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DEVELOPMENT OF MOIRE MACHINE VISION

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ABSTRACT

Three-dimensional perception will be essential to the development of versatile robotics systems capable of handling complicated manufacturing tasks in the factory of the future and in providing the high accuracy measurements needed in flexible manufacturing and quality control. The program described here will develop the potential of moire techniques to provide this greatly needed capability in vision systems and automated measurements, and demonstrate Artificial Intelligence (AI) techniques to take advantage of the unique strengths of moire sensing. Moire techniques provide a means of optically manipulating the complex visual data in a three-dimensional scene into a form which can be easily and quickly analyzed by computers. This type of optical data manipulation will provide higher productivity through integrated automation, producing a higher quality product while reducing computer and mechanical manipulation requirements and thereby the cost and time of production. The objective of this program will be to develop this nondestructive evaluation technique such as to be capable of full-field range measurement and 3-dimensional scene analysis.

BACKGROUND

One of the most powerful senses available to humans is vision. Vision allows us to collect and analyze vast amounts of empirical data at an astounding rate. Many years of research have been devoted to developing sophisticated image processing systems for medical and military applications. Modern computing capabilities have greatly aided these systems by handling the vast amounts of information at faster and faster speeds. These systems often use large computing systems, yet still often require highly skilled operators. For a vision system to be practical for industrial application it must be versatile, fast (less than 0.1 seconds typically), inexpensive, and it must require a minimal amount of human operator support[1,2]. Given these requirements and the current limits of small computer systems, the amount of data which can be processed is limited.

There are currently three basic approaches to three-dimensional machine vision; range finding including structured lighting, stereo or binocular vision, and gray scale methods[3-16]. There are varying degrees to the range finding approach. A simple version is to focus a beam of light on the object at a given distance. As the object surface moves closer or more distant, the spot on the object surface will enlarge, the size of the spot being directly proportional to the change in surface height. The most popular versions use the triangulation method where a beam of light is projected onto the object's surface at some angle and the image of this spot or line of light is viewed at some other angle. As the object distance changes a spot of light on the surface will move along the surface by (change in spot position) = (change in distance) x (tan(incident angle) + tan(viewing angle)). If a line is projected onto the surface by imaging or by scanning a beam, the line will deform as it moves across a contoured surface as each point of the line move as described above[5-9]. Other range finding systems often use selected point measurements to supplement some other system[10]. Other systems use multiple lines or patterns such as reticles to cover more area at a time[4,11,12].

Stereo or binocular vision methods work on the same principle as human vision by obtaining parallax information by viewing the object from two different perspectives (as our two eyes do)[4,13-15]. The two views must be matched up and then the difference in the position of a correlated feature gives the depth information from the geometry of the two view points (similar to the triangulation methods). These methods are full-field, thereby keeping the data acquisition time to a minimum, and they do provide all the 2-D feature information (in fact they depend on these surface features). There has been some success using special purpose correlation hardware in a method similar to those developed for military surveillance industrial. Generally the software manipulation is necessarily intensive[4,15].

Shape form shading methods work on the principle that a uniform field of light incident on a uniformly reflecting surface will vary in intensity depending on its angle of incidence. That is, as the angle of incidence increases, a given portion of the light field will be spread over a wider area of the surface, thereby decreasing how brightly that area is illuminated[4,16]. This system does not provide an absolute measurement relative to the machine coordinates (the other two approaches do provide this information) since it is insensitive to step changes. An auxiliary system such as a rangefinder would need to be added.

Precision full-field part measurement is an even more complicated task. Manual point-by-point measurements are often long and laborious. Without full-field object data, some imperfections can be missed altogether. There are some coordinate measuring machines on the market which can be programmed to measure one or a few specific parts[17]. This approach saves human labor and human error but does not necessarily work any faster. Therefore, measurements for quality control are often limited to a spot check system. A versatile automated contouring system capable of measuring either large or even small areas at a time would provide the opportunity for better and more complete inspections. For many applications, speed is a very important factor as well. An approach which simplifies the required computing capabilities while providing added data processing speed is to use some form of optical preprocessing of the visual image. Optical data manipulation and encoding acts on an entire visual scene simultaneously in a parallel fashion. Parallel processing of this type is very fast and can be used to arrange or sort information into a form which can more easily and more quickly be analyzed with a computer than by direct digitizing techniques. Unwanted information can be disposed of and the desired information can be highlighted, sorted, or encoded for easier manipulation. In particular, moire techniques can transform the out-of-plane shape information of an object into a two-dimensional intensity pattern in such a way as to separate the third dimension completely from the other two without losing information.

TECHNICAL DISCUSSION

Two main technologies support this program: moire interferometry for optical processing and data acquisition, and iterative model-driven constraint directed reasoning for scene analysis.

Moire interferometry is a full-field, noncontact measurement technique[18,19]. A moire pattern is made by forming a subject grating, by projecting, shadowing, or contacting a grating onto the object to be measured, and comparing this grating to some reference grating by overlaying the two grating images. If the reference grating is a straight line grating, the beat pattern between the two gratings will form a contour map of the object's surface in the same way that a topographic map delineates the contours of the land. A diagram of a simple projection moire system is shown in Figure 1. In this case, the grating is imaged onto the surface, then the surface is imaged back to a reference plane, from an angle different from the illumination angle, and the resulting image is viewed through the reference grating. As an illustration of the pattern produced, Figure 2 shows a contour moire of a turbine blade. For this example a grating was placed in front of the statue and simply shadowed onto the statue, then the shadow was viewed through the original grating. This shadow moire effect can often be seen in everyday situations such as the patterns seen when an object is viewed through a screen door or through sheer woven draperies.

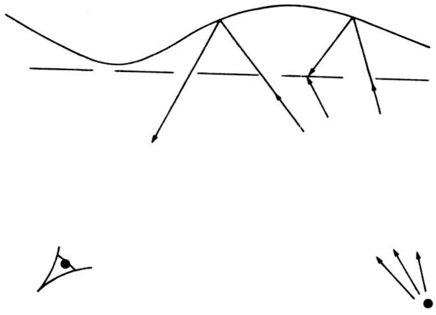

Figure 1. Diagram of moire setup.

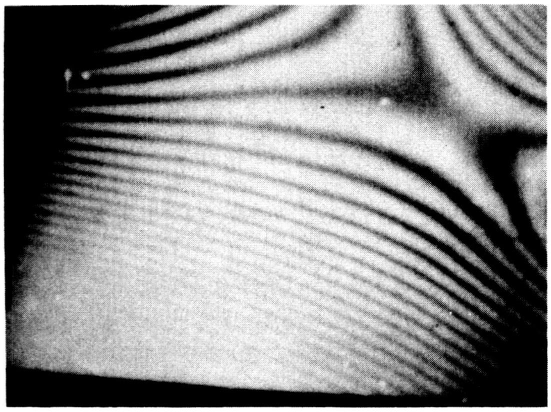

Figure 2. Moire pattern on a turbine blade.

If the reference grating is made by recording the image of the object grating, then the moire pattern can be used to show only differences between the reference object or reference state of an object and some new object or state. In this way, moire can be used to show only deviations from a good part. When applied to an on-line inspection system this difference moire approach greatly reduces the amount of information to be analyzed to determine if a part is within tolerances or to simply identify the part.

The sensitivity of moire contouring is given by the same relationship as other triangulation methods, ie.

$$Z = p/(\tan(i) + \tan(v))$$

where p = the grating period on the object
i = the angle of incidence of the projected pattern
v = the viewing angle
Z = the sensitivity per fringe

(the projected beam has been assumed to be approximately collimated, though this is not necessary in practice)
Typically, with digitizing methods a fringe can be measured to one tenth of a fringe. With such methods a sensitivity of 0.001 inches over a full field of a few square feet is not unreasonable with higher sensitivity over small areas. For example, over a one square foot area, the sensitivity could exceed 0.0005 inches, and over one square inch changes as small as 10 microinches have been recorded using moire techniques[18]. The particular sensitivity that would be practical would depend on many factors such as part geometry, system resolution, etc.. The sensitivity of the moire pattern can be tailored to fit the requirement by simply adjusting the grating period.

Since moire is full-field, the contour of an entire area of an object can be mapped out at one time and recorded during a single video frame. This allows anomalies as well as large-scale shape features to be viewed and measured to the same precision and at the same point in time (important in situations where thermal drifts or other factors may be warping the part with time). The instantaneous contour plot can be viewed immediately with high-accuracy numerical results available after a reasonable amount of analysis time. Such real-time viewing of a component is a common practice in fabricating high-quality optical components to tolerances of a few microinches. Many facilities and interferometer manufacturers have incorporated computer systems to digitize and analyze fringe data much like those from moire contouring[18,20-23]. As an example of such digitizing methods, Figure 3 shows a high sensitivity moire pattern (about 0.04 inches per fringe) of a machined part with bevelled surfaces. Figure 4 shows the computer generated isometric plot of the surface shape. The actual value of each point on the disk was then available to the computer to the spacial resolution of the computer model. In this case the depth information was available to about 0.001 inches.

As with the line projection techniques, the depth information is effectively encoded by the moire interferometer into a 2-dimensional map that is both easy for the computer system to record, since it is only from one perspective, and is independent of 2-D features on the surface of the object. This ability makes the 2-D features separable from the depth information which means the 2-D outlines can be analyzed separately using well established vision algorithms.

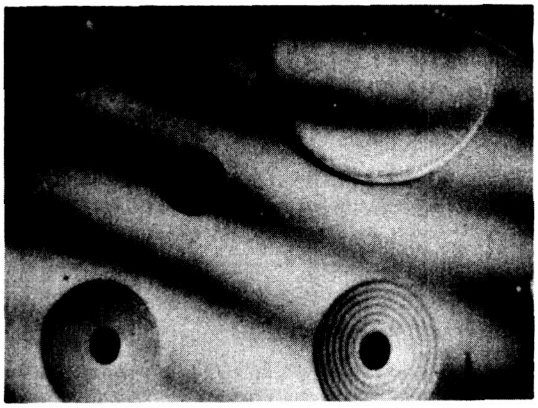

Figure 3. Moire patern on a machined part.

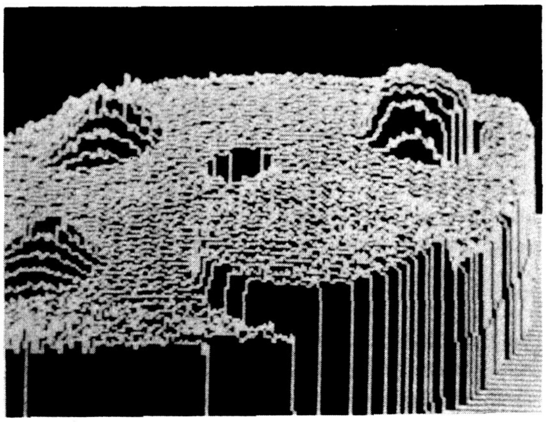

Figure 4. Shape information from moire.

Optically specular surfaces can and are routinely inspected using moire methods, though the method used for contouring specular surfaces is typically different than that employed for diffuse surfaces. It is typically easier to treat diffuse surface and specular surface contouring differently, but the results and the analysis are largely the same.

Peaks and valleys can easily be distinguished and absolute measurements made by a variety of methods. The sign of the slope being measured can be determined by a wide range of methods such as moving one grating with respect to the other (the fringes will move in different directions depending on whether the slope is positive or negative) or by moving the object between two consecutive recordings or by using mismatched gratings. These methods are very familiar to people working in moire interferometry and are well documented in the literature[18,24-31]. Absolute reference points in space can be established by encoding the grating in much the same way that some structured lighting techniques employ.

Scene analysis technology reasons from the 2-D and 3-D information returned by the moire system to identify and locate physical objects in the field of view [39]. Scene analysis is less complex if the system takes advantage of the limited population of potential objects to do model-driven recognition. This approach requires the system to store a model of each object that it may be required to recognize. Industrial applications deal with well-defined mass-produced parts with consistent characteristics, and so lend themselves well to a model-based approach [36].

An object can be represented with a semantic net formalism modeled on ACRONYM's prediction graph [33]. An object is represented as a set of *features*, such as edges and faces, together with *relationships* between those features.

Each frame in the net corresponds to a *feature*, with slots for the characteristics of the feature. A frame that corresponds to a line records the length of the line. A frame that corresponds to a face records such information as its area, perimeter, first moment of area, centroid, minimum and maximum diameters, and dimensions of smallest enclosing rectangle. In some cases, entire components of an object may be usefully modeled as a frame recording their extended gaussian images [40]. The range and gradient data provided by the moire sensor lends itself readily to extracting region-based analysis useful for characterizing faces of an object in this way. Region-growing on the basis of intensity information is difficult, since shadows or other secondary interference can produce spurious differences. Data showing constant gradient and continuous range is a much more robust indicator of a continuous plane face. Furthermore, the range and gradient data allows us to normalize the slot values recorded for a face so that they are invariant with respect to rotation or tilting of the part, within reasonable limits. Thus the use of a range and gradient image permits the construction of a feature-based representation of the object that is much more detailed and discriminatory than would be feasible from monocular intensity data alone.

Often the characteristics of a single feature will not be enough to diagnose the presence of a part, and the *relationships* among features must be taken into account. These relationships are represented as arcs in the semantic net, and include

- adjacency between features (lines to lines; faces to faces; lines bounding faces);
- the angles between adjacent lines or between the gradients of adjacent faces;
- mutual exclusion between features that cannot be simultaneously visible (such as two ends of a brick);
- Euclidean distance in 3-space between the centroids of two features.

The range and gradient data from the moire sensor permits efficient computation of the angular and normalized distance relations between features, data that otherwise would be very inefficient to obtain.

The network has nodes not only for features, but also for *objects*. Each feature that belongs to an object is joined to it with a "part-of" arc. The object node provides a place to store information such as gripping points for the object, indexed by the features that are visible from each orientation.

Our strategy is *iterative*, seeking to identify only one or a few objects in the scene, removing it, and then acquiring and analyzing a new scene. Some scene-analysis strategies seek to identify every item in the scene from a single image [37, 32]. The combinatorial complexity of matching features to models can become very high in this case. Furthermore, once a robot begins to manipulate parts in the bin, it may inadvertently move other parts, so that a repeated analysis may well be necessary anyway. Because moire gives range data, we can immediately identify the topmost features in the field of view and focus our attention on the objects to which they belong. Once the robot removes these objects, we take a new view of the bin and repeat the process. Since moire yields a full-field range image with a single exposure and very little computation, acquiring repeated images is cheap, and the combinatorial simplification obtained by identifying only a few objects at a time reduces the cost of analyzing multiple images.

One disadvantage of an iterative approach is that the robot cannot pick up parts in the order required by a sequential assembly plan, but must take them "as they come." There are solutions to this problem. The robot may buffer the parts for later reordering. Furthermore, if the robot is scheduled opportunistically rather than sequentially [34, 35], the probability increases that it will be able to make use of what it finds on top of the bin.

As a *model-driven* program, the system recognizes objects by comparing features visible in the frame with the prediction graphs stored for expected parts. The system does not aimlessly analyze every region visible in its field, but begins with the highest pixels (those nearest the sensor) to define the "topmost" features. As these are matched with features from the prediction graphs, graphs that are candidates for matching suggest additional features with known relations to the ones already observed that the system searches for to confirm or disprove hypothetical identifications. The use of expectations to drive the analysis of image data can significantly reduce the amount of visual processing necessary to reach an identification.

The system identifies regions with models by *constraint propagation*, along the lines used by [38]. Any single region may match several different models. The system maintains with each region a list of the objects and their features that the region matches.

As more and more regions are matched, the system compares the relationships between adjacent regions with the relationships specified in the prediction graphs for the candidate objects, and refines its estimates of the objects to which the features belong on the basis of those relationships.

For example, assume that two regions are adjacent, and both match features from two objects, A and B. If the relationship between the regions matches the relationship between the corresponding features in A but not in B, the system refines the identification of the regions by eliminating B from the list of candidate objects.

APPLICATIONS

The distinct characteristics of moire machine vision make it particularly suitable to many industrial applications where other systems would have problems. Unlike systems which depend on surface marks or shading effects, moire contouring is very amenable to dirty or hostile environments. Such environments often exist in automated manufacturing. Moire contouring could also be applied in situations where the part may be very hot or vibrating where neither physical contact nor long scanning measurement times are practical. An example of this would be a metal extruding operation or an operation in which the parts have been freshly painted or lacquered. A moire vision system would permit such operations to be better controlled by providing inspection during otherwise inactive waiting times in the manufacturing process. This would reduce waste and increase productivity, while removing human inspectors from a potentially hazardous environment.

The noncontact measurement capability of the moire machine vision system would have great value in many precision measurement applications. As a specific example of the need for a full-field optical measurement system, NASA has encountered a problem in measuring aircraft models for wind tunnel tests. The complexity of these models requires that they be completely measured to an accuracy of about 0.001 inches. To measure the models point by point manually requires two to three days at considerable expense. If any small anomalies are missed, the model may not react as predicted in the wind tunnel or may fail completely. In addition, because of the delicate nature of the surfaces of the models, physical contact may actually damage the model. The moire vision system could measure the entire model in minutes and could even be used as a diagnostic tool during a wind tunnel test to measure the model deflections (a task impossible for a coordinate measuring machine). NASA has been very interested in such technology.

Another specific example of great current interest in the aerospace industry is the inspection of turbine and compressor blades for turbine engines. In this case, there are a number of different inspection requirements. For example, on the leading edge and on a region from 0.03 to 0.1 inches back from the leading edge center the tolerance is typically on the order of 0.0005 inches. On the concave and convex faces of the airfoils, which typically have a cord width of 2 inches or less, the tolerances are typically in the range of 0.002 inches (for some finished turbine blades) to 0.004 inches. These inspections are often performed using mechanical reference slides by measuring the gap between the airfoil and the slide with feeler gages. This process is laborious and highly dependent on the accuracy of the reference slide, the feeler gage and positioning. This is typically purely a Go/No-Go type of test.

With the capability to easily vary the sensitivity of moire interferometry, and the high sensitivity of moire methods over small areas, a system could be developed which would zoom in on the leading edge area with high sensitivity and yet be versatile enough to provide only the 0.002 inch tolerance measurement needed over areas of 2 inches square or more.

Finally, since the moire data is full-field, and available (with the encoding) in one video frame, the data can actually be taken in microseconds with a strobed camera or lighting. This allows freezing of dynamic objects. As the data is built up with scanning in the standard line of light structured light sensors, the time to obtain the data is 0.1 to 0.3 seconds, thus precluding the freezing of dynamic objects.

In the area of robot guidance, a moire assisted vision system offers a distinct advantage in both speed and size over current three-dimensional vision systems or range finder gages. The optical preprocessing would make real-time three-dimensional information available for locating identified parts in a pile (which part is on top of the other) or for distinguishing parts with the same two-dimensional shape but different thickness. Since the third dimension is obtained through the vision system, the sensor can be a compact, light-weight, solid-state camera such as has already been applied to robot guidance and have even been mounted directly on the robot arm in some applications.

SUMMARY

Moire contouring can provide high resolution depth information to a vision system by encoding the information into an easily analyzed 2-D pattern. The depth and surface feature information can be easily separated for simplified analysis. Absolute contouring information regarding the sign of a slope and the relative position of the subject to some reference surface is available with this technique. Full-field data measuring all points on the object, not just where there is a reference point, with variable sensitivity and insensitivity to dirt, stray light or vibrations is available with moire contouring. A moire vision system would solve many of the problems now encountered by 3-D vision systems using technology which has been well developed for other applications. The application of scene analysis techniques similar to those used for 2-D images, can provide a means of part recognition, and three-dimensional locating tasks required for true flexibility of robotic operations.

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