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A review of current research in 3-D machine vision and robot accuracy

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Abstract

It has been shown that the major contributor to down time in robot automated production lines is error in positioning. The faults that cause such errors can be corrected for provided they are identified early enough. Conventional instrumentation, such as displacement measurement probes, is unsuitable for the task, since the number of fixed transducers results in high costs. This review supports a programme of research to measure robot position and repeatability using a non-invasive optical technique based on photogrammetric principles. This paper reviews the following areas:

1. General 3-D machine vision.
2. Photogrammetry and camera calibration.
3. Robot accuracy.

Introduction

Traditionally computer vision has used a single camera to provide information about a scene. Machine vision is extensively used for 2-D inspection of components, providing quantitative measurements and tolerance data of desired features. A single camera limits the amount of data that can be gained, as distance can only be found if the object viewed is of a known size. If two or more cameras are used to gain image information then 3-D measurements can be taken.

The particular application of the research being undertaken is within the field of robot accuracy and repeatability. It is foreseen that the resulting work will also be useful in large scale component metrology for the purposes of inspection and reverse engineering. The objectives of the research are:

- Create a system capable of measuring position and orientation.
- A strategy for correcting errors in a robot arm.

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- A procedure to give early warning of robot failure.

General 3D vision metrology

The various methods of extracting 3D information from 2D images can be grouped into two categories:

- Triangulation methods, e.g. stereo-vision, laser scanner etc.
- Interference techniques, e.g. holography, moiré fringes etc.

Triangulation methods can offer a large range and area of measurement yet at a lower resolution. Many methods require structured lighting which can make them difficult to use outside the laboratory. El-Hakim[1] has used a structured light technique in an attempt to gain information about a scene and allow a robot to locate objects and manipulate them. However one method has been used in practical applications for many years and is now gaining a new lease of life with fast computers and relatively cheap CCD cameras, photogrammetry. It has already been used for large scale measurements in the aeronautical industry and for reverse engineering of large structures[2]. Photogrammetry has also been used to reverse engineer plant in dangerous situations e.g. the nuclear industry[3].

Interference techniques usually require complicated optical arrangements often with a coherent light source. The coherence length of the source limits the range over which reliable measurements can be taken. Problems can also occur if the displacement is in-plane.

Photogrammetry and camera calibration

The use of two cameras to provide distance and size information is already well documented[2], and is known as photogrammetry. It requires photographs taken using cameras (with known internal dimensions, metric cameras) that are a known distance apart. A skilled operator then creates measurements using the images. It is possible to use non-metric cameras, these have unknown internal geometry and have not been designed to minimise errors caused by lens distortion etc. Karara *et al* [4] state the advantages of using non-metric cameras are:

- General availability.
- Flexibility in focusing range.
- Some are motor driven, allowing for a quick succession of photographs.
- They are usually smaller and lighter in weight.
- They can be easily hand held and thereby oriented in any direction.
- They use readily available film.
- The price is considerably less than metric cameras.

The disadvantages are:

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- Lenses are designed for high resolution at the expense of geometric quality, as evidenced by generally large and often irregular distortion.
- Instability of interior orientation.
- The absence of orientation aids such as level vials; orientation provisions preclude the precise orientation of the camera along desired directions.
- The absence of a proper film flattening device.

A number of data reduction schemes have been created to reduce or eliminate the errors caused by the above, which are outlined in [5]. They involve solving simultaneous non-linear equations which have certain constraints applied. The schemes are complicated due to the unknown dimensions of the cameras.

A number of systems are now using CCD cameras to capture images, these have additional advantages, the sensor is flat, on-line processing and the lack of wet developing (use of chemicals). However, the major disadvantage is sensor spatial resolution and size.

When using non-metric cameras calibration of the camera must be carried out in order to relate the images taken to the real world. Jain *et al* [6] provide a description of the four calibration problems in photogrammetry:

- Absolute orientation, determines the transformation between two co-ordinate systems or the position and orientation of a range sensor in an absolute co-ordinate system from the co-ordinates of calibration points.
- Relative orientation, determines the relative position and orientation between two cameras from projections of calibration points in the scene.
- Exterior orientation, determines the position and orientation of a camera in an absolute co-ordinate system from the projections of calibration points in the scene.
- Interior orientation, determines the internal geometry of a camera, including the camera constant (position of the assumed point through which all the rays of light pass), the location of the principal point (position of the lens centre projected onto the sensor), and corrections for lens distortions (whether for poor lens quality or the simplified assumption of the camera constant).

The mathematics used in photogrammetry are similar to those used for calculating robot trajectories etc.(homogeneous transforms), the formulae used in robotics are well documented [7, 8]. Therefore relating the camera system to the robots is relatively easy.

R. Y. Tsai *et al* [9, 10, 11] have calibrated a camera's position on the end effector of a robot arm with respect to the position of the wrist joint. This is done by using a calibration block (placed anywhere in the arm's work space) with a number of geometrical features on its surface, these features being circles [9, 10] or squares [11]. A camera mounted on the end effector of a robot arm is then moved to at least three different positions, at which an image is taken. More positions gives greater accuracy. By taking account of the lens distortion (one term for radial distortion modelled by a second order polynomial, to give the interior orientation of the camera system), magnification, and position of the end effector, the relevant homogeneous transformations can be constructed and solved giving the position of the camera. The calibration process only takes 25 ms [10], however, this excludes the time taken for feature extraction. The speed difference between interpreting a fairly structured scene (a target plate) and an un-structured scene is vastly different. Rygol *et al* [12] have developed a multiprocessor system to visually guide a robot arm to pick objects up. The system images the robots workspace from outside using 2 cameras and guides the arm to pick up the desired object. The implementation consists of a transputer network using a SUN workstation as a host. The processing time for a cluttered scene is around 10 seconds.

The theme of lens distortion is developed by M. A. Sid-Ahmed *et al* [13] who state that by ignoring the tangential distortion caused by misalignment in the lens the accuracy is greatly reduced. By using three radial terms and a tangential term the error is reduced by a factor of 3. However, by using just one radial term the error is reduced by an order of magnitude [10]. The time required for calibration is undoubtedly much longer due to the computational complexities. A similar view is expressed by Karara *et al* [14] that for practical purposes only the first radial lens distortion term need be used when modelling a lens.

Cosandier *et al* [15] have developed a photogrammetric system to test viability for industrial metrology applications. They used retro-reflective targets to reduce lighting problems, and (using sub-pixel techniques) found it was possible to obtain 1/20th of a pixel accuracy. They also found that more camera stations improved the results. The specific positioning of camera stations with respect to the final system's accuracy has also been highlighted in [2]. This is known as network design and depends on the final measurement accuracy required and the camera resolution.

Robot Accuracy

Starr *et al* [16] state that up to 20% of down time on highly automated production lines is due to robot failure. Statistics show that 45% of the failures are related to inaccuracy of position.

Terminology, testing procedures etc. are given in the ISO standards [17, 18, 19, 20, 21, 22]. A number of parameters must be known when using robots, the most important being accuracy and repeatability. ISO 9283: 1990 cites the required performances and suggests test methods, and therefore any system created to measure robot accuracy should comply with this standard. Kovac [23] gives a brief and simplified account of the basic requirement of ISO 9283: 1990. Van Brussel [24] analyses the error sources and groups them under two headings:

- Pose error.
- Path error.

The paper describes various systems that can be used to measure a robot position and pose, for example laser tracking, ball bar testing, stereo triangulation etc.

Kovac *et al* [25] outline the different methods of measuring a robot position, pose and/or path. The accuracy, advantages and disadvantages of each system along with a reference for the method is discussed. A contact method developed by Kovac *et al* is also outlined, the Anthropoidic Measuring Device AMG-1. The device is further described in the earlier references [26, 27, 28]. It is similar in form to a robot arm, having 6 rotational axes but no drives. The robot arm being measured manipulates the measuring device and the encoders attached provide the position data. The major draw back, however, with any contact system is that it invades the robot's workspace and prevents the robot from performing its normal tasks and can therefore be used only in the laboratory.

Another contact system has been developed by Schweigert [29], who reviews a number of sensors and analyses their possible accuracy and uses within the framework of guiding a robot for fine assembly work. The paper presents a method of measuring position using piezotranslators.

Zik *et al* [30], have created a system using laser tracking which can give measurements of robot position and can also be used for large scale metrology. The system uses a retro-reflective target to return the laser beam to the measuring device, this measures 3-D position. By including encoders on a motorised target, pitch and roll measurements can also be taken.

A non contact method is used by Preising *et al* [31] who employ a similar method to Tsai, in that a single camera and calibration block are used. However, the calibration block is on the end effector and the camera views this from outside the arm's workspace. The system also allows the pose of the robot to be measured as opposed to just calibrating the camera with respect to the last joint. This is important because the instrumentation is non-contact it can be located outside the robot cell, this has been identified as an important factor [23]. The system used was said to give an improved accuracy of 100 fold although only a small working volume can be used.

A similar method is used by G. D. van Albada *et al* [32]. In this case the camera is attached to the robot arm and the calibration block is somewhere in the robot's workspace. The system can be used to measure 6-D robot pose in a limited part of the robot's operating volume. Both of the above camera systems operate over a limited volume and rely on the robot to generate a path to calibrate the cameras. The systems are there to improve the accuracy of the robot yet rely on the "in-accurate" robot for calibration purposes.

Byun *et al* [33] created a system capable of sensing the 3-D pose of a flexible object (wires). They used a robot arm with a camera mounted on it, this then views the object from a number of positions. After manipulating and extracting data from the images the 3-D pose of the object is found and allows the robot to move to the end of the object to grasp it.

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Hudgens *et al* [34] have developed a system which is capable of tracking 1 to 7 circular targets. The system provides 3-D information for each point. The system uses two Pulnix cameras, Matrox frame grabber and an IBM PC-AT. Stated resolutions are 0.02 inch for 10 ft^3.

Schraft *et al* [35] use a single camera, however, the camera is specially built and has a movable CCD positionable in 3 dimensions. A target is positioned on the end of the robot arm and the camera views this target from outside the workspace. Since the CCD is moveable multiple images can be taken and 3-D information reconstructed.

Of particular relevance to the research being carried out is the work done by Andersson [36], who has developed a robot ping pong player using stereo vision to detect the balls position and path. This allows the robot to intercept and return the ball. The table and the background are black, this creates a good contrasting image allowing for easier feature extraction. This is similar in concept as there are few targets, one, and it is spherical and therefore no additional information can be gained from perspective as the object will always appear circular, however, this system is for guidance through path planning and does not compensate errors in the robot.

Conclusions

Photogrammetry offers a wide range of uses in industrial metrology, in particular large scale measurement, that are only now being realised. It can cope with relatively unstructured environments and can still produce the accuracy required and it has a proven track history. Although much work has been done on robot calibration and accuracy, no one system fulfils all the requirements. Vision which is non-contact and requires little structuring, offers a fast, low cost system. Such a system would be easily portable and could offer a means of condition monitoring for a robot system. This could reduce down time, loss of production and possible damage to the robot itself.

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