eta_{12})^2 + 3(\eta_{21} - \eta_{03})^2$$
$$\phi_4 = (\eta_{30} + \eta_{12})^2 + (\eta_{21} + \eta_{03})^2$$

Constraint Invariant Moments:

$$\beta_1 = \sqrt{\phi_2} / \phi_1$$
$$\beta_2 = \phi_3 \mu_{00} / \phi_2 \phi_1$$

Hough transform is a very useful approach to space-domain analysis of shape. In this technique global edges are detected through a mapping of x-y space to parametric line space [35].

A recent addition to shape matching techniques is "planar shape matching based on binary tree shape representation" [34]. This representation is claimed to be insensitive to translation, rotation, scaling and skewing changes of shape caused by the change in the view point. The representation has multiresolution.

In this approach two trees representing two shapes to be matched are compared node by node according to breadth-first fashion. Top down comparison is done, which allows the lower resolution comparison as the starting point. If the lower resolution match is negative the comparison stops, else the finer details of the two shapes are compared. The two corresponding trees are compared entirely if and only if the difference is minimal.

Most of the early visual sensors used a constant in-time sensing field. They used a fixed over head video camera located above the work area. In this setup the field of view of the system is blocked while the robot arm is approaching the object for retrieval purpose. To fix this problem the next development was camera-in-hand systems. This system does not block the field of view of the system when robot is retrieving an object, but the robot has to be stopped to allow image processing by the camera and to permit calculation of position and orientation of the object. Another disadvantage of the camera-in-hand systems is that the size of the camera is not small enough to allow physical integration with the gripper. To overcome the shortcomings of the camera-in-hand systems dynamic sensing operation have been proposed and implemented. One of the recent additions to this family is an " eye-in-hand system using 512 x 1 solid state linear scanner" [38]. The resolution and the accuracy of image processing is enhanced with this dynamic linear scanner.

2.2 2D Vision .

2D vision is based on perception of 3D real objects using their projections on 2D space. Essentially 2D vision looses the depth information. All the processing discussed above have been in 2D vision analysis. 2D vision could limit perception in cases where depth information is important, so we might have to use 3D vision in such cases.

Following features can be obtained using 2D vision :

1) Size

Size of a region also called diameter (D) can be a useful feature. Diameter is given by two extrema on the region that have the greatest distance between them. Heuristic search can be used to calculate diameter [46]. Given n boundary points P = $\{p_1, p_2, \ldots. p_n\}$ in a 2D plane, we look for two points in p1,p2 which satisfy the following condition :

distance(p1,p2) > distance[(i1,j1),(i2,j2)]

(such that (p1,p2) and all (i1,j1) and (i2,j2) are in the set P and distance calculated is the euclidean distance.)

This scheme is only practical for small n. For large n it leads to $O(n^2)$.

An alternate fast but not very accurate scheme is to construct Feret box [21]. Feret box is the smallest circumscribing rectangle whose sides are arbitrarily chosen to be parallel to the coordinate axis. Two lines are given by the intersection points for each pair of parallel lines. The largest of the two lines form the diameter D. This method is sensitive to orientation of the object.

Another approach which is orientation invariant is to compute the convex hull of the object. The problem of finding the maximum distance between the extrema is simple, for only a single global extrema exists in this case [35].

2) Boundary Curvedness

Boundary curvedness [5] can be determined using Hough transform, moments, fourier descriptors , Turtle algorithm, or chain coding. Boundary curvedness is scale, rotation, and translation invariant.

3) Symmetry

Symmetry [5] can be measured from shape descriptors, segmented image and edge detection.

4) Compactness

Compactness [5] can be determined from the image histogram. It can be also measured from Area and Perimeter of the object. One possible clue of compactness can be Area/Perimeter .

5) Angular Variability

Angular variability is a very significant indicator of object identification [5]. Variation in angles from pixel to pixel or from segment to segment can give clues for corners and curvedness. Angular variability can form the basis for many features. It is scale, rotation and translation invariant.

6) Size of Angles

Size of angles [35] can be a useful feature. For example in case of an object having four sides, if the angles between all pairs of adjacent sides is 90 degrees then the object has a rectangular shape. Size of angles can also help in determination of corners and shape curvedness. Size of angles is correlated to angular variability.

7) Length of Sides

Length of sides can be a good feature [35]. It can be measured through turtle algorithm, Hough transform, chain codes and other shape descriptors, Edge detection, etc. It could be translation and rotation invariant (depending upon the technique used) but it will be difficult to make its measurement scale invariant.

8) Radial Length

Radial length can be measured from the shape descriptors. It is correlated to the size (or diameter of the object). Moments can be very useful in the measurement of radial length. One can estimate the center of the object body using moments. Once the center of the body is located then the radial length is the maximum distance from the center to the object boundary. Hence one algorithm of finding Radial Length can be :

a) Find the center of the object body (Xc,Yc) using moments given :

$Xc = m_{10}/m_{00}$, $Yc = m_{01}/m_{00}$

b) Find the boundary of the object using turtle algorithm.

c) Find (Xm,Ym) in the set of boundary coordinates such that the distance between (Xm, Ym) and (Xc, Yc) is more than the distance between another pair of coordinates in the boundary set and (Xc, Yc).

9) Actual Boundary Coordinates

Actual boundary coordinates [35] can be very helpful in measurement of other features as well as giving some direct clues for object identification. They can be used to measure Radial Length and Size of the object.

10) Complexity

Complexity [30] of an object is a rather vague term. One definition can be jaggedness of the boundary. Complexity can explain the texture of the contour. This feature is concerned with the micropropeties of the shape [35].

11) Uniformity of Side Lengths

How uniform are the side lengths? The answer to this question can reveal some important information about the object in consideration [30]. This feature like the previous one explain the microproperties of shape [35]. Hence it gives some local information.

12) Narrowness

This feature provides macroproperties of shape. It gives clues for elongation of the object shape [30]. Narrowness can be measured using shape descriptors.

13) Convexity

This feature also provides macroproperties of shape. It explains roundedness of object shape [30,18]. It can be measured using shape descriptors. In 2D convexity is mainly in terms of the boundary (whereas in 3D convexity is in terms of surface).

14) Concavity

Concavity is just the opposite of convexity. Therefore, this feature might seem redundant. But in some applications concavity might be more feasible than convexity. Concavity can be approximated using shape descriptors. Since concavity is really a function of boundary (in 2D case), therefor turtle algorithm could help finding concavity. Concavity has been used by a lot of researchers as an important feature [18].

15) Maxima

Critical points in the shape contour can help a lot while identifying an object [35,46]. Maxima are candidates for critical points. Maxima can be found using heuristic search.

16) Minima

Minima are also critical points in the shape contour [35,46]. They can be also found using heuristic search.

17) Points of Inflection

These form another class of critical points. Psychologists have proved their importance [5]. It is suggested that the dominant points which coincide with points of maximum inflection along the contour play an important role in shape segmentation. Points of inflection can be extracted from the boundary of the object. Hence turtle algorithm can be applied to find points of inflection. Image processing techniques such as edge detection can also be applied, and shape descriptors can also help. Of course actual boundary coordinates can be very useful in determining points of inflection.

18) Discontinuities in Curvature

Discontinuities in the curvature can give quite useful information [35]. They can help determining the corners and points of inflection. This feature can be extracted from the boundary information.

19) Endpoints

Endpoints have been used by researchers as an aid to understand object shape [35]. One practical way of finding endpoints will be using the actual boundary coordinates.

20) Intersection Points

Intersection points can be quite handy in case of contours having intersecting curves. These points may provide global features of the object with few intersections. In case of Grids the information provided by the intersection points can be considered as local. Intersection points can be found using edge detection and shape descriptors. Hough transform can also be very handy in finding intersection points.

21) Tangent Points

Tangent points can be useful in case of objects with tangent curves in their shape [35]. The role played by tangent points in case of tangent curves is analogous to that of intersection points in case of intersecting curves.

22) Perimeter

Perimeter can be found following the boundary of the shape by distinguishing between its interior and exterior. In case of a binary image this will be simply the distinction between 1s and 0s. Thus the number of pixels having both 0 and

1 neighbors is the perimeter [35,33,22,42,1,52].

Measurement of perimeter is translation and rotation invariant. But it will depend upon its orientation with respect to the camera.

23) Area

Complexity can be easily found using moments [29,35]. Area is simply m_{00}. Area can be also found using chain codes. Another way of finding area is to find the sum of all the pixels in the region; in case of binary image this will be simply the sum of 1s.

24) Circularity

Circularity can be calculated as Perimeter^2/Area [11]. Circularity has been used by many researchers as an important feature [37,38].

25) Adjusted circularity

Adjusted circularity has also found some interest among object identification researchers [39]. No definition of adjusted circularity has been given. It can be assumed to be adjusted with respect to scale or another such characteristic. Adjusted circularity should give more information than simple circularity and should be less dependant on translation, rotation and scale.

26) Maximum distance from the center of gravity to edge contour

It is synonymous to radial length. It has been used for object identification along with minimum distance from the center of gravity to edge contour and some other features [39].

27) Minimum distance from the center of gravity to edge contour

This feature can be found using heuristic search. The information required will be the actual boundary coordinates and the center of gravity. As mentioned earlier the center of gravity can be found using moments.

28) Eccentricity (elongation)

Eccentricity or elongation of the object is a useful feature [35,39]. Eccentricity can be estimated from the narrowness of the object.

29) Shape

Shape is the most important feature. This feature has been used by itself for object identification quite successfully [28,34]. Shape could be approximated using shape descriptors that has been described above. Most of the research done has used planar shape [28]. Shape is probably the most accurate feature, but for domains with large number of objects shape matching could be very expensive (computationally).

30) Height

Object height is another useful feature [7]. It can be found using edge detection, hough transform and shape descriptors. Height depends upon the orientation of the object, and it is sensitive to rotation.

31) Silhouettes

Silhouette of an object shape is simply the binary image of the object. Silhouettes and associated statistics have been used for object identification [7,12]. Single Silhouettes along with occluding contours and corners can guide object recognition process [12].

32) MIC

Moment of Inertia about the centroid (MIC) is a useful feature [38]. It can be computed using the following formula

$$MIC = (m_{20} + m_{02})/m00$$

MIC is translation and rotation invariant. (m_{xy} is the respective second order moment.)

33) MAER

Minimum Area enclosing rectangle (MAER) can provide useful features [38]. Width and length of MAER is used to get another useful feature (ASPR).

34) ASPR

Aspect Ratio (ASPR) [38] can be computed from :

ASPR = MAER width/ MAER length

35) Color

Color of an object can be an important feature [35,28]. Humans use color as a primary feature.

2.3 3D vision.

This vision system is built on top of 2-D vision. Different approaches could be used to get the depth information (the 3rd dimension). 3-D vision is synonymous with Range Imaging.

A range imaging sensor is used to measure the distance from itself to an image. Range image sensors are based on two techniques : "trigonometry of triangulation", and "time of flight" of light or sound [53].

"Trigonometry of triangulation" techniques can be further subclassified into two schemes : stereo vision and a scheme based on projection of a sheet of light by a scanning transmitter and recording the image of the reflected light by a television camera. The second scheme can also use transmission of light by a rocking receiver. Stereo vision has the problem of matching points in two images. Both schemes have poor accuracy. They may miss data for points seen by the transmitter but not seen by the receiver and vice versa.

Sensors based on "time of flight" techniques can overcome the disadvantages of the sensors based on trigonometry of triangulation by using a laser scanner. The "time of flight" techniques can be also subclassified into two schemes. First scheme measures the arrival time of the signal reflected by transmission of a laser pulse, and the second measures phase shift of the signal reflected by transmission of amplitude modulated laser beam.

There are some problems with "time of flight" techniques also. Problems similar to those of "trigonometry of triangulation" techniques are found with "time of flight" techniques for some applications such as determination of edges and reflectance variations. Bair, Sampson and Zuk [7] have implemented a generic 3D imaging sensor using an amplitude modulated CW laser source which improves upon the traditional "time of flight techniques". The implementation has resolution versatility and applications diversity.

Most of the research done on 3D object identification has used object surface parameters [10,17,32,8,41,36,43,7]. Giving such importance to surface parameters makes perfect sense, because by adding another dimension we transform regions into surfaces. Surfaces can be classified on the basis of curvature as planar, cylindrical or curved by analyzing Gaussian curvature everywhere[2]. Another classification based on morphological, patch and boundary information classifies a surface as planar, convex, or concave [31]. These classification schemes may be combined to get a better scheme.

Following are the features obtained using 3D vision : (Notice all these features have been reported in literature using 3D techniques, but some of these features can also be obtained using 2D techniques. Also some of the features have been renamed for reader's convenience.)

1) Perimeter

This suggests the size of the surface [31]. It could be found using the same methods as used in 2D.

2) Number of connected background components

This is the number of connected background components within the convex hull enclosing the set of non-background pixels.

3) Surface Span

This is span of the surface patch. This also suggests the size of the surface [31].

4) Boundary-background Fit

It is piece wise Linear Fit of the boundary of the surface patch with the background [31].

5) Boundary Type

This is type of boundary between two patches.

6) Normal angle

Normal angle between two patches can be a useful feature [31].

7) Minimum-patch distance

Minimum distance between patches can provide critical information [31].

8) Maximum-patch distance

Maximum distance between patches is an important feature [31].

9) Boundary angle

Boundary angle between two patches can suggest the extent of uniformity of the object surface. It can also give some information about the texture of the surface.

10) Patch-fit

Linear fit of boundary between two patches is a very handy feature [31].

11) Jump-gap

Jump gap between two patches is very useful for object identification [31].

12) Surface Aspect

Surface aspect or appearance is a good surface classification tool [7].

13) Surface Azimuth

Surface azimuth has been used as a potential identification feature [7].

14) Surface Elevation

Surface Elevation can provide critical information [7].

15) Curvatures

Curvatures are a class of primitive features [7]. They can be used for surface classification.

16) Displacements

Displacements of many types can provide useful information [7].

17) Surface Smoothness

Surface smoothness is highly correlated with the texture. They have found a lot of interest in 3D object identification [7].

18) Spatial Symmetries

Spatial symmetries are really a tool for perceptual organization. They have been used as object identification tool using 3D techniques [7].

2.4 Discussion.

Historically 2D vision have been the most used technique for object identification. Because of the lack of depth information in 2D techniques 3D vision techniques are getting more popular. 2D techniques mostly use region-based representation and with 3D techniques surface-based representation is used.

3.0 NON VISUAL TECHNIQUES AND PERCEPTUAL ORGANIZATION

This chapter will discuss the non-visual techniques for extraction of potential features of objects for robotic object identification. It will talk about "touch" and NDE (Non-Destructive Evaluation) techniques. The role of Perceptual Organization in object identification will also be discussed.

3.1 Touch.

Touch is an important sense for object identification. Human beings use touch as a complement to vision for object identification in situations where vision is either not adequate at all or gives incomplete information. Imagine trying to find your way in the dark; there touch is very essential to identify objects that come in the way. This is an example where vision is not adequate and the primary useful sense is touch. An example of a situation where touch might complement vision is differentiating between a plastic and a real fruit. The main output of touch is a sense of contact force. One could think of the human hand having millions of contact force sensors which help analyze an object. The development of tactile sensors has been based on using the human hand as a model. So most of the tactile sensors are array of contact sensors. Research in tactile sensing has borrowed some ideas from the research in computer vision. Hence in tactile sensing we have 2D tactile images just like 2D visual images in computer vision. As we have pixel in computer vision, we have taxel (tactile elements) in tactile sensing. Lot of interest has been initiated in object identification using tactile sensing. The main motivation has been the speed of tactile sensing vs. computer vision. Computer vision may require minutes while tactile sensing only requires seconds. Also tactile sensors are less expensive than visual sensors, and hence they are good candidates for industrial environment.

According to Staugard Jr. [60.0] a tactile sensor must have six ideal properties :

1. An array of sensors.
2. Skinlike.
3. Fast response.
4. Sensitive.
5. Low hysteresis.
6. Smart.

An array of sensors is required to identify objects and their orientation. The sensors should consist of small force or pressure sensing elements with an inter-element distance of about 0.1 inch. The final size and resolution of the sensor array will depend upon application. Many applications may need less than ten sensing elements per inch.

It will be nice to have a tactile sensor with a surface as flexible and durable as human skin. Flexibility helps the sensor to conform to the shape of the object. Durability assists repeated handling of objects.

An ideal response time is about 1ms. It helps to coordinate the tactile data with other sensory data. Fast response assists the robot to perform in real-time.

Minimum dynamic range of 1000:1 for the tactile sensing elements is essential to satisfy most applications. An ideal sensor output will be linear within this range. Software look-up tables can help in the adjustment of nonlinear data.

Hysterisis is related to the lag of the effect in the sensor induced by the change in the force acting on it. The sensing elements should have very low hysterisis.

The tactile sensing system should have some intelligence. It must have on-board signal conditioning and sensory data processing.

There are two classes of sensory elements: binary tactile sensors and analog tactile sensors. This classification is based on the sensor output.

Binary tactile sensors are the simpler of the two types. They consist of binary switches. Some members of this class are : Limit Switches, Whisker Sensors, and Binary Switch

Arrays.

A simple touch sensor may have two limit switches, one on the inner side of each gripper finger. This sensing system can detect the presence of an object, as well as the thickness of the object. A potentiometer is used to measure the distance between the fingers. The presence of object is detected from the output of the potentiometer. A nonzero output suggests the presence and the thickness of the object. Binary switches can also be used as external sensing plates to detect contacts with object surface. For this purpose binary switches are placed around the outside of the gripper fingers.

The limit switch systems are very rigid and require high contact force to actuate the sensing elements. Hence, these systems may not be very useful for manipulation of lighter objects. A whisker sensor can give much better performance in case of lighter objects. A superlight whisker sensor is attached to the end of the robot gripper. It is used to probe a given area before grasping an object. Extraction of object features can be done by the tactile-sensing elements inside the gripper. A simple pneumatic whisker sensing system can be constructed by placing the whisker assembly inside the robot finger. The system needs a vacuum source and an air-pressure source. Hence the whisker can be extended and retracted. Semiconductor pressure sensors can be used for detection of deflection of the whisker and transmission of a logic signal to the robot controller. The whisker sensing system can help in object identification by tracking an edge, groove or seam.

Binary switch arrays can be used to obtain tactile image of an object. Binary switches are placed in an array and attached to the inner surface of a robot gripper to form an area tactile sensor. As the gripper closes on an object, the switches touching the object are actuated and produce a logic 1, and the rest of the switches produce a logic 0. This results in a binary tactile image. A binary switch array system can be built using an array of snap-action pressure switches. An array of small spherical domes is formed by punching a thin steel plate. The plate is sandwiched between a flexible insulating gripping surface and a high pressure air supply. A voltage supply is connected to the plate through a pull-down resistor. If there is no contact between a particular switch and an object then the switch is kept open, suggesting a logic 0. In case of a contact between a switch and an object, the switch closes under the influence of contact force, suggesting a logic 1. The switch matrix is multiplexed and decoded to generate the binary tactile image. The sensitivity of the system can be adjusted through the adjustment of the air pressure.

The main difference between a binary sensor and an analog sensor is that the first one produces a two-state output, and the second one produces a continuous output proportional to an applied force. The analog sensing element is mostly a resistive element with a resistance which is a function of the applied force. The members of this class of tactile sensors are : Conductive Sensing Elements, Conductive Rubber, Conductive Foam, Semiconductor Sensors, and Pressure-sensitive Paint.

Most conductive-rubber tactile sensing elements are built from silicon rubber mixed with metallic compounds. The silicon rubber helps the conductive-rubber elements to be flexible, where as the quantity of metallic compound in the mix controls their conductive properties. The conduction of the rubber is the function of the applied force. A tactile sensor can be built by placing a sheet of the conductive rubber over a PC board that has been etched to provide an array of concentric ring pairs. Each pair acts as electrode of a variable resistor. The conductive rubber creates a resistance between the outer ring and the center ring which depends upon the applied pressure. The outer rings are linked together on the PC board to form the column of the array. An external dioding circuit is connected to the center rings of each element in a given column via diodes. Four outer rings are connected together and connected to the collector of a column-select transistor (Refer to 48, page 321 for schematic diagram). The PC board provides this common connection. One of the four columns is selected by the column-select logic by applying a logic 1 to the base of the respective column-select transistor. The next step is the multiplexing of the voltages developed across the four sensors within that column into an A/D converter, one by one, through an analog multiplexer. The same is done for each of the other three columns. A tactile matrix is obtained from the converted tactile data. The interpretation of this tactile matrix is similar to that of a gray-scale picture matrix in a vision system.

Conductive rubber also has a resistance property that depends upon the applied pressure. A conductive foam sensor is extremely sensitive and quite linear. A change in resistance of 19 k ohms can be realized by a compression change of only 0.15 inch. One approach to building a tactile sensor using conductive rubber is to sandwich a layer of foam between rows and columns of conductors. Columns of the array are obtained by placing a set of parallel conductors on top of the foam. Similarly, Rows of the array are formed by placing another set of parallel conductors under the foam. The row and column conductors must be spaced far enough apart preventing false resistance readings. The scanning procedure for the conductive-foam array is similar to that of the conductive-rubber array describer earlier.

Semiconductor pressure sensors have a lot of advantages: high sensitivity, reliability, good linearity, low hysteresis, relatively low cost, and established technology.

They often have on-board signal-conditioning circuit. A semiconductor sensing element may consist of an N-type semiconductor material that has been etched to form a vacuum cavity. An extremely thin pressure diaphragm is attached over the top of the cavity for pressure detection. On the top (or pressure) side of the diaphragm, four pressure resistive elements are formed by diffusion of a P-type semiconductor into the diaphragm, or by deposition of thick-film resistors onto the diaphragm. A Wheat-stone bridge is formed by the internal connection of the four pressure resistive elements. This improves the sensitivity of the system. Semiconductor sensors look very promising. The only disadvantage they have is noncompliance which limits their flexibility.

Pressistor or pressure-sensitive paint can provide a possible solution to the disadvantage of the semiconductor sensor. Pressistor is a mixture of piezoresistive (pressure resistive) semiconductor powders and an organic material. Pressistor can be painted onto electrode arrays or impregnated into porous foam to construct a tactile sensor.

Following features can be extracted from tactile sensing:

1) Compliance

It is the estimate of hardness of surface . Compliance can be measured by a robot finger using the formula : compliance = distance(p1,p2) where p1 is the position with a contact force of F and p2 is the position with a contact force of 2F [35]. Compliance is inversely proportional to hardness. Distance(p1,p2) is almost zero for hard objects, while for softer objects distance is greater.

2) Elasticity

Elasticity determines the extent to which original shape can be recovered when an object is subjected to deformation. It can be measured in terms of compliance.

Given positions p1,p2,and p3; where p1 is the position with a contact force F, p2 is a contact force of 2F, and p3 is the position obtained after backing away from p2 until contact force is reduced to F; elasticity can be found using the following formula:

elasticity = distance(p1,p2)/distance(p3,p2) [35].

Notice distance(p1,p2) is the compliance of the surface.

3) Normal-contact position

It measures surface position and orientation at a single point on a surface. It could be thought as a "device-dependent estimation of surface normal" [35]. Stansfield has suggested the following algorithm to determine normal-contact position [35] :

" Move to position(x,y,z) until contact surface.

Reposition sensor until the area of the contact is greater than THRESH.

OR current area is less than previous area.

If current area is less than previous area

then return to previous position.

Obtain the position and euler angles for the tool

origin in world coordinates. "

Surface position at the contact point can be determined by the world (x,y,z) of the tool coordinate frame, and the orientation is given by the euler angles. Surface normal is approximately the tool z axis.

4) Contact

Contact can be defined as presence or absence of tactile sensation. Contacts can be classified as extended, point or edge type.

Extended contact is a rather less elongated region of contact covering a large portion of the sensor pad. Sensor flush is placed on the surface of an object larger than the sensor pad to obtain extended contact. This type of contact gives a measure of the roughness of the surface.

Point contact is a wide region of contact covering a small portion of the sensor. Standard deviation of the region in consideration gives an estimate of the sharpness of the object. Point contact can be measured by placing the sensor on an object smaller than the sensor pad. It can be also measured by placing the sensor on some portion of a larger object such that either the size of the portion is less than the sensor pad or the portion is quite sharp e.g. a corner.

Edge contact is an extremely elongated region of contact. Edge contact is a measure of the narrowness of a surface.

5) Roughness

Gray-scale statistics of the extended contact can give an estimate of roughness of a surface [35]. The standard deviation in this case is directly proportional to the roughness of the surface. Smaller standard deviation suggests smoother surfaces and larger standard deviation suggests rougher surface.

6) Surface Shape

The surface shape can be determined from the statistics for Euler angles of four normal-contact positions. These four normal-contact positions can be found by moving a tactile sensor on the surface. The surface shape can be classified as planar or curved [35]. For planar surfaces the standard deviation of the Euler angles of the four-contact positions is small, and it is large for curved surfaces.

7) Parts and Semiparts

Parts and Semiparts can provide some useful information for object recognition. Parts decompose the surface and semiparts decompose parts. Semiparts can be defined as "some aspect of a part" e.g. the horizontal component [35].

8) Contour

This a closed series of edge contacts. Contour can be divided into two types. A contour can be a rim type or a border type. There is an associated "coplanar" to the border contour, while there is none for the rim type. A contour may be curved or polygonal. A curved contour can be approximated by a circle. It consists of constantly oriented edge segments without any associated corners [35].

A polygonal contour can be approximated by a series connection of edges ; connected by a set of corners.

9) Tactile Edge

Tactile edge can give information comparable to the visual edge. It can be detected by actively following the edge using a tactile sensor [35].

10) Corner

Corners can provide critical information. Corner can be found by making the sensor actively following the contour of an object. The corner is felt different based on the kind of edge i.e border-type or rim-type [35].

11) Hole

Holes can be defined as right cylinders having constant arbitrary cross section with a negative volume. They have approach axis perpendicular to their planar cross section. The hole coordinate frame can be defined by the homogenous matrix (H) suggested by Allen [2] :

$$H = \begin{vmatrix} P1x & P2x & P3x & Cx \\ P1y & P2y & P3y & Cy \\ P1z & P2z & P3z & Cz \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

P1, P2, P3 and C are features of the hole's planar cross section. P1 is axis of maximum inertia; P2 is the axis of minimum inertia; P2 is the normal to the cross section, and C is the centroid. Moments m_{02} and m_{20} alongwith area, P1, P2, P3 and C were used by Allen for object identification [2].

12) Cavity

A cavity is similar to a hole but it has only one open side. Cavities were also used by Allen along with holes to aid object identification [2]. They can be modeled in a fashion similar to that of holes . They also need coordinate frame and moment set ; with one extra attribute of depth. The depth of a cavity is the "distance along the cavity's approach axis from the cavity's opening to the surface below" [2].

3.2 Material Properties.

Materials have a lot of properties which are unique for different materials. There could be lot of situations where material properties could help in object identification. The least they can do is eliminate a number of candidates for object identification. Three interesting research topics in materials quality assurance and reliability are active, they are : NonDestructive Characterization (NDC), NonDestructive Evaluation (NDE) and NonDestructive Testing (NDT). These three areas are extremely correlated and can be dubbed as essentially one area. A lot of research in NDC, NDE and NDT can find direct application in object identification. Some of the techniques used in NDT and NDE are Acoustic Emission, X-Ray Diffraction, Infrared Thermography, Eddy Current Measurement, Flash Radiography, Nuclear Magnetic Resonance Imaging, and Ultrasonic Measurements.

Detailed information from the detected acoustic emission (AE) signals can be recovered by applying signal processing analysis. AE signals can be produced using broad-band or by resonant piezoelectric sensors. The combination of the two types of sensors can give better results. AE signals are obtained in real time by a microcomputer-based AE analyzer and a high speed waveform digitizer [61]. AE techniques can be used to determine the mechanical properties of material such as tensile strength and can also be used for texture analysis.

X-ray diffraction has been very useful in Quality Control/Quality Assurance for quite some time. In the beginning x-ray diffraction was based on photographic film, and was a tedious technique. Nuclear track plates increased the spatial resolution limit of the photographic technique to about 1-3 micro meter. Photo densitometer is used to digitize the photographic data to be analyzed by computers.

A new trend in X-ray diffraction is the use of electronic detectors for direct recording of the phenomena. The electronic detectors range from point counters to 2-D x-ray array detectors. The 2-D real time x-ray imaging system is getting quite popular [3].

X-ray diffraction can be measured by two techniques :

a. Conventional x-ray diffractometry

b. Double crystal X-ray diffractometry (rocking curve analysis)

In conventional diffractometer the specimen and the detector rotate about the diffractometer axis with "theta" - "2 * theta" angular velocity relationship (where theta is the angle of incidence).

In double crystal diffractometer the first crystal is the monochromator and the second crystal is the crystal to be analyzed. The detector is fixed while the sample is rocked about the diffractometer axis. This technique has been used with point counters and linear position sensitive detectors to study materials and microstructural morphologies. The diffraction domain is probed by rocking the specimen about the diffractometer axis while the detector can be fixed at any double theta (2 * theta) value. X-ray diffraction can provide with signatures of objects which can aid in their identification. It can also provide microstructural morphology which is a good clue for the nature of the material, and may be for the object made of that material.

All objects possess temperature and they continually radiate energy. The radiation of very high temperature objects (greater than 800 K) may be visible, but the radiation for most of the objects is in infrared, invisible to the naked eye. Thermal image of an object can be seen by using a thermal imaging system (TIS), given there is a large difference in the temperature of the object and its surroundings. Irradiation is transmitted from an object to the TIS through an atmosphere. In TIS the radiation is converted into a visible display [14]. TIS can be used to detect subsurface features, and to detect holes and cavities.

Eddy current signals can be used to detect holes in an object. Bailey [6] developed an Automatic Eddy current Signal Acquisition system (AECSAS) which allows real-time remote (depot) evaluation of field level NonDestructive Inspection (NDI) eddy current test signals. The system was proposed to meet the need of a depot requirement to closely monitor field level eddy current inspections of aircraft fastener holes.

High-energy flash radiography can be used to detect the internal features of objects. Adequate radiographic penetration of copper,iron, and tantalum step wedges with maximum areal densities in the range of 25-35 g/square cm has been demonstrated [13]. Internal and external contours of axially symmetrical objects can be determined to within 0.2 mm and their masses to within 1 or 2 percent.

Nuclear magnetic resonance imaging (NMRI) can become an important tool for aiding ceramics processing development. In NMRI technique the sample is subjected to RF and static magnetic fields. The sample can be only substantially nonmagnetic and possess only moderate electrical conductivity. NMRI is inherently 3-D, but 3-D data collection requires considerable time. Therefore, a series of 2-D views are used. It is possible to get nondestructive images of the internal volumes in a green-state ceramic body using NMRI. Features of about 300 micrometer size can be detected in a field of view of 100 mm. Porosity can be imaged and measured as a fraction of maximum signal intensity.

Ultrasonic NDE techniques can be used to measure mechanical properties of materials. Mechanical properties are determined through the speed of wave propagation and wave energy loss. Microstructure and morphology of materials control the measurement of physical and acoustic properties through the interaction of elastic stress waves. Some applications may require more than one NDE measurements. For instance, the measurements of velocity and Brinell hardness will help in calculation of tensile strength in cast iron. Two methods for ultrasonic signal acquisition are currently used : the pulse-echo method, and the acousto-ultrasonic method.

In pulse echo mode coupling a transducer (probe) to a material sample gives a series of ultrasonic echoes that can be analyzed either in the time or frequency domain. A single transducer probe is used to excite and collect ultrasonic signals.

Acousto-ultrasonic method is a generalized version of the pulse-echo method. It has qualities that make it practical for assessing mechanical properties of composite laminates and other highly heterogeneous, anisotropic structures.

The construction of Acousto-Ultrasonic system varies from the pulse-echo system in the following ways :

1) two probes are used (separate sender and receiver),

2) the probes are coupled to the material in a manner that does not permit acquisition of a set of direct

echoes,

3) the received signals are complicated and depend on boundary conditions, microstructure, etc.

The Acousto-Ultrasonic method produces elastic waves which interact with the material morphology and boundary surfaces in a manner similar to spontaneous stress waves arising at the onset of microcrack nucleation. The resultant output waveform is like a "burst" type acoustic emission. It has been demonstrated empirically that the acousto-ultrasonic waveform may yield significant correlations with mechanical properties [51].

Following properties of materials can be potential features for object identification:

3.2.1 Thermal Properties

1) Thermal Conductivity

Thermal conductivity of a material is the rate at which it absorbs heat. Thermal conductivity is a unique feature for each material. It can be measured using tactile sensors. A temperature gradient between the tactile sensor and the object in consideration is created by electrically heating the appropriate part of the tactile sensor upto a suitable temperature higher than room temperature [15]. The sensor is then guided to make contact with the object. The rate of heat flow is measured for a small interval of time to get an estimate of thermal conductivity.

1) Thermal diffusivity

Thermal diffusivity of the touched govern the time variations of the sensor's temperature [15]. Warmer feel of the material suggests lower thermal diffusivity.

3.2.2 Electrical Properties

1) Electrical Conductivity

This can be an excellent feature for object identification. It can be measured quite easily and accurately. It can be measured by providing a potential gradient at two points on the object surface and measuring the current passing through the material. Eddy current techniques can be used to get "on-line" measurement of electrical conductivity [9].

2) Dielectric Constant

Dielectric constant determines the extent to which a material can be a good insulator. It can be measured using impedance analyzer.

3.2.3 Optical Properties

1) Illuminance

Illuminance is a quite difficult property to measure. It can be measured using spectral information. If measured correctly it can be a very useful feature.

2) Irradiance

Irradiance is similar to illuminance. Tough thing to be measured, but a very useful feature.

3.2.4 Mechanical Properties

1) Elastic Moduli

Elastic moduli can be measured using tactile [15] or ultrasonic [51] sensors. In case of tactile sensing approach the knowledge of the relationship between contact pressure and object deformation is required to determine the moduli of elasticity. The contact pressure can be detected using either of the two approaches : using local information from the sensing elements, or by approximating as total contact force divided by the contact area [15]. Longitudinal and transverse ultrasonic velocity measurements can be used to measure elastic moduli [51].

2) Tensile Strength

Ultrasonic techniques can be used to measure the tensile strength of the material of an object. Tensile strength can be measured using longitudinal and transverse velocity measurements [51]. Some materials may demand more than one NDE technique to find its tensile strength; e.g. velocity and Brinell hardness measurements are required to calculate tensile strength of cast iron.

3) Hardness

Hardness can be found using NDE techniques like acoustic emission or acousto-ultrasonic techniques [51].

4) Porosity

Ultrasonic techniques can be used to detect porosity in the material [51]. Radiographic techniques can also be used [9].

5) Grain Structure

Grain structure can be revealed by the analysis of attenuation of acoustic waves [9]. X-ray diffraction can also be helpful.

6) Texture

X-ray and ultrasonic techniques can be used to measure texture of the material [9]. Using X-ray diffractometer the relative amounts of particular texture components can determined from the relative intensities of specific diffraction peaks at selected points. Improvements in velocity measurement has made ultrasonic techniques very promising for texture measurement [9].

3.3 Perceptual Organization.

Perceptual Organization provides appropriate groupings and structures from an image without previous knowledge of its contents. Human beings can detect many classes of patterns and arrangements of images. According to Lowe [37] the three most important functions of perceptual organization are : Segmentation, Three-space Inference and Indexing World Knowledge.

Segmentation can reduce the search space tremendously. Instead of matching the image of the complete object, one looks for matching components of images. Image Segmentation has been an area of active research for quite long, but the emphasis has been mostly on region analysis. Lowe suggests Image Segmentation based on general methods of perceptual organization.

Perceptual organization can provide constraints on depth leading to 2D as well as 3D segmentation. Perceptual organization gives 2D relations between image features, which can lead to specific three dimensional interpretations [37].

Object identification in a large domain mainly depends on the method of selection of candidate objects from a large search space of world knowledge. Perceptual organization can provide reliable index to the world knowledge to extract the most suitable candidates.

Following features can be used to assist object identification. Features from 1 - 6 are general features used as part of perceptual organization, and the rest of them discuss mapping of 2D relations to 3D space.

1) Proximity

Elements which are close together can be combined to form one part.

2) Similarity

Similar elements form one class.

3) Continuation

Elements lying on a same line or curve can be grouped into one class.

4) Closure

Every curve tend to have a closure.

5) Symmetry

Elements having bilateral symmetry about some axis belong to one class.

6) Familiarity

Familiar elements are grouped together.

8) Collinearity

Collinearity of points or line segments in 2D image suggests collinearity in 3D space.

9) Curvilinearity

If points or arc are curvilinear in 2D then they are curvilinear in 3D space.

10) Terminations at a common point

Two or more termination at common point in 2D space suggest curves terminating at a common point in 3D space.

11) Termination at a continuous curve

A termination at a continuous curve in 2D space infers that the distance between terminating curve and the camera is not less than the distance between it and the continuous curve (in 3D space).

12) Crossing of continuous curves

If there is a crossing between two continuous curve then both of them cannot be occluding geometric edges.

13) Parallelism

Parallel curves in 2D image are parallel in 3D space.

14) Lines converging to a common point

Convergence of three or more parallel lines in 2D image suggests two possibilities in 3D space : either the lines are parallel or they have a common convergence point.

15) Equal spacing

If 2D image shows equal spacing of collinear points or parallel lines then it is implies that there are equal spacing in 3D space and that parallel lines are coplanar.

16) Virtual lines and points

The nature of relations held between terminations or virtual lines in 2D space, and those between virtual features in 3D space is the same.

17) Parallel virtual lines (created by shadows)

Existence of parallel virtual lines between tangent discontinuities in curves in 2D space infers correspondence of curves to geometric edges and their cast shadow boundaries in 3D space.

3.4 Summary of the chapter.

This chapter discussed different sources of feature extraction. Features discussed were mentioned with the sources as seen in the literature. A lot of features can be obtained using a number of different techniques. As mentioned perimeter can be calculated using 2D vision and 3D vision techniques. Though not mentioned with tactile sensing perimeter and a number of other features (e.g area) reported as being obtained using 2D vision techniques can be measured using tactile sensing. Another example of multi-source feature is texture. Texture can be obtained using vision, tactile sensing and NDE techniques. It will be a good idea to come up with a list of features and the possible techniques for their extraction. Then we can get estimates for cost and accuracy for each technique and prepare an appropriate plan for object identification.

4.0 EVALUATION OF FEATURES AND SOURCES

In this chapter evaluation of features and sources will be discussed. The discussion will cover cost of sources, cost of computation of features, accuracy of computation, and applicability of sources. In the previous two chapters vision, touch, material properties and perceptual organization were discussed as sources of features for object identification. Vision covered both 2D and 3D techniques. Touch basically meant tactile imaging using transducers elements made of piezoelectric material. Material properties mostly consisted of properties analyzed using Non Destructive Evaluation (NDE) techniques. Perceptual organization is not a direct source of features. It could be based on the other three sources. All the features mentioned in chapters 2 and 3 were discussed along with the sources that were used to extract them. But after understanding the techniques of machine vision, tactile sensing, and NDE, one can easily find out that most of the features can be obtained using either of the three sources; there are only few exceptions. For example vision is required to extract color. Tactile sensing or NDE techniques (without requiring some vision) can not be used to obtain the color information. Similarly thermal properties, electrical properties, and mechanical properties like elasticity can not be computed using vision; they require either tactile sensing or NDE techniques.

4.1 Cost of Sources

The actual cost of the sources will be a one time expenditure so it might not be an important factor. However it might help to have an idea of the initial cost. Tactile sensing systems are the least expensive ,mainly because of low cost of tactile sensors. NDE techniques have variable cost depending upon the technique used; for example ultrasonic systems are not very expensive, but X-ray diffraction systems can be very expensive.

Assuming more than one NDE techniques will be used, NDE system will be most expensive among the three systems to be used. Vision system will have a cost more than tactile and less than NDE system.

4.2 Cost of Computation.

By cost of computation is meant the time required to extract a feature. The difference of cost of computation is basically governed by the efficiency of the sensors; because all major feature extraction systems have most of other things common; that is they have A/D converter and digital signal analyzer. The response time of touch sensors is the least; with NDE sensors being second in the race and vision sensors requiring relatively more time. Sensors are not the only factor responsible for cost of computation; data analysis time can also play a major role. Some sources are better equipped for particular type of features.

Features discussed in the previous chapters can be classified as geometrical, Mechanical, Thermal and discontinuities. Vision will be most suitable for geometric features. Touch will be the best candidate for thermal features, and mechanical features and discontinuities will favor NDE techniques like ultrasonic imaging. Ultrasonic techniques are the most useful techniques among the NDE techniques. They are low cost, efficient and safe.

Table 4.1 shows the relative cost of computation of various features depending upon the source used to extract them. The estimation of the cost is based on the efficiency of the sensor technology and the amount of computation required to extract a particular feature using a specific source.

Table 4.1 Cost of computation

	Vision	Touch	NDE
1) Size	M	L	M
2) Boundary Curvedness	H	L	L
3) Symmetry	L	M	M
4) Compactness	H	M	L
5) Angular Variability	H	M	L
6) Size of Angles	H	M	L
7) Length of Sides	H	M	L
8) Radial Length	M	M	L
9) Actual Boundary Coordinates	L	L	M
10) Complexity	H	M	L
11) Uniformity of Side Lengths	M	L	H
12) Narrowness	H	M	L
13) Convexity	H	M	L
14) Concavity	H	M	L
15) Maxima	H	M	L
16) Minima	H	M	L
17) Points of Inflection	H	M	L
18) Discontinuities in Curvature	H	M	L
19) Endpoints	H	M	L

20) Intersection Points	H	M	L
21) Tangent Points	H	M	L
22) Perimeter	M	L	H
23) Area	M	L	H
24) Circularity	L	M	M
25) Adjusted circularity	L	M	M
26) Maximum distance from center of gravity to edge contour	H	M	L
27) Minimum distance from the center of gravity to edge contour	H	M	L
28) Eccentricity (elongation)	H	M	L
29) Shape	M	M	H
30) Height	H	M	L
31) Silhouettes	H	M	L
32) Number of connected background components	L	L	H
33) Surface Span	H	L	M
34) Boundary-background Fit	M	M	L
35) Boundary Type	M	L	M

36) Normal angle	M	L	L
37) Minimum-patch distance	M	L	L
38) Maximum-patch distance	M	L	L
39) Boundary angle	M	L	L
40) Patch-fit	M	L	L
41) Jump-gap	L	M	M
42) Surface Aspect	H	M	L
43) Surface Azimuth	H	M	L
44) Surface Elevation	H	M	L
45) Curvatures	H	M	L
46) Displacements	H	M	L
47) Surface Smoothness	H	M	L
48) Spatial Symmetries	M	L	L
49) Compliance	NA	L	M
50) Elasticity	NA	L	M
51) Normal-contact position	NA	L	M
52) Contact	NA	L	M
53) Roughness	H	L	M
54) Surface Shape	H	L	M
55) Parts and Semiparts	H	L	M
56) Contour	M	L	H
57) Tactile Edge	NA	L	NA

58) Corner	H	L	L
59) Hole	H	M	L
60) Cavity	H	M	L
61) MIC	H	L	M
62) MAER	H	L	M
63) ASPR	H	L	M
64) Thermal Conductivity	NA	L	H
65) Thermal diffusivity	NA	L	H
66) Electrical Conductivity	NA	L	L
67) Dielectric Constant	NA	L	L
68) Illuminance	H	NA	H
69) Irradiance	H	NA	H
70) Elastic Moduli	NA	H	L
71) Tensile Strength	NA	M	L
72) Hardness	NA	M	L
73) Porosity	H	H	L
74) Grain Structure	NA	NA	M
75) Texture	H	M	L
76) Proximity	H	M	L
77) Similarity	M	M	H
78) Continuation	M	M	H
79) Closure	H	L	M
80) Symmetry	L	M	H
81) Familiarity	M	M	M

82) Collinearity	M	L	H
83) Curvilinearity	M	L	M
84) Terminations at a common point	L	M	H
85) Termination at a continuous curve	L	M	H
86) Crossing of continuous curves	L	M	H
87) Parallelism	M	M	H
88) Lines converging to a common point	M	M	H
89) Equal spacing	M	L	L
90) Virtual lines and points	M	L	L
91) Parallel virtual lines (created by shadows)	M	NA	NA

4.3 Accuracy of Computation.

Accuracy of computation is based on the resolution of the system used to extract features, accuracy of the sensors and complexity of computation required. Vision sensors have a problem of signal noise, but being an older technology the resolution of vision systems (512 X 512 or 1024 X 1024) are typically higher than that of other technologies (256 X 256). A single ultrasonic sensor by itself have a very good accuracy, but because of being a new technology integration of ultrasonic sensor elements still represents some problems, which decreases the accuracy of ultrasonic arrays (which are required to get high resolutions). Again, just like cost of computation some features may present different computation burdens to different sources.

Table 4.2 shows the accuracy of computation of different features depending upon the source used to extract them. Criteria used to estimate the accuracy of computation is based on the discussion in the previous paragraph.

Table 4.2 Accuracy of computation

	VISION	TOUCH	NDE
1) Size	H	M	M
2) Boundary Curvedness	H	M	M
3) Symmetry	H	M	M
4) Compactness	L	M	H
5) Angular Variability	H	H	M
6) Size of Angles	H	H	M
7) Length of Sides	M	H	H
8) Radial Length	M	H	H
9) Actual Boundary Coordinates	M	H	H
10) Complexity	H	M	L
11) Uniformity of Side Lengths	H	H	H
12) Narrowness	H	M	M
13) Convexity	H	H	M
14) Concavity	H	H	M
15) Maxima	L	M	H
16) Minima	L	M	H
17) Points of Inflection	H	M	L
18) Discontinuities	L	M	H

in Curvature			
19) Endpoints	L	M	H
20) Intersection Points	L	M	H
21) Tangent Points	L	M	H
22) Perimeter	L	H	M
23) Area	L	H	M
24) Circularity	H	M	M
25) Adjusted circularity	H	M	M
26) Maximum distance from center of gravity to edge contour	L	M	H
27) Minimum distance from the center of gravity to edge contour	L	M	H
28) Eccentricity (elongation)	L	M	H
29) Shape	H	M	L
30) Height	M	M	H
31) Silhouettes	H	M	L
32) Number of connected background components	H	M	L

33) Surface Span	L	H	M
34) Boundary-background Fit	M	M	H
35) Boundary Type	H	M	L
36) Normal angle	H	H	M
37) Minimum-patch distance	M	L	H
38) Maximum-patch distance	M	L	H
39) Boundary angle	H	M	M
40) Patch-fit	H	M	M
41) Jump-gap	H	M	M
42) Surface Aspect	L	L	H
43) Surface Azimuth	L	L	H
44) Surface Elevation	L	L	H
45) Curvatures	M	M	H
46) Displacements	M	M	H
47) Surface Smoothness	M	H	H
48) Spatial Symmetries	H	M	M
49) Compliance	NA	H	M
50) Elasticity	NA	H	M
51) Normal-contact position	NA	H	M
52) Contact	NA	H	M
53) Roughness	L	H	M

54) Surface Shape	M	H	L
55) Parts and Semiparts	H	M	L
56) Contour	H	M	L
57) Tactile Edge	NA	H	NA
58) Corner	H	H	H
59) Hole	L	H	H
60) Cavity	L	H	H
61) MIC	L	H	M
62) MAER	L	H	M
63) ASPR	L	H	M
64) Thermal Conductivity	NA	H	M
65) Thermal diffusivity	NA	H	M
66) Electrical Conductivity	NA	H	H
67) Dielectric Constant	NA	H	H
68) Illuminance	L	NA	NA
69) Irradiance	L	NA	NA
70) Elastic Moduli	NA	M	H
71) Tensile Strength	NA	M	H
72) Hardness	NA	M	H
73) Porosity	NA	L	H
74) Grain Structure	NA	M	NA
75) Texture	M	H	H
76) Proximity	L	M	H
77) Similarity	M	L	L

78) Continuation	M	L	L
79) Closure	M	L	L
80) Symmetry	M	L	L
81) Familiarity	H	M	M
82) Collinearity	H	M	M
83) Curvilinearity	M	M	H
84) Terminations at a common point	H	M	L
85) Termination at a continuous curve	H	M	L
86) Crossing of continuous curves	H	M	L
87) Parallelism	H	M	M
88) Lines converging to a common point	H	M	M
89) Equal spacing	M	H	H
90) Virtual lines and points	M	L	L
91) Parallel virtual lines (created by shadows)	L	NA	NA

4.4 Applicability of Sources

As mentioned in the beginning of the chapter each source of features have different applicability. More than one source can be used to obtain certain features, and some features might require certain sources. For example color and printed or painted patterns or any kind of drawing would require vision; temperature sensing would require touch or some kind of thermal imaging; and elasticity will require touch or NDE techniques. So the best use of sources of features will be to realize the applicability of each source and use their combination to complement their utility.

4.5 D-matrix.

The list of features obtained from the previous chapters and used in table 4.1 and 4.2 is quite extensive. Some of the features are bound to be redundant. We can either analyze the features and decide about the redundancy of features or let the computer take care of it by writing a computer program which lists the redundant features. We can use a "distinguishability matrix" also referred to as "D-matrix" [13]. D-matrix is a table which lists the separability of each pair-wise combination of objects with respect to all available features. Each column refer to a pair of objects, and each row refers to a particular feature. All entries in the table are compared against a threshold to create a binary form of the D-matrix. A 1 in any block shows that the corresponding pair of objects can be separated using a particular feature. To identify all the objects in the domain there should be at least one 1 in each column of the D-matrix which gives a "covered" table. If a covered table can not be obtained using the available set of features and the initial threshold then two possible solutions are suggested: either find another feature or raise the threshold. The D-matrix will have the inherent redundant information based on the type of features used. The redundancy test is : if deletion of a row in the D-matrix keeps the table covered then the feature denoted by that row is redundant. Minimal set of features can be found by borrowing minimization techniques from switching theory and logical design [27]. Notice the features until now are independent of the source obtained. With each feature we can keep a list of sources and along with their ratings based on cost of computation, accuracy of computation or both.

At this stage CESM takes over. CESM stands for Classification Expert Systems Maker. The Next Chapter discusses CESM and its usefulness in Object Identification.

5.0 CESM

Classification Expert System Maker (CESM) has been developed by Dr. Zeigler and his students at AI and SImulation Lab (at the Electrical and Computer Engineering Department of University of Arizona, Tucson). Originally CESM was designed to run on IBM PC or compatible machines using PC Scheme/SCOOPS; a dialect of LISP.

Recently CESM has been transported to TI/Explorer Scheme (by the author) and thus can also run on TI/Explorer a LISP machine. The porting on TI/Explorer is not complete, some more work has to be done to run CESM on TI/Explorer without interruption. The RAM requirement for the IBM PC version is 512 K or larger.

5.1 Expert Systems Development Tool.

CESM is a tool to develop classification expert systems. Many expert systems can be termed as classification expert systems. For example diagnosis systems are classification systems. In a diagnosis expert system the problem to be diagnosed is classified as one of the candidate classes of problems. The reasoning done in CESM is evidence based; it uses Dempster-Shafer based evidence accumulator. CESM makes the development of expert systems quite straightforward. The first step is to come up with an entity structure. An entity structure is a hierarchical semantic data structure. It starts with a root and ends with leaves. Between the root and a leave there might be a zero or more nodes. Predicates are associated with node entities and semantic relations exist on predicates. The next step is to enter the entity structure into the knowledge base using the knowledge engineering interface. After completing the entry of entity structure knowledge, one can add the synonym, anti-synonym, expression and/or function description. Synonyms and antisynonyms are the respective predicates e.g a list of synonyms can be (small little) and a list of anti-synonyms can be (small large). Expression defines a combination of predicates e.g. square = four-sides and equal-sides. Functions can be very useful; they can be used to define complex functions of predicates or to interface with real time devices to get some measurement.

5.2 Knowledge Representation and Data types.

Entity structure described above is the knowledge representation used in CESM. Each entity denotes a class or a subclass of a concept or a real world object having properties described by a set of predicates. Inheritance is from top to bottom; children entities inherit attributes of their parents.

A child entity is a subclass of its parent. Predicates are used to distinguish between the subclasses. Predicates can be related to each other using synonym, anti-synonym or expression definition.

CESM uses two main data types: predicate and class. A predicate is used to describe a property of a class with a range of [True, False, Unknown]. The evidential status value has a range of [CEF, EF, EA, CEA, N, X] with following definitions :

CEF - Conclusive Evidence For

EF - Evidence For

EA - Evidence against

CEA - Conclusive Evidence Against

N - Neutral Evidence

X - Inconsistent

A four-tuple (ef,ea,n,x) is used to represent the evidential status, with the following conditions :

1) $0.0 <= (ef,ea,n,x) <= 1.0$ and

2) $ef + ea + n + x = 1.0$

The evidential status and the 4-tuples are related through the following relations :

CEF = (1,0,0,0)

EF = (ef,0,1 - ef,0)

CEA = (0,1,0,0)

EA = (0,ea,1 - ea,0)

N = (0,0,1,0)

X = (0,0,0,1)

For efficiency purposes CESM only store a triple (ef,ea,n) since x can be computed as x = 1 - (ef + ea + ea + n). Class and Predicate values are made compatible using the following relations : (1 0 0) = True, (0 1 0) = False, and (0 0 1) = Unknown.

5.3 Composition of CESM.

CESM consists of five parts :

(1) Knowledge Acquisition Module,

(2) Knowledge Base Compiler,

(3) Working Memory,

(4) Inference Engine, and

(5) User Consultation Module.

Both Knowledge Acquisition Module and User Consultation Module have a user interface to assist the user. To get a detailed discussion of the five modules refer to the CESM Documentation [54].

For purpose of completion the main tasks of the above mentioned modules will be stated. Knowledge acquisition module is responsible for acquiring the knowledge of the entity structure given by the user. It takes care of all aspects of input knowledge including the semantic relations of predicates. CESM provides a simple KBDL (knowledge base description language). The output of this module is a list of classes, a list of predicates, a list of expression definitions, a list of function definitions, a list of synonyms, a list of anti-synonyms and an entity structure. All this knowledge is stored in a file with a suffix .kb.

Knowledge base compiler compiles the output of the Knowledge acquisition module into a set of rules that can be recognized by the inference engine. The primary output of this module is a set of production rules. The set of production rules and the other parts of the compiled knowledge is stored in a file with a suffix .rb. The .rb files are ready to run and consulted using the user consultation module.

Working Memory Module serves both Knowledge base module and User Consultation Module. During Knowledge base development it contains the information that gets stored in a .kb file. During consultation, the working memory contains the original information from a .rb file plus updated values of predicates and the evidence information.

CESM has a dual inference engine. It supports both forward and backward chaining. The forward chaining process starts form a neutral position and accumulates evidence for predicates as it goes along. Based on the values of predicates associated to an entity, the entity with the most positive evidence is declared to be the most suitable candidate. Backward chaining is a hypothesis verification process. It starts with a guessed entity and confirms/disconfirms the entity based on the value assigned to the predicates associated with the guessed entity.

User Consultation Module provides an interface between the user and the inference engine. It only asks the facts which are related to current goal. It provides on-line deduction report. Different Windows are used to prompt questions depending upon the inference strategy, but the querying window is common.

5.4 Building a Knowledge Base.

As mentioned earlier the first step towards building a knowledge base is defining an entity structure which describes the classification problem to be solved. CESM has a very user friendly interface for knowledge development. Following the step by step instructions one can easily enter the knowledge base. Semantic relations of predicates can be entered after completing the entry of the entity structure. While entering the entity structure information, any english word, abbreviation or phrase can be used to declare a class or a predicate. To separate the words in a phrase we can use anything but a space, because space is a separator in Scheme Language. The recommended separators are "-" or "_". "Usually" and "rarely" are reserved words. To declare complex predicates boolean operators _and_, _or_ and _not_ can be used.

5.5 Consulting a Rule-based system.

Consulting a rule-based system is even easier than developing a knowledge base. In the beginning of the consultation one might want to change the default parameters. Parameters consist of : Conflict resolution strategy, Grain factor, Threshold, and EF/EA levels. A choice can be made among four conflict resolution strategies : most positive and most certainly, most certainly and most positive, most negative and most certainly, and most certainly and most negative. Grain factor will determine the speed of inference. Higher grain factors will require more time than lower grain factors. Threshold will limit the number of possible candidates for the unknown entity. EF/EA level will also determine the speed of inference. The next step can be the selection of inference strategy (forward chaining or backward chaining).

In case of backward chaining the first step is to make a hypothesis. Then the system will ask for the values of the predicates associated with the hypothesized entity. Based on the user response to the predicate values the entity will be confirmed or disconfirmed. If the hypothesis is disconfirmed then the user may make another hypothesis and start all over again. The user can have as many iterations of inference as may be required.

If forward chaining is selected then the user will be asked to input the values for broad-ranging predicates to begin with. As the search narrows more specific predicates get evaluated. Final decision about the evidential status of various entities is made based on the values of predicates associated with the entities. In this strategy only one iteration of inference is allowed.

6.0 SAMPLE EXPERT SYSTEMS

In this chapter different approaches to the design of a rule based system to identify objects in a particular domain will be discussed. First approach is based on intuition only. The second approach is based on Peter Allen's work [2], and the final approach is based on the study of the potential features (chapter 2 and chapter 3).
All three versions of the system were implemented on CESM.

6.1 Domain of Objects to be identified.

Objects to be identified belong to a chemical lab. The following objects are to be identified :

1. Bunsen Burner,
2. Test-tube Stand,
3. Tripod Stand,
4. Faucet,
5. Beaker*,
6. Funnel*,
7. Flask*, and
8. Jar.

Consider a lab with three areas: Work Area, Storage Area and Supply Area. It is assumed that bunsen burner, test-tube stand, tripod stand, and faucet could only be in the work area, and similarly Jar could only be in the supply area, but the objects with * could be either in the work area or in the storage area. A robot is assumed to be working in this lab. A primary task of the robot will be to perform experiments in the lab, but before taking any step the robot will have to identify objects that he need to manipulate. One easy solution might be to label all objects and the robot will just have to read the label to identify objects. This approach could be helpful but it might have some limitations. The objects need to be in the right orientation for reading the label; and due to some error in the labelling system some objects might get mislabelled or don't get labelled at all. Also if the system is to completely automated, some object identification techniques will be required to label the objects. So object identification is very necessary.

In order to identify an object, the first thing the robot will have to do is to identify the area he is in, because that reduces the evidence for objects which are not supposed to be in that area. As the experimental systems in this chapter and study of other object identification shows, the local environmental knowledge and knowledge of the domain is extremely important for object identification. A feature which works very well in one domain might be useless in another domain. So the first step in object identification is to study the environment and domain of the objects to be identified and get the best list of features.

6.2 First Approach.

The first approach to Chem-lab (chemical lab) objects identification system is quite primitive. The objects were studied from a human perspective. The main question asked was how a human might identify these objects in the environment discussed in the previous section. The first thing to be found might be the area of concern (work area, storage area, or supply). It was assumed that the robot will identify objects using machine vision only. Each object was studied individually. As mentioned earlier the study was based on vision only. Let us discuss the visual features of all the objects in the domain discussed. Some of the features are based on the other features.

Bunsen Burner

The material used for the bunsen burner is metallic, usually iron, so it is opaque. It has a gas pipe connected at the bottom. It can not be used as a container.

Test tube stand

Assuming the test tube stand is made of wood, the main feature of this object is its opaqueness. An indirect feature is the use of test tube stand, that is to hold test tubes. A CESM expression can be used to define the use of test tube stand in terms of its rectangular shape and the fact that it has holes to hold test tubes. The expression definition used was : used-to-hold-testtubes = (and have-rectangular-shape have-holes). Notice this was not a very creative approach but it was a good learning experience.

Tripod Stand

The material of the tripod stand is not transparent. It is a three legged object. It is used to hold things, and has a rounded top.

Faucet

It is assumed that the faucets used in the lab are opaque. A main feature of a faucet is that it has a knob.

Beaker

A beaker has cup like shape. Beaker is usually made of glass, so it is transparent. It is used as a container.

Funnel

Like a beaker funnel is also transparent. It has a conical shape.

Flask

Like a beaker flask is also transparent and used as a container, but with a different shape; it has a rounded bottom.

Jar

Jar is also transparent and used as a container. The main difference between jar and other containers is the size; they are big. Instead of using "transparent" the predicate used was "usually transparent". The assumption was that if jars are filled with opaque materials then they may not be transparent. (This assumption is probably inconsistent).

Appendix 1 shows the knowledge base for this approach.

6.3 Second Approach.

This approach was based on object identification system designed by Peter Allen [2]. The system had a sense of vision and sense of touch. It used active touch and passive vision. Assuming that the Chem-lab system has access to the same sensors and signal processing system a second version of the system was designed.

A general identification test was designed. An object would be identified completely if it has an appropriate label that can be read by the robot, or the components and features extracted from the unknown object find a match in the database. Hence for each object, without a proper (or not visible) label, a logical decomposition was done to identify its components; and its features were extracted. The object was represented by the following generic structure :

****

- * Object Bounding Box .
- * Description of the components of the object:
  - ** For each component (bottom, top, or some extended component) the information required :
    - *** Bounding Box
    - *** Area
    - *** Closed or Open
    - *** shape (cylinderical, planar or circular)
    - *** transparent or opaque
- * Description of the features of the object:

  Two types of feature may be found holes or cavities with the following information.
  - ** Hole :
    - *** Area
    - *** M_{02}
    - *** M_{20}
    - *** P_1
    - *** P_2
    - *** P_3
    - *** Centroid
  - ** Cavity :

*** Area

*** depth

*** M02

*** M20

*** P3

*** Centroid

****

For descrition of the elements of the data structure described above either refer to chapter 3 or refer to [2]. Appendix 2 shows the CESM knowledge base for the second approach.

6.4 Final Approach .

Assume the following definitions :

A -- Bunsen Burner

B -- Tripod Stand

C -- Test-tube Stand

D -- Facet

E -- Beaker

F -- Flask

G -- Funnel

H -- Jar

and

F1 -- Area

F2 -- Perimeter

F3 -- Circularity

F4 -- Electrical Conductivity

F5 -- Thermal Conductivity

F6 -- Texture

F7 -- Hole

F8 -- Cavity

F9 -- Surface shape

	A	B	C	D	E	F	G	H
F1	14	6	25	7	15	16	13	30
F2	9	4	18	5	9	12	10	21
F3	5.78	2.66	12.96	3.57	5.4	9	7.7	14.7
F4	97	97	20	34	50	50	50	50
F5	95	95	30	50	60	60	60	60
F6	30	30	70	50	20	20	20	20
F7	1	4	10	3	-100	-100	.5	-100
F8	13	-100	-100	-100	15	16	-100	30
F9	10	20	25	15	20	28	13	22

10 = pure cyliderical

20 = pure planar

30 = pure circular

-100 is used to denote that the feature in consideration can not be detected. A high negative value is convenient to show the absence of the feature for a wide range of threshold values.

The data for hole or cavity is its size. All the above given data is fake data for the purpose of showing the effectiveness of the D-matrix approach. Some numbers are intuitive while others are just some numbers. Let us start with a threshold of 5. Notice a feature having a value of zero will pass the threshold test irrespective of the threshold value selected. Let A-B denote whether Bunsen Burner can be differentiated from Tripod stand based on the feature in consideration, B-C denote the distinguishability between tripod stand and test-tube stand and so on. A 1 means the differentiation is possible, and a 0 means it can't be done. Before we use threshold to get 1's and 0's we will have to get the difference in feature values.

	A-B	A-C	A-D	A-E	A-F	A-G	A-H
F1	1	1	1	0	0	0	1
F2	1	1	0	0	0	0	1
F3	0	1	0	0	0	0	1
F4	0	1	1	1	1	1	1
F5	0	1	1	1	1	1	1
F6	0	1	1	1	1	1	1
F7	0	1	0	1	1	1	1
F8	1	1	1	0	0	1	1
F9	1	1	1	1	1	0	1

	B-C	B-D	B-E	B-F	B-G	B-H
F1	1	0	1	1	1	0
F2	1	0	1	1	1	1
F3	1	0	1	1	1	1
F4	1	1	1	1	1	1
F5	1	1	1	1	1	1
F6	1	1	1	1	1	1
F7	1	0	1	1	0	1
F8	0	0	1	1	0	1
F9	1	1	1	0	1	1

	C-D	C-E	C-F	C-G	C-H
F1	1	1	1	1	1
F2	1	1	1	1	0
F3	1	1	0	1	0
F4	1	1	1	1	1
F5	1	1	1	1	1
F6	1	1	1	1	1
F7	1	1	1	1	1
F8	0	1	1	0	1
F9	1	1	0	1	0

	D-E	D-F	D-G	D-H
F1	1	1	1	1
F2	0	1	1	1
F3	0	1	0	1
F4	1	1	1	1
F5	1	1	1	1
F6	1	1	1	1
F7	1	1	0	1
F8	1	1	0	1
F9	1	1	0	1

	E-F	E-G	E-H

F1	0	0	1
F2	0	0	1
F3	0	0	1
F4	0	0	0
F5	0	0	0
F6	0	0	0
F7	0	1	0
F8	0	1	1
F9	1	1	0

	F-G	F-H
F1	0	1
F2	0	1
F3	0	1
F4	0	0
F5	0	0
F6	0	0
F7	1	0
F8	1	1
F9	1	1

	G-H
F1	1
F2	1
F3	1
F4	0
F5	0
F6	0
F7	1
F8	1
F9	1

Hence we get the following matrix :

F1: 1110001101110111111111001011

F2: 1100001101111111100111001011

F3: 0100001101111110100101001001

F4: 0111111111111111111111000000

F5: 0111111111111111111111000000

F6: 0111111111111111111111000000

F7: 0111111011011111111101010101

F8: 1110011001101011011101011111

F9: 1111101111011110101101110111

where F1 .. F9 represent rows of the thresholded distinguishability matrix and the columns represent the columns of the matrix. Hence F1 stands for Area, the first column represents the column A-B , and so on.

If try to optimize the above matrix we get :

F1: 1110001101110111111111001011

F4: 0111111111111111111111000000

F9: 1111101111011110101101110111

It can be noticed right away that F4, F5, and F6 i.e, Electrical conductivity, Thermal Conductivity, and Texture give redundant information. Electrical Conductivity is picked based on the assumption that it's cost of computation is less than the cost of the other two features. Another important observation is that Column No. 22 (distinguishability between beaker and flask) has only one 1 and that comes through F9 (surface shape). Therefore F9 can not be deleted. Hence following rules were used to get the optimized matrix :

1. If there are redundant features pick one based on cost of computation.
2. For all rows do the following :

   take one row out at a time from the thresholded d-matrix. If the matrix is still covered delete that row.

Appendix 3 shows the CESM knowledge base for the final approach.

6.4.1 Pseudo code using D-matrix and CESM

Read the list of objects and the list of features

Extract the features from each object (give a high negative value for the feature that can not be extracted) and prepare a F-matrix (a feature matrix ; rows denote features and columns denote objects)

```
D-col = 0
Thresh = Initial Threshold value
matrix-covered = false
Do while the thresh-d-matrix is not covered
   For col = 1 to tot-col - 1
      For comp-col = col + 1 to tot-col
         D-col = D-col + 1
         For row = 1 to tot-rows
           D-matrix[row,D-col] = F-matrix[row,col]
                    - F-matrix[row,comp-col]

  Tot-D-col = D-col

  for row = 1 to tot-rows
     for col = 1 to tot-d-col
        thresh-d-matrix[row,col] = d-matrix[row,col] -
                                          thresh
  (* Check the coverage of the matrix *)
     covered = true
     for col = 1 to tot-d-cols
       tot-zeros = 0
       for row =1 to tot-rows
         tot-zeros = thresh-d-matrix[row,col] +
                         tot-zeros
       if tot-zeros = tot-rows then
```

```
        covered = false
        exit for loop

    matrix-covered = covered
```

Optimize the matrix (delete rows that are not needed)

Generate a classification tree using the information from D-Matrix

Convert the classification tree into CESM .KB

Compile .kb into .Rb and make it available for consultation

The above pseudocode can be easily transferred to actual code.

7.0 A MULTI SENSOR APPROACH

Based on the study of potential features of objects for robotic object identification a comprehensive multisensor system is proposed. Fig. 7.1 shows the architecture of the proposed system.

7.1 Sensors Interface.

Its job will be to activate the sensors as they are needed and pass that data to feature extractor.

7.2 Features Extractor.

It will receive data from the sensors interface and extract features of the object from that information. It will use a list of features, and will try to extract as many features as it can. For the features that can not be extracted it will use a high negative number, to help in obtaining a thresholded d-matrix. In learn mode this module will extract features for all objects in the domain; and send that information to feature optimizer.

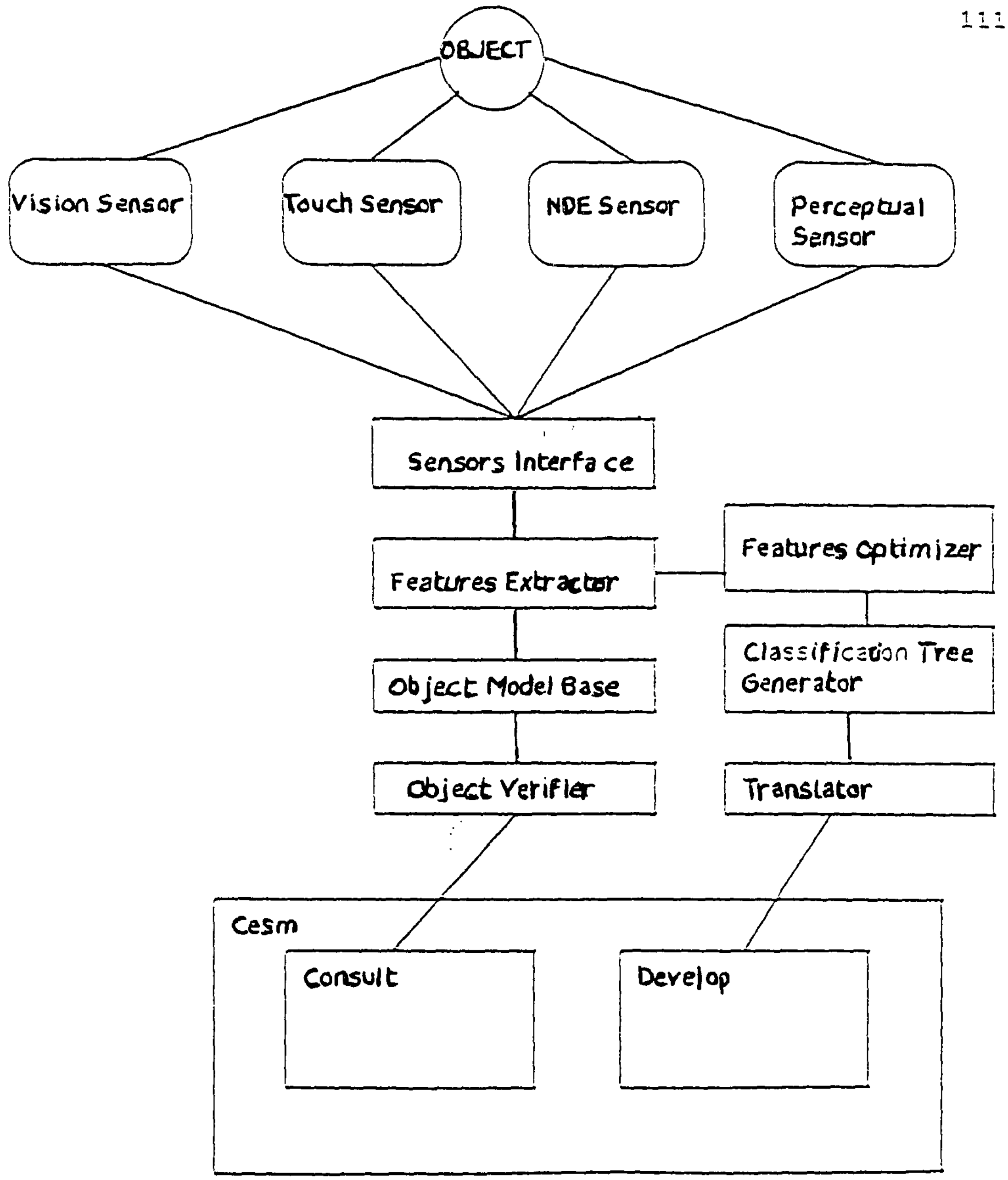

Fig 7.1 - A Multisensor Object Identification System

7.3 Feature Optimizer.

It will build an F-matrix (feature matrix). Rows will be features and columns will be objects. From the F-matrix it will get the d-matrix. It will then use a default threshold to get a thresholded d-matrix. If the matrix is not covered it will decrease the threshold value. If even for a threshold of 1 the matrix remains not covered, then it should halt and print out a message to the user that more features should be discovered in order to completely identify the objects in the given domain.

In case of a covered thresholded d-matrix this module will optimize the matrix to get rid of features whose deletion does not affect the coverage of the matrix. So the output of this module will be an optimized thresholded d-matrix.

7.4 Classification Tree Generator.

This module will generate a classification tree using the optimized thresholded d-matrix provided by the feature optimizer. The algorithm of this module will try to produce a tree with an optimal (largest possible) branching factor.

7.5 Translator.

This module will translate the classification tree generated by the previous modules into the CESM knowledge base.

7.6 Object Model Base.

This module will be only required for hypothesis verification; or for extra accuracy purposes.

7.7 Object Verifier.

This will be basically a pattern matcher. It will look for a match in the features extracted for an unknown object and the features stored for the hypothesized object.

7.8 CESM.

CESM has been explained in chapter 5. Cesm will be used both in learn mode and in recognition mode. In learn mode it will compile the knowledge base generated by the translator into a rule base. During recognition mode it will use the rule base to extract features from the feature extractor and make identification decisions using the object model base and the object verifier.

APPENDIX 1 - CESM KB FOR THE FIRST APPROACH

```
;; Domain name: root-ls
(CHEM-LAB)
;; Class counter
15
;; A list of all the classes
(CHEM-LAB WORK-AREA STORAGE-AREA SUPPLY-AREA BUNSEN-BURNER
TEST-TUBE-STAND
TRIPOD-STAND FAUCET BEAKER-IN-WORKAREA FUNNEL-INWORKAREA
FLASK-INWORKAREA
BEAKER-IN-STORAGE-AREA FUNNEL-IN-STORAGE-AREA
FLASK-IN-STORAGE-AREA JARS)
;; Input control stack
()
;; Break point, pred or clas
CLASS
;; Predicates list
(IN-WORK-AREA IN-STORAGE-AREA CYLINDERICAL
USED-TO-HOLD-TESTUBES THREE-LEGGED
HAS-KNOB CUP-SHAPED CONICAL-SHAPED ROUNDED-BOTTOM
CONICAL-SHAPED IN-SUPPLY-AREA
```

```
BIG RECTANGULAR-BASE HAS-HOLES HAS-BASE RECTANGULAR CIRCULAR
(NOT TRANSPARENT)
GAS-PIPE-CONNECTED-AT-BOTTOM    (NOT    CONTAINER)    HOLDER
ROUNDED-TOP TRANSPARENT
CONTAINER CONTAINER (USUALLY TRANSPARENT))
 ;; Synonym list
()
 ;; Anti-synonym list
((IN-SUPPLY-AREA IN-STORAGE-AREA IN-WORK-AREA) (ROUNDED-BOTTOM
CONICAL-SHAPED
CUP-SHAPED   HAS-KNOB   USED-TO-HOLD-TESTUBES   THREE-LEGGED
CYLINDERICAL))
 ;; Conflict resolution mechanism
1
 ;; Grain factor
100
 ;; Threshold
0.3
 ;; Ef-ea-level
()
 ;; Expressions associated with their predicates
((USED-TO-HOLD-TESTUBES  (AND  RECTANGULAR-BASE  HAS-HOLES))
(RECTANGULAR-BASE (AND
HAS-BASE RECTANGULAR (NOT CIRCULAR))))
 ;; Its expression will be evaluated first: expr-goes
```

```
(RECTANGULAR-BASE USED-TO-HOLD-TESTUBES)
 ;; Functions associated with their predicates
()
 ;; Its function will be evaluated first: func-goes
()
 ;; Predicates and their assoiate picture name: pict-list
((CYLINDERICAL BUNSEN-B) (BIG JARS))
 ;; File in which the function variables are defined
()
 ;; Variables existed in func and need to be defined
()
 ;; KB entity structure: (parent (children) (predicates))
(CHEM-LAB (WORK-AREA STORAGE-AREA SUPPLY-AREA) ())
(WORK-AREA (BUNSEN-BURNER TEST-TUBE-STAND TRIPOD-STAND FAUCET
BEAKER-IN-WORKAREA
FUNNEL-INWORKAREA FLASK-INWORKAREA) (IN-WORK-AREA))
(BUNSEN-BURNER () (CYLINDERICAL (NOT TRANSPARENT)
GAS-PIPE-CONNECTED-AT-BOTTOM (
NOT CONTAINER)))
(TEST-TUBE-STAND () (USED-TO-HOLD-TESTUBES (NOT TRANSPARENT)))

(TRIPOD-STAND () (THREE-LEGGED HOLDER (NOT TRANSPARENT)
ROUNDED-TOP))
(FAUCET () (HAS-KNOB (NOT TRANSPARENT)))
(BEAKER-IN-WORKAREA () (CUP-SHAPED TRANSPARENT CONTAINER))
```

```
(FUNNEL-INWORKAREA () (CONICAL-SHAPED TRANSPARENT))
(FLASK-INWORKAREA () (ROUNDED-BOTTOM TRANSPARENT CONTAINER))
(STORAGE-AREA (BEAKER-IN-STORAGE-AREA FUNNEL-IN-STORAGE-AREA

FLASK-IN-STORAGE-AREA) (IN-STORAGE-AREA))
(BEAKER-IN-STORAGE-AREA () (CUP-SHAPED TRANSPARENT CONTAINER))

(FUNNEL-IN-STORAGE-AREA () (CONICAL-SHAPED TRANSPARENT))
(FLASK-IN-STORAGE-AREA     ()     (ROUNDED-BOTTOM     CONTAINER
TRANSPARENT))
(SUPPLY-AREA (JARS) (IN-SUPPLY-AREA))
(JARS () (BIG CONTAINER (USUALLY TRANSPARENT)))
```

APPENDIX 2 - CESM KB FOR THE SECOND APPROACH

```
;;Domain name: root-ls
(CHEM-LAB)
 ;; Class counter
15
 ;; A list of all the classes
(CHEM-LAB WORK-AREA STORAGE-AREA SUPPLY-AREA BUNSEN-BURNER
TEST-TUBE-STAND
TRIPOD-STAND FAUCET BEAKER-IN-WORK-AREA FUNNEL-IN-WORK-AREA
FLASK-IN-WORK-AREA
BEAKER-IN-STORAGE-AREA   FUNNEL-IN-STORAGE-AREA
FLASK-IN-STORAGE-AREA JARS)
 ;; Input control stack
()
 ;; Break point, pred or clas
CLAS
 ;; Predicates list
(IN-WORK-AREA IN-STORAGE-AREA IN-SUPPLY-AREA
HAS-BUNSEN-BURNER-COMPONENTS HAS-BUNSEN-BURNER-FEATURES
 HAS-BEAKER-COMPONENTS
HAS-BEAKER-FEATURES
HAS-FUNNEL-COMPONENTS HAS-FUNNE-FEATURES
 HAS-FLASK-COMPONENTS
```

HAS-FLASK-FEATURES

HAS-TEST-TUBE-STAND-COMPONENTS HAS-TEST-TUBE-STAND-FEATURES

HAS-TRIPOD-STAND-COMPONENTS HAS-TRIPOD-STAND-FEATURES

HAS-FAUCET-COMPONENTS HAS-FAUCET-FEATURES

HAS-JARS-COMPONENTS HAS-JARS-FEATURES

TRANSPARENT

ID-TEST-BUNSEN-BURNER ID-TEST-TEST-TUBE-STAND

ID-TEST-TRIPOD-STAND

ID-TEST-FAUCET ID-TEST-BEAKER-IN-WORK-AREA

ID-TEST-FLASK-IN-WORK-AREA

ID-TEST-FUNNEL-IN-WORK-AREA ID-TEST-BEAKER-IN-STORAGE-AREA

ID-TEST-FLASK-IN-STORAGE-AREA

ID-TEST-FUNNEL-IN-STORAGE-AREA ID-TEST-JARS

HAS-BUNSEN-BURNER-BODY

HAS-BUNSEN-BURNER-BOTTOM HAS-BUNSEN-BURNER-INLET

HAS-BUNSEN-BURNER-CAVITY

HAS-BUNSEN-BURNER-HOLE BUNSEN-BURNER-BODY-BOX

BUNSEN-BURNER-BODY-AREA

CLOSED CYLINDERICAL BUNSEN-BURNER-BOTTOM-BOX

BUNSEN-BURNER-BOTTOM-AREA

BUNSEN-BURNER-INLET-BOX BUNSEN-BURNER-INLET-AREA

CURVED BUNSEN-BURNER-CAVITY-AREA BUNSEN-BURNER-CAVITY-DEPTH

BUNSEN-BURNER-CAVITY-M02 BUNSEN-BURNER-CAVITY-M20

BUNSEN-BURNER-CAVITY-P3

BUNSEN-BURNER-CAVITY-CENTROID BUNSEN-BURNER-HOLE-AREA
BUNSEN-BURNER-HOLE-M02
BUNSEN-BURNER-HOLE-M20 BUNSEN-BURNER-HOLE-P1
BUNSEN-BURNER-HOLE-P2
BUNSEN-BURNER-HOLE-P3 BUNSEN-BURNER-HOLE-CENTROID

BUNSEN-BURNER-BOX TEST-TUBE-STAND-BOX FAUCET-BOX
TRIPOD-STAND-BOX
BEAKER-BOX FLASK-BOX FUNNEL-BOX JARS-BOX

HAS-TEST-TUBE-STAND-HOLE HAS-TEST-TUBE-STAND-BODY
HAS-TEST-TUBE-STAND-BOTTOM
TEST-TUBE-STAND-BODY-BOX TEST-TUBE-STAND-BODY-AREA
TEST-TUBE-STAND-BOTTOM-BOX TEST-TUBE-STAND-BOTTOM-AREA
MULTIPLE-HOLES TEST-TUBE-STAND-HOLE-AREA
TEST-TUBE-STAND-HOLE-M02
TEST-TUBE-STAND-M20 TEST-TUBE-STAND-HOLE-P1
TEST-TUBE-STAND-HOLE-P2
TEST-TUBE-STAND-P3 TEST-TUBE-STAND-HOLE-CENTROID
HAS-TRIPOD-STAND-BODY HAS-TRIPOD-STAND-LEGS
HAS-TRIPOD-STAND-HOLE
TRIPOD-STAND-BODY-BOX TRIPOD-STAND-BODY-AREA
TRIPOD-STAND-LEGS-BOX TRIPOD-STAND-LEGS-AREA
TRIPOD-STAND-HOLE-AREA TRIPOD-STAND-HOLE-M02
TRIPOD-STAND-M20 TRIPOD-STAND-HOLE-P1 TRIPOD-STAND-HOLE-P2

TRIPOD-STAND-P3 TRIPOD-STAND-HOLE-CENTROID

FAUCET-CAVITY-DEPTH FAUCET-CAVITY-AREA FAUCET-CAVITY-M02

FAUCET-CAVITY-M20 FAUCET-CAVITY-P3

TRIPOD-STAND-CAVITY-CENTROID

HAS-FAUCET-BOX FAUCET-KNOB-AREA FAUCET-KNOB-BOX

FAUCET-BODY-BOX FAUCET-BODY-AREA

HAS-FAUCET-CAVITY HAS-FAUCET-BODY HAS-FAUCET-KNOB

BEAKER-CAVITY-DEPTH BEAKER-CAVITY-AREA BEAKER-CAVITY-M02

BEAKER-CAVITY-M20 BEAKER-CAVITY-P3 BEAKER-CAVITY-CENTROID

HAS-BEAKER-BOTTOM-BOX BEAKER-BOTTOM-KNOB-AREA

BEAKER-BODY-BOX BEAKER-BODY-AREA HAS-BEAKER-CAVITY

HAS-BEAKER-BODY HAS-BEAKER-BOTTOM

FUNNEL-HOLE-AREA FUNNEL-HOLE-M02

FUNNEL-HOLE-M20 FUNNEL-HOLE-P1 FUNNEL-HOLE-P2 FUNNEL-HOLE-P3

FUNNEL-HOLE-CENTROID

FUNNEL-STEM-BOX FUNNEL-STEM-AREA FUNNEL-BODY-BOX

FUNNEL-BODY-AREA

CONICAL HAS-FUNNEL-HOLE HAS-FUNNEL-BODY HAS-FUNNEL-STEM

FLASK-CAVITY-DEPTH FLASK-CAVITY-AREA FLASK-CAVITY-M02

FLASK-CAVITY-M20 FLASK-CAVITY-P3 FLASK-CAVITY-CENTROID

FLASK-STEM-BOX FLASK-STEM-AREA FLASK-BODY-BOX FLASK-BODY-AREA

CIRCULAR HAS-FLASK-CAVITY HAS-FLASK-BODY HAS-FLASK-STEM

JARS-CAVITY-DEPTH JARS-CAVITY-AREA JARS-CAVITY-M02

JARS-CAVITY-M20 JARS-CAVITY-P3 JARS-CAVITY-CENTROID

JARS-STEM-BOX JARS-STEM-AREA JARS-BODY-BOX JARS-BODY-AREA

```
HAS-JARS-CAVITY HAS-JARS-BODY HAS-JARS-STEM OPAQUE
)
 ;; Synonym list
()
 ;; Anti-synonym list
((IN-SUPPLY-AREA   IN-STORAGE-AREA   IN-WORK-AREA)   (OPAQUE
TRANSPARENT)
(OPEN CLOSED) )
 ;; Conflict resolution mechanism
1
 ;; Grain factor
100
 ;; Threshold
0.3
 ;; Ef-ea-level
()
 ;; Expressions associated with their predicates
((HAS-BUNSEN-BURNER-COMPONENTS (AND  HAS-BUNSEN-BURNER-BODY
HAS-BUNSEN-BURNER-BOTTOM
HAS-BUNSEN-BURNER-INLET))
(HAS-BUNSEN-BURNER-FEATURES (AND HAS-BUNSEN-BURNER-CAVITY
 HAS-BUNSEN-BURNER-HOLE  ))

(HAS-BUNSEN-BURNER-BODY    (AND    BUNSEN-BURNER-BODY-BOX
BUNSEN-BURNER-BODY-AREA
```

```
CLOSED CYLINDERICAL  OPAQUE ))
(HAS-BUNSEN-BURNER-BOTTOM    (AND    BUNSEN-BURNER-BOTTOM-BOX
BUNSEN-BURNER-BOTTOM-AREA
CLOSED CURVED  OPAQUE ))
(HAS-BUNSEN-BURNER-INLET    (AND    BUNSEN-BURNER-INLET-BOX
BUNSEN-BURNER-INLET-AREA
CLOSED CYLIDERICAL  OPAQUE ))

(HAS-BUNSEN-BURNER-CAVITY    (AND    BUNSEN-BURNER-CAVITY-AREA
BUNSEN-BURNER-CAVITY-DEPTH
BUNSEN-BURNER-CAVITY-M02    BUNSEN-BURNER-CAVITY-M20
BUNSEN-BURNER-CAVITY-P3
BUNSEN-BURNER-CAVITY-CENTROID))
(HAS-BUNSEN-BURNER-HOLE    (AND    BUNSEN-BURNER-HOLE-AREA
BUNSEN-BURNER-HOLE-M02
BUNSEN-BURNER-HOLE-M20    BUNSEN-BURNER-HOLE-P1
BUNSEN-BURNER-HOLE-P2
BUNSEN-BURNER-HOLE-P3 BUNSEN-BURNER-HOLE-CENTROID))

(HAS-TEST-TUBE-STAND-COMPONENTS (AND HAS-TEST-TUBE-STAND-BODY
HAS-TEST-TUBE-STAND-BOTTOM
))
(HAS-TEST-TUBE-STAND-FEATURES HAS-TEST-TUBE-STAND-HOLE)
```

```
(HAS-TEST-TUBE-STAND-BODY (AND TEST-TUBE-STAND-BODY-BOX
TEST-TUBE-STAND-BODY-AREA
CLOSED OPAQUE))
(HAS-TEST-TUBE-STAND-BOTTOM (AND TEST-TUBE-STAND-BOTTOM-BOX
TEST-TUBE-STAND-BOTTOM-AREA
OPEN PLANAR OPAQUE))

(HAS-TEST-TUBE-STAND-HOLE (AND MULTIPLE-HOLES
TEST-TUBE-STAND-HOLE-AREA TEST-TUBE-STAND-HOLE-M02
TEST-TUBE-STAND-M20 TEST-TUBE-STAND-HOLE-P1
TEST-TUBE-STAND-HOLE-P2
TEST-TUBE-STAND-P3 TEST-TUBE-STAND-HOLE-CENTROID))

(HAS-TRIPOD-STAND-COMPONENTS (AND HAS-TRIPOD-STAND-BODY
HAS-TRIPOD-STAND-LEGS
))
(HAS-TRIPOD-STAND-FEATURES HAS-TRIPOD-STAND-HOLE)

(HAS-TRIPOD-STAND-BODY (AND TRIPOD-STAND-BODY-BOX
TRIPOD-STAND-BODY-AREA
PLANAR OPEN OPAQUE))
(HAS-TRIPOD-STAND-LEGS (AND TRIPOD-STAND-LEGS-BOX
TRIPOD-STAND-LEGS-AREA
OPEN CYLIDERICAL OPAQUE))
```

(HAS-TRIPOD-STAND-HOLE (AND TRIPOD-STAND-HOLE-AREA TRIPOD-STAND-HOLE-M02
TRIPOD-STAND-M20 TRIPOD-STAND-HOLE-P1 TRIPOD-STAND-HOLE-P2
TRIPOD-STAND-P3 TRIPOD-STAND-HOLE-CENTROID))

(HAS-FAUCET-COMPONENTS (AND HAS-FAUCET-BODY HAS-FAUCET-KNOB
))
(HAS-FAUCET-FEATURES HAS-FAUCET-CAVITY)

(HAS-FAUCET-BODY (AND FAUCET-BODY-BOX FAUCET-BODY-AREA
CLOSED CURVED OPAQUE))
(HAS-FAUCET-KNOB (AND HAS-FAUCET-KNOB-BOX FAUCET-KNOB-AREA
OPEN PLANAR OPAQUE))

(HAS-FAUCET-CAVITY (AND FAUCET-CAVITY-DEPTH
FAUCET-CAVITY-AREA FAUCET-CAVITY-M02
FAUCET-CAVITY-M20 FAUCET-CAVITY-P3
TRIPOD-STAND-CAVITY-CENTROID))

(HAS-BEAKER-COMPONENTS (AND HAS-BEAKER-BODY HAS-BEAKER-BOTTOM

))
(HAS-BEAKER-FEATURES HAS-BEAKER-CAVITY)

(HAS-BEAKER-BODY (AND BEAKER-BODY-BOX BEAKER-BODY-AREA
CLOSED CYLINDERICAL TRANSPARENT))
(HAS-BEAKER-BOTTOM (AND HAS-BEAKER-BOTTOM-BOX
BEAKER-BOTTOM-KNOB-AREA
OPEN PLANAR TRANSPARENT))

(HAS-BEAKER-CAVITY (AND BEAKER-CAVITY-DEPTH
BEAKER-CAVITY-AREA BEAKER-CAVITY-M02
BEAKER-CAVITY-M20 BEAKER-CAVITY-P3 BEAKER-CAVITY-CENTROID))

(HAS-FUNNEL-COMPONENTS (AND HAS-FUNNEL-BODY HAS-FUNNEL-STEM
))
(HAS-FUNNEL-FEATURES HAS-FUNNEL-HOLE)

(HAS-FUNNEL-BODY (AND FUNNEL-BODY-BOX FUNNEL-BODY-AREA
CONICAL CLOSED TRANSPARENT))
(HAS-FUNNEL-STEM (AND FUNNEL-STEM-BOX FUNNEL-STEM-AREA
CLOSED CYLINDERICAL TRANSPARENT))

(HAS-FUNNEL-HOLE (AND FUNNEL-HOLE-AREA FUNNEL-HOLE-M02
FUNNEL-HOLE-M20 FUNNEL-HOLE-P1 FUNNEL-HOLE-P2 FUNNEL-HOLE-P3
FUNNEL-HOLE-CENTROID))

(HAS-FLASK-COMPONENTS (AND HAS-FLASK-BODY HAS-FLASK-STEM
))

(HAS-FLASK-FEATURES HAS-FLASK-CAVITY)

(HAS-FLASK-BODY (AND FLASK-BODY-BOX FLASK-BODY-AREA
CIRCULAR CLOSED TRANSPARENT))
(HAS-FLASK-STEM (AND FLASK-STEM-BOX FLASK-STEM-AREA
CLOSED CYLINDERICAL TRANSPARENT))
(HAS-FLASK-CAVITY (AND FLASK-CAVITY-DEPTH FLASK-CAVITY-AREA
FLASK-CAVITY-M02
FLASK-CAVITY-M20 FLASK-CAVITY-P3 FLASK-CAVITY-CENTROID))

(HAS-JARS-COMPONENTS (AND HAS-JARS-BODY HAS-JARS-STEM
))
(HAS-JARS-FEATURES HAS-JARS-CAVITY)

(HAS-JARS-BODY (AND JARS-BODY-BOX JARS-BODY-AREA
CIRCULAR CLOSED TRANSPARENT))
(HAS-JARS-STEM (AND JARS-STEM-BOX JARS-STEM-AREA
CLOSED CYLINDERICAL TRANSPARENT))
(HAS-JARS-CAVITY (AND JARS-CAVITY-DEPTH JARS-CAVITY-AREA
JARS-CAVITY-M02
JARS-CAVITY-M20 JARS-CAVITY-P3 JARS-CAVITY-CENTROID))

(ID-TEST-BUNSEN-BURNER (OR HAS-BUNSEN-BURNER-LABEL (AND
BUNSEN-BURNER-BOX HAS-BUNSEN-BURNER-COMPONENTS

```
HAS-BUNSEN-BURNER-FEATURES)))

(ID-TEST-TEST-TUBE-STAND (OR HAS-TEST-TUBE-STAND-LABEL (AND
TEST-TUBE-STAND-BOX HAS-TEST-TUBE-STAND-COMPONENTS
HAS-TEST-TUBE-STAND-FEATURES)))

(ID-TEST-TRIPOD-STAND (OR HAS-TRIPOD-STAND-LABEL
(AND TRIPOD-STAND-BOX HAS-TRIPOD-STAND-COMPONENTS
HAS-TRIPOD-STAND-FEATURES)))

(ID-TEST-FAUCET-STAND (OR HAS-FAUCET-LABEL
(AND FAUCET-BOX HAS-FAUCET-COMPONENTS HAS-FAUCET-FEATURES)))

(ID-TEST-BEAKER-IN-WORK-AREA (OR HAS-BEAKER-IN-WORK-AREA-LABEL

(AND BEAKER-BOX HAS-BEAKER-COMPONENTS HAS-BEAKER-FEATURES)))

(ID-TEST-FLASK-IN-WORK-AREA (OR HAS-FLASK-IN-WORK-AREA-LABEL
(AND
FLASK-BOX HAS-FLASK-FEATURES
HAS-FLASK-COMPONENTS
)))

(ID-TEST-FUNNEL-IN-WORK-AREA (OR HAS-FUNNEL-IN-WORK-AREA-LABEL
```

```
(AND FUNNEL-BOX HAS-FUNNEL-COMPONENTS HAS-FUNNEL-FEATURES)))


(ID-TEST-BEAKER-IN-STORAGE-AREA (OR
HAS-BEAKER-IN-STORAGE-AREA-LABEL
(AND BEAKER-BOX HAS-BEAKER-COMPONENTS HAS-BEAKER-FEATURES)))

(ID-TEST-FLASK-IN-STORAGE-AREA (OR
HAS-FLASK-IN-STORAGE-AREA-LABEL (AND
FLASK-BOX HAS-FLASK-FEATURES
HAS-FLASK-COMPONENTS
)))

(ID-TEST-FUNNEL-IN-STORAGE-AREA (OR
HAS-FUNNEL-IN-STORAGE-AREA-LABEL
(AND FUNNEL-BOX HAS-FUNNEL-COMPONENTS HAS-FUNNEL-FEATURES)))


(ID-TEST-JARS (OR HAS-JARS-LABEL
(AND JARS-BOX  HAS-JARS-COMPONENTS HAS-JARS-FEATURES)))


)
 ;; Its expression will be evaluated first: expr-goes
()
```

```
;; Functions associated with their predicates
()
;; Its function will be evaluated first: func-goes
()
;; Predicates and their assoiate picture name: pict-list
()
;; File in which the function variables are defined
()
;; Variables existed in func and need to be defined
()
;; KB entity structure: (parent (children) (predicates))
(CHEM-LAB (WORK-AREA STORAGE-AREA SUPPLY-AREA) ())
(WORK-AREA (BUNSEN-BURNER TEST-TUBE-STAND TRIPOD-STAND FAUCET
BEAKER-IN-WORK-AREA
FUNNEL-IN-WORK-AREA FLASK-IN-WORK-AREA) (IN-WORK-AREA))
(BUNSEN-BURNER () ( ID-TEST-BUNSEN-BURNER))
(TEST-TUBE-STAND () (ID-TEST-TEST-TUBE-STAND))
(TRIPOD-STAND () (ID-TEST-TRIPOD-STAND))
(FAUCET () (ID-TEST-FAUCET))
(BEAKER-IN-WORK-AREA () (ID-TEST-BEAKER-IN-WORK-AREA))
(FUNNEL-IN-WORK-AREA () (ID-TEST-FUNNEL-IN-WORK-AREA))
(FLASK-IN-WORK-AREA () (ID-TEST-FLASK-IN-WORK-AREA))
(STORAGE-AREA ( BEAKER-IN-STORAGE-AREA FUNNEL-IN-STORAGE-AREA

FLASK-IN-STORAGE-AREA) (IN-STORAGE-AREA))
```

```
(BEAKER-IN-STORAGE-AREA () (ID-TEST-BEAKER-IN-STORAGE-AREA))
(FUNNEL-IN-STORAGE-AREA () (ID-TEST-FUNNEL-IN-STORAGE-AREA))
(FLASK-IN-STORAGE-AREA () (ID-TEST-FLASK-IN-STORAGE-AREA))
(SUPPLY-AREA (JARS) (IN-SUPPLY-AREA))
(JARS () (ID-TEST-JARS))
```

APPENDIX 3 - CESM KB FOR THE FINAL APPROACH

```
;; Domain name: root-ls
(CHEM-LAB CHEM-LAB)
;; Class counter
21
;; A list of all the classes
(CHEM-LAB CHEM-LAB WORK-AREA SUPPLY-AREA STORAGE-AREA
WORKAREA-AREA-GROUP1
WORKAREA-AREA-GROUP2 WORKAREA-AREA-GROUP3
WORKAREA-A1-EC-GROUP1
WORKAREA-A1-EC-GROUP2 BUNSEN-BURNER BEAKER-IN-WORKAREA
FLASK-IN-WORKAREA
FUNNEL-IN-WORKAREA TRIPOD-STAND FAUCET TEST-TUBE-STAND
BEAKER-IN-SUPPLY-AREA
FLASK-IN-SUPPLY-AREA FUNNEL-IN-SUPPLY-AREA JAR)
;; Input control stack
()
;; Break point, pred or clas
CLAS
;; Predicates list
(EX IN-WORKAREA AREA-13..16 EC_IS_97 EC-IS-50 SHAPE-NUM-IS-20
```

```
SHAPE-NUM-IS-28
SHAPE-NUM-IS-13  AREA-6..7  EC-IS-97  EC-IS-34  AREA-IS-25
IN-SUPPLY-AREA AREA-IS-30
IN-STORAGE-AREA)
 ;; Synonym list
()
 ;; Anti-synonym list
()
 ;; Conflict resolution mechanism
1
 ;; Grain factor
100
 ;; Threshold
0.3
 ;; Ef-ea-level
()
 ;; Expressions associated with their predicates
()
 ;; Its expression will be evaluated first: expr-goes
()
 ;; Functions associated with their predicates
()
 ;; Its function will be evaluated first: func-goes
()
 ;; Predicates and their assoiate picture name: pict-list
```

```
()
 ;; File in which the function variables are defined
()
 ;; Variables existed in func and need to be defined
()
 ;; KB entity structure: (parent (children) (predicates))
(CHEM-LAB (WORK-AREA SUPPLY-AREA STORAGE-AREA) ())
(WORK-AREA    (WORKAREA-AREA-GROUP1    WORKAREA-AREA-GROUP2
WORKAREA-AREA-GROUP3) (
IN-WORKAREA))
(WORKAREA-AREA-GROUP1   (WORKAREA-A1-EC-GROUP1
WORKAREA-A1-EC-GROUP2) (AREA-13..16
))
(WORKAREA-A1-EC-GROUP1 (BUNSEN-BURNER) (EC_IS_97))
(BUNSEN-BURNER () ())
(WORKAREA-A1-EC-GROUP2 (BEAKER-IN-WORKAREA FLASK-IN-WORKAREA
FUNNEL-IN-WORKAREA)
(EC-IS-50))
(BEAKER-IN-WORKAREA () (SHAPE-NUM-IS-20))
(FLASK-IN-WORKAREA () (SHAPE-NUM-IS-28))
(FUNNEL-IN-WORKAREA () (SHAPE-NUM-IS-13))
(WORKAREA-AREA-GROUP2 (TRIPOD-STAND FAUCET) (AREA-6..7))
(TRIPOD-STAND () (EC-IS-97))
(FAUCET () (EC-IS-34))
(WORKAREA-AREA-GROUP3 (TEST-TUBE-STAND) (AREA-IS-25))
```

```
(TEST-TUBE-STAND () ())
(SUPPLY-AREA (BEAKER-IN-SUPPLY-AREA FLASK-IN-SUPPLY-AREA
FUNNEL-IN-SUPPLY-AREA)
(IN-SUPPLY-AREA))
(BEAKER-IN-SUPPLY-AREA () (SHAPE-NUM-IS-20))
(FLASK-IN-SUPPLY-AREA () (SHAPE-NUM-IS-28))
(FUNNEL-IN-SUPPLY-AREA () (SHAPE-NUM-IS-13))
(STORAGE-AREA (JAR) (IN-STORAGE-AREA))
(JAR () (AREA-IS-30))
(CHEM-LAB (WORK-AREA SUPPLY-AREA STORAGE-AREA) ())
(WORK-AREA (WORKAREA-AREA-GROUP1 WORKAREA-AREA-GROUP2
WORKAREA-AREA-GROUP3) (
IN-WORKAREA))
(WORKAREA-AREA-GROUP1 (WORKAREA-A1-EC-GROUP1
WORKAREA-A1-EC-GROUP2) (AREA-13..16
))
(WORKAREA-A1-EC-GROUP1 (BUNSEN-BURNER) (EC_IS_97))
(BUNSEN-BURNER () ())
(WORKAREA-A1-EC-GROUP2 (BEAKER-IN-WORKAREA FLASK-IN-WORKAREA
FUNNEL-IN-WORKAREA)
(EC-IS-50))
(BEAKER-IN-WORKAREA () (SHAPE-NUM-IS-20))
(FLASK-IN-WORKAREA () (SHAPE-NUM-IS-28))
(FUNNEL-IN-WORKAREA () (SHAPE-NUM-IS-13))
(WORKAREA-AREA-GROUP2 (TRIPOD-STAND FAUCET) (AREA-6..7))
```

```
(TRIPOD-STAND () (EC-IS-97))
(FAUCET () (EC-IS-34))
(WORKAREA-AREA-GROUP3 (TEST-TUBE-STAND) (AREA-IS-25))
(TEST-TUBE-STAND () ())
(SUPPLY-AREA   (BEAKER-IN-SUPPLY-AREA   FLASK-IN-SUPPLY-AREA
FUNNEL-IN-SUPPLY-AREA)
(IN-SUPPLY-AREA))
(BEAKER-IN-SUPPLY-AREA () (SHAPE-NUM-IS-20))
(FLASK-IN-SUPPLY-AREA () (SHAPE-NUM-IS-28))
(FUNNEL-IN-SUPPLY-AREA () (SHAPE-NUM-IS-13))
(STORAGE-AREA (JAR) (IN-STORAGE-AREA))
(JAR () (AREA-IS-30))
```

LIST OF REFERENCES

[1] Agrawal, A.K., and Kulkarni A. V., "A Sequential Approach to the Extraction of Shape Features", Computer Graphics and Image Processing, vol 6, No.6, December 1977, pp. 538 - 557.

[2] Allen P. K., Robotic Object Recognition using Vision and Touch, Kluwer Academic Publishers, 1987.

[3] Ananthanarayanan, T. S., "Renaissance in X-Ray Diffraction Topography", International Advances in NonDestructive Testing, ed. Warren J. Mc Gonnagle, Gordon and Breach, vol 13, 1988, pp. 251-266.

[4] Andrews H.C. (ed.), Digital Image Processing, IEEE Press, 1978.

[5] Attneave F., "Physical Determinants of the Judged Complexity of Shape", Journal of Experimental Psychology, vol. 53, 1957,pp. 221-227.

[6] Bailey, D. M., "Automatic Eddy Current Signal

Acquisition System", International Advances in NonDestructive Testing, ed. Warren J. McGonnagle, Gordon and Breach, vol 13, 1988, pp 295-310.

[7] Bair, M. E., Sampson, R., and Zuk D., "Three dimensional imaging and applications", Intelligent Robots and Computer Vision : Fifth in a Series, David P. Casasent, Editor, Proc. SPIE 726, 1987, pp 264-274.

[8] Besl, P. J., and Jain, R. C., "Invariant Surface Characteristics for 3D Object Recognition in Range Images", Comput. Visoin, Graphics & Image Process. (USA), vol. 33, no. 1, Jan 1986, pp 33-80.

[9] Bridenbaugh, P. R., Shabel B. S., and Govada A. K . , "Material Characterization for process control for Aluminum alloys and advanced materials", Nondestructive Characterization of Materials II, ed. Bussiere, J. F., Monchalin, J., Ruud, C. O., and Green Jr.,R. E., 1987, pp 179-194.

[10] Brown, M. K., "Feature Extraction Techniques for Recognizing Solid Objects with an Ultrasonic Range

Sensor", IEEE Journal of Robotics and Automation, vol. RA-1,no. 4, December 1985.

[11] Castleman K. R. , Digital Image Processing, Prentice-Hall, 1979.

[12] Chien, C. H., and Aggarwal, J. K., "Shape recognition from single silhouettes", Proceedings of the First International Conference on Computer Vision (Cat.NO. 87CHH2465-3). IEEE. Int. Assoc. Pattern Recognition, 1987, London, England. 8-11, June 1987.

[13] Christian, J. M., Muller Jr, K., Schwalbe, L., Draxel, V., and Williamson, F., "High-Energy Flash Radiography of Two Axissymmetric Copper Explosively Formed Penetrators", International Advances in NonDestructive Testing, ed. Warren J. Mc Gonnagle, Gordon and Breach, vol 13, 1988, pp.365-396.

[14] Cohen, J., "Fundamentals and Applications of Infrared Thermography",International Advances in NonDestructive Testing, ed. Warren J. Mc Gonnagle, Gordon and Breach, vol 13, 1988, pp. 39-82.

[15] De Rossi, D. and Dario, P., "Multiple Sensing Polymeric Transducer for Object Recognition through Active Touch

Exploration", Proceedings of Society of Manufacturing Engineers : Robotics Research - The Next Five years and Beyond, Bethlem, PA, August 14-16, 1984 (MS84-492).

[16] Durrant-Whyte, H., Integration, Coordination, and Control of Multisensor Systems, Kluwer, Boston, MA., 1988.

[17] Fisher R. B., "Recognizing objects using surface information and object models", Second International Conference on Image Processing and its Applications (Conf. Pupl. No. 265). IEEE 1986. London, England. 24-26 June 1986.

[18] Freeman. H, "Lines, Curves and Characterization of Shape", Report no. IPL-TR-80-004 Image Processing Lab., Electrical and Systems Engineering Dept., Rennselaer Polytechnic Institute, Troy, N. Y., March 1980.

[19] Freeman. H., and Saghri, A., "Generalized Chain Codes for Planar Curves", Proceedings of the 4th International Joint Conference on Pattern Recognition, Kyoto, Japan, NOv. 7-10, 1978, pp. 701-703.

[20] Gonzalez, R. C., and Wintz, P., Digital Image

Processing (2nd ed.), Addison-Wesley, 1979.

[21] Grant G., and Reid A. E., "An Efficient Algorithm for Boundary Tracing and Feature Extraction", Computer Graphics and Image Processing, vol. 17, no. 3, Nov. 1981, pp. 225-237.

[22] Gray, S. B., "Local Properties of Binary Images in Two Dimensions", Transactions on Computers, vol. C-20, no. 5, May 1971, pp. 551-561.

[23] Green, W. B., Digital Image Processing : A Systems Approach, Van Nostrand Reinhold Co., 1983.

[24] Hager, G. D., Active Reduction of Uncertainty in Multi-sensor Systems, Ph. D. Dissertation, University of Pennsylvania, Philadelphia, PA, 1988.

[25] Hall, E. , Computer Image Processing and Recognition, Academic Press, 1979.

[26] Hamming, R. W., Digital Filters, Prentice-Hall, 1983.

[27] Hill F. J., and Peterson G. R., Introduction to Switching Theory and Logical Design (3rd ed.) , Wiley,

New York, 1981.

[28] Horn, B. K., "Obtaining Shape from Shading Information", in P. H. Winston (ed.), The Psychology of Computer Vision, Mc Graw Hill Book Company, 1975, pp 115-155.

[29] Horn, B. K., Robot Vision, MIT Press, 1986

[30] Ishikawa, S., "Geometrical Indices Characterizing Psychological Goodness of Random Shapes", Proceedings of the 4th International Joint Conference on Pattern Recognition, Kyoto, Japan, Nov 7-10, 1978, pp. 414-416.

[31] Jain, A. K., Hoffman R., "Evidence-Based Recognition of 3D objects", Transactions on Pattern Analysis And Machine Intelligence, vol. 10, no. 6, November, 1988, pp. 783-802.

[32] Kofakis, P., "Recognition and localization of Objects using sparse data", Proceedings CVPR '86 : IEEE Computer Society Conference on Computer Vision and Pattern Recognition (Cat. No. 86HCH2290-5). IEEE. 1986. Miami Beach, Fl, USA. 22-26 June 1986.

[33] Kulpa, Z., "Area and Perimeter Measurement of Blobs in

Discrete Binary Pictures",Computer Graphics and Image Processing, vol. 6, no. 5, 1977, pp. 434-451.

[34] Leu, J., and Huang, I., "Planar Shape Matching Based on Binary Tree Shape Representation", Pattern Recognition, vol. 21, No. 6, 1988, pp. 607-622.

[35] Levine, M. D., Vision in Man and Machine, Mc Graw-Hill Book Company, 1985.

[36] Li, Z. N., and Song, Q., "multiresolution modelling and matching using salient features", Proceedings of Vision Interface '88., Canadian Image Process. & Pattern Recognition Soc. et. al. 1988. Edmenton, Alta., Canada, 6-10 June 1988.

[37] Lowe, D. G., Perceptual Organization and Visual Recognition, Kluwer Academic Publishers, 1985.

[38] Luo, R. C., "Microcomputer-Based Robot Dynamic Sensing Using Linear Array Sensor for Object Recognition and Manipulation", Journal of Robotic Systems, vol. 4, no. 2, 1987, pp 199-213.

[39] Luo, R. C., Scherp, R. S., and Lanzo, M., "Object

Identification Using Automated Decision Tree Construction Approach for Robotic Applications", Journal of Robotic Systems, vol. 4, no. 3, 1987, pp 423-433.

[40] Maslouhi, A., Proulx D., and Tasnon M., "Development of a comprehensive approach for acoustic emission monitoring of carbon-epoxy composites", Nondestructive Characterization of Materials II, ed. Bussiere, J. F., Monchalin, J., Ruud, C. O., and Green Jr.,R. E., 1987, pp. 69-78.

[41] Mc Pherson, C. A., "Three-dimensional robot vision", Proc. SPIE Int. Soc. Opt. Eng. (USA)., vol. 449, pt1, pp 116-126, 1984.

[42] Mohwinkel, C., and Kurz, L., "Computer Picture Processing and Enhancement by Localized Operations" ,Computer Graphics and Image Processing, vol 5, no. 4, December 1976, pp. 401-424.

[43] Ruokangas, C. C., Black,, M. S., and Martin, J. F., "Stereo Vision : two alternative approaches for the matching problem, Intelligent Robots and Computer Vision : Fifth in a Series, David P. Casasent, Editor,

Proc. SPIE 726, 1987, pp 182-187.

[44] Saghri, J. A., and Freeman, H., "Analysis of the Precision of Generalized Chain Codes for the Representation of Planar Curves", IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. PAMI-3, no. 5, September 1981, pp. 533- 539.

[45] Schneiter, J. L., "An Objective Tactile Sensing Strategy For Object Recognition And Localization", Proceeding 1986 IEEE International Conference on Robotic and Automation (Cat. No. 86H2282-2). IEEE. 1986. San Francisco, CA USA. 7-10 April 1986.

[46] Snyder, W. E., and Tang, D.A., "Finding the Extrema of a Region", IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. PAMI-2, no. 3, May 1980, pp. 266-269.

[47] Stansfield, S. A., "A Robotic Perceptual System Utilizing Passive Vision and Active Touch", The International Journal of Robotics Research, vol. 7, no. 6, December 1988, pp 138-161.

[48] Staugaard Jr., A. C., Robotics and AI : An Introduction

to applied mchine intelligence, Prentice-Hall, 1987.

[49] Stucki, P. (ed.), Advances in Digital Image Processing : Theory, Application, Implementation, Plenum Press, 1979.

[50] Pratt, W., Digital Image Processing, John Wiley & Sons, 1978.

[51] Vary Alex, "Ultrasonic Measurement of Mechanical Properties", International Advances in NonDestructive Testing, ed. Warren J. Mc Gonnagle, Gordon and Breach, vol 13, 1988, pp. 1-38.

[52] Weschler, H., "A New and Fast Algorithm for Estimating the Perimeter of objects for Industrial Vision Tasks", Computer Graphics and Image Processing, Vol 17, no. 4, December 1981, pp. 375- 381.

[53] Zuech, N., and Miller R. K., Machine Vision, The Fairmont Press, 1987.

[54] Zhu S., CESM Documentation , (a manual for CESM), February 1988.