STATE OF THE ART OF 3D MEASUREMENT SYSTEMS
FOR INDUSTRIAL AND ENGINEERING APPLICATIONS

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ABSTRACT

Industrial 3D measurement systems have been in a rapid development phase during the last ten years. The rapid change has been generated primarily by demands for accuracy and efficiency from the aerospace and manufacturing industries, along with very strong competition amongst commercial providers of systems and services. The current trends are toward total automation of the measurement set up and acquisition process, user-directed real time measurement, and provision for direct input of three dimensional coordinates, strings or geometric objects into a CAD model, within a user defined reference frame. Almost as a minor consequence, the precision and reliability of the acquired data are steadily improving, due to both better system design and increased computer processing capability. Inevitably such systems are now seen by users as "off the shelf" tools to produce the desired results for a particular application in the most appropriate and efficient way. Optical techniques such as theodolite and vision metrology systems, mechanical systems such as portable coordinate measuring machines, and hybrid systems such as the integration of vision metrology and motorised control, are described and discussed.

RESUME

Les systèmes de mesures industrielles en trois dimensions ont progressés fortement ces dix dernières années. L’évolution rapide ayant été due premièrement aux critères rigoureux de précision et d’efficacité qui exigeaient l’industrie notamment aérospatiale, mais aussi la très forte compétition parmi les principaux fournisseurs. La tendance actuelle s’oriente vers l’ automation totale des mesures et des procédés d’acquisition, mesure en temps réel dirigées par l’utilisateur et disposition nécessaires pour l’entrée directe des coordonnées en trois dimensions, chaînes ou objets géométriques dans le cadre d’un modèle CAD. En conséquence, la précision et la fiabilité des données acquises s’améliorent régulièrement grâce a un meilleur système de design et un accroissement des capacités de traitement informatique. Inévitablement de tels systèmes sont maintenant vus par les utilisateurs comme des outils disponibles pour produire les résultats désirés de la manière la plus efficace pour une applications particulière. Les techniques optiques telles que théodolite et systèmes de vision métrologie, systèmes mécaniques comme les machines portables de mesure de cordonnées, et des systèmes hybrides tels que l’intégration de vision métrologie sont décrits et discutés.

ZUSAMMENFASSUNG


mische Systeme wie tragbare Koordinatennmessmaschinen und hybride Systeme wie die Integration von vision metrology und motorisierter Kontrolle werden beschrieben und diskutiert.
INTRODUCTION

During the last two decades, industrial measurement systems have become an accepted tool for three dimensional (3D) measurement in the aerospace, manufacturing and engineering sectors. Although the initial acceptance of optical systems based on theodolites and photogrammetry was very slow, such systems are now seen as viable 3D measurement techniques which compete with more traditional, mechanical systems such as coordinate measuring machines (CMMs).

The acceptance of optical systems is due to many factors. Perhaps the principal amongst these factors has been the continual improvement of theodolite and photogrammetric systems, partly due to advances in the technology and partly due the demands of industry. Commercial suppliers have been eager to provide measurement solutions which were not seen as specialised systems which could only be operated by surveyors and photogrammetrists, in order to improve their competitiveness against established techniques. Other factors which must be considered are the development of niche markets and specific applications of different systems, and the necessity for large aerospace and manufacturing organisations to have a range of “off the shelf” measurement systems to apply to existing and new applications.

The most important development in all types of industrial measurement systems has been progress toward automation. The most significant disadvantages of the early theodolite and photogrammetric systems were the requirements for a complex set up or design procedure and the requirement for manual or at least operator-assisted measurement. Although no general purpose industrial measurement system could arguably claim to be fully automated in all phases of the set up, measurement and analysis processes, many systems are at a stage of development where semi-skilled operators can successfully conduct accurate and reliable measurements with minimal training. The current trend is also toward online or real-time systems where the user controls the measurements which are taken and the data captured is input directly into a CAD system. The controlling software may well have the capability to accept data from a number of different industrial measurement systems, generate and analyse geometric objects automatically within a user defined coordinate reference frame, and report immediately on both the quality of the measurements and the departures of the measured objects from preset tolerances.

The intent of this paper is to provide a review of the different techniques which fall into the category of general purpose, highly accurate, 3D measurement systems for industrial and engineering applications. The emphasis here is on portable systems which can be deployed on the factory floor in order to provide a flexible measurement solution. Established optical techniques such as theodolites, total stations, vision metrology and laser rangers will be assessed in terms of the progress in the technology since the last overview of the state of the art (Shortis and Fraser, 1991). In addition, some recent innovations in CMMs, portable non-optical devices and hybrid systems will be outlined.

SURVEY SYSTEMS

Theodolite Systems

Advances in the technology of theodolites, recording devices and computing in the 1980s resulted in the first industrial measurement systems based on the digital theodolite. The development of the digital theodolite was an offshoot of advances in total stations, such as the introduction of encoded angle circles and electronic data recording for field survey equipment. The combination of the total station, data recorder and PC software realised the “field to finish” process which has been universally adopted by the surveying profession and more recently translated to new data gathering technologies such as real time satellite navigation systems and hand held laser rangers.

The first electronic theodolites were distinguished from total stations by the lack of any integral distance meter or data recording facility. The later incorporation of a serial communications port for data output allowed the on-line measurement of angles and the potential to compute real time XYZ
coordinates. By the early 1980s a number of industrial measurement systems based on two or more digital theodolites had been released. One of the earliest systems was AIMS (Vyner and Hanold, 1982), developed by Keuffel and Esser, which made a significant impact on the aerospace industry in North America and as a consequence was quickly followed by the Wild RMS, Kern ECDS and Zeiss TOK systems. Typical systems comprise two or more digital theodolites linked directly to a PC, which has appropriate software to compute XYZ coordinates and appropriately inject the data into a CAD model for the geometric construction or analysis of the object being measured. Typical examples of measurement applications are deformation surveys, surface shape characterisation, alignment surveys and robot calibration (Woodward, 1987), whilst other more novel applications include calibration of a sensor probe in a large scale wind tunnel (Shortis and Adams, 1990) and the final dimensional inspection of a fully assembled, large aircraft (Holting, 1995).

Systems and applications in the 1990s are largely unchanged. Digital theodolites have improved in their angular precision and electronic reliability, whilst the complexity and versatility of the industrial measurement software has resulted in very sophisticated solutions. The early systems used straightforward intersections computed from 3D geometry in order to minimise the computer processing overhead. The intersection computations are used within a local, plane coordinate system which is established once the theodolites are levelled and the horizontal circles are mutually referenced. The system set up process also requires the measurement of a calibrated scale bar or other length standard to establish accurate lengths and distances from the theodolite angle measurements, and the measurement of points which define the design coordinate datum for the object to be measured. In principle a minimum of five locations must be observed from each theodolite, however in practice more locations may be measured to provide some redundancy in the initial set up to reliably define the coordinate datum, length standard and theodolite orientations.

In preference to intersections, current theodolite systems commonly use a functional model for coordinate computations which is analogous to a photogrammetric bundle solution. The bundle solution takes advantage of the considerably greater processing power of computers to incorporate all available data and carry out more comprehensive data quality testing. The bundle solution may incorporate all or groups of measured points, or every new measured location may be processed with current set up data. Use of the bundle solution generally does not diminish the requirement for the initial set up procedure and periodic checking of the set up and, regardless of the computation method, a post-computation transformation into a design coordinate datum is needed.

Industrial measurement systems using standard digital theodolites have little scope for automation. During both the set up and measurement phases, theodolite operators are required to point the theodolites at passive targets or other points of interest. The operators must both coarsely identify each target point and accurately align the theodolite cross hairs with the centre of the target point. Manual operation of theodolites is labour intensive and not as efficient or reliable as other techniques such as vision metrology. The use of human operators inevitably raises the possibility of errors caused by mis-identifications, poor synchronisation between the operators or other problems, leading to loss of accuracy or a further decrease in efficiency.

Despite the drawbacks of industrial measurement systems based on manually operated theodolites, there may be several hundred such systems in use in the aerospace and manufacturing industries worldwide. Applications such as tool and jig inspection, alignment surveys and surface characterisation involving small numbers of points of interest remain the common tasks. However it is clear that this type of system has realised its maximum potential and the number of systems is unlikely to substantially increase in the future.
Industrial measurement systems based on digital theodolites owed their genesis to general purpose total stations developed for field use, and total stations have again contributed to a quantum advance in such systems. The addition of stepping motors produced “automatic” or motorised total stations which were developed in the mid 1980s to improve the efficiency of field survey operations, for tracking of moving targets and repeated measurements for deformation studies and precise surveys (Kliem, 1989), and are still widely used for this work (Rueger and Sippel, 1996). Motorised theodolites and/or total stations are currently available from all of the principal survey instrument manufacturers, and industrial measurement systems may incorporate either theodolites or total stations. Whilst the extra facilities of distance measurement and onboard data storage are not mandatory for industrial measurement systems, the addition of measured distances may be useful for some measurement applications (Shortis and Ganci, 1995).

Motorised theodolites convey the same advantages on industrial measurement systems as they supply to field survey operations and were very quickly adopted (Katowski, 1987). The capability to drive to particular directions allows, for example, the set up measurements to be repeated more efficiently, as the theodolites carry out the coarse pointing and the operators simply verify or adjust the fine pointing. In a situation where there is a long period of measurement or there is uncertainty associated with the stability of the theodolites, the efficient checking of the theodolite orientations is valuable. In a production line situation, the same measurements on similar parts can be efficiently carried out using the same technique. Within a design volume, XYZ coordinate positions can be used to compute directions with respect to local theodolite orientation, allowing automated pointing to predicted locations. This function can be used to coarsely drive to key points on a jig or a tool for dimensional inspection or alignment applications, for example, largely eliminating problems caused by misidentifications. The ability to drive the theodolites to predicted locations in design space, coupled with the incorporation of a coaxial laser, facilitates the efficient processing of tolerance violations if online remedial action is necessary.

However, a high level of automation of this type of industrial measurement system requires the complete elimination of manual operation. Tracking systems which rely on the return of the distance measurement signal are widely used for large scale surveys, but are not well suited to precise industrial measurement as the “intensity maximum pointing” technique realises accuracies of no better than approximately $\pm 3$ arcseconds (Rueger and Sippel, 1996; Ingensand and Bockem, 1997). Angular accuracies for industrial measurement should be of the order of $\pm 1$ arcsecond or better to achieve tolerances which are acceptable for, in particular, the aerospace industry. Further, a corner cube or similar type of reflector is required, which would not be universally feasible in industrial measurement applications.

The highest level of automation of theodolite systems has been achieved by the integration of charge-coupled device (CCD) arrays into or adjacent to the optical path of the theodolite (Katowski, 1987). The CCD array is used to capture real time images of the theodolite field of view in order to detect high contrast or identifiable targets. Retro-reflective targets are commonly used in conjunction with a near coaxial light source, in a very similar fashion to retro-targets used by film photogrammetry and vision metrology systems with a flash or continuous light source adjacent to the camera lens. The digital images of the field of view of the telescope are used as an adjunct to pointing so that the theodolite can be automatically centred on the target. Any bias in the CCD array can be effectively eliminated by centring the target within the field of view using the stepping motors. Whilst this type of system can be constructed by simply attaching a CCD camera to a motorised theodolite and paying due attention to the alignment of the optical axes (Wester-Ebbinghaus, 1988), in the late 1980s the survey instrument manufacturers produced extremely refined systems which realised an encouraging potential for automation. The Kern SPACE (Roberts and Moffitt, 1987) and Wild ATMS systems, based on “video-theodolites”, appeared at approximately the same time with similar features and applications.
The initial set up of a video-theodolite system closely parallels that of a manual system. The theodolites must be mutually referenced, a standard scale established and locations defining the object coordinate system observed. The measurement of the points of interest is somewhat different, as the stepping motors can be used to point each theodolite in the direction of each target in turn, assuming that approximate target coordinates are known. Ideal applications for this type of automated theodolite system are repeated measurements on a production line, or industrial inspection where the tooling locations are pre-defined. Unlike manual theodolite systems, the number of targets which can be measured is not limited to small sets by operator fatigue, particularly if the locations can be predicted. If the target is within the field of view predicted by the XYZ location of the target then the direction can be located precisely by the CCD image without any operator intervention. The whole process can be efficiently overseen by a single operator, regardless of the number of theodolites in use, by monitoring the video signals from the CCD arrays. In situations where there are no known points there is the option of centring targets on video monitors so that a single operator can control the entire measurement process. Other possibilities are line following on strips of retro-reflective targets, trilateration to mini-prisms and surface measurement using one theodolite with a coaxial laser and one or more theodolites with CCD arrays.

Industrial measurement systems based on video-theodolites remain relatively unusual, partly due to the specialised nature of the systems and the higher initial cost as compared to manual theodolite systems. There are relatively few systems in routine use within industry (Meyer, 1993), and the lack of success of this type of system has forced instrument manufacturers to pursue other measurement solutions. However, the development of theodolite systems has continued in other ways. The motorisation of theodolites, both for general use and specifically for industrial measurement, has been further refined and is now a fully integrated feature of many “automated” theodolites and total stations. Tracking techniques such as the intensity maximum pointing continue to be developed, and more recently CCD arrays have again been employed for automatic target recognition (Bayer, 1997). In this case the return beam of the distance meter is detected by the reflection in the corner cube prism. Initial results indicate that the angular precision is again of the order of ±3 arcseconds. The accuracy of the distance measurement is continually improving, and many instrument manufacturers now offer total stations with distance accuracies of ±0.5 millimetres to mini-prisms and retro-targets, albeit over short ranges, specifically for industrial applications (Whitted, 1993).

Whilst these levels of accuracy are not acceptable for the stringent tolerances typical of the aerospace industry, there are many applications in the manufacturing, automotive and large scale engineering sectors where the combination of an angular accuracy of ±3 arcseconds and a distance accuracy of ±0.5 millimetres would be very competitive. The increasing number of motorised total stations is likely to reduce the cost of manufacture of the instruments, which may in turn make these systems more attractive as a solution to specific measurement problems. It is likely that, as a consequence, automated theodolites will have a greater presence in industrial measurement systems in the future.

Laser Ranging

The rising star of geodetic industrial measurement systems in the 1990s has certainly been laser ranging. The first systems were introduced by Automated Precision and Chesapeake Laser Systems in the late 1980s, but initially laser rangers were not well accepted due to the high capital cost, the requirement for a prism reflector for accurate results at key points, an extended set-up time and the inherent reliability and geometric weaknesses of polar radiations. A typical system combines a laser interferometer or coherent laser radar with an optical head and angle encoders, and if used from a single location then the reliability of measurement is minimal (equivalent to single radiations) and the accuracy can be strongly affected by poor measurement geometry.

Despite the early teething problems, laser ranging systems did find appropriate applications, particularly in the areas of surface shape measurement and tracking of single targets. Coherent laser radar systems were hampered by their inability to produce accurate results for all surface materials and finishes using
reflectorless measurement, and as a consequence interferometric systems are now dominant. Successful applications rapidly followed the refinement of these systems and the increasing expertise of users. Perhaps the most widely reported application has been the calibration of industrial robots and CMMs, where laser rangers can take advantage of their ability to record very accurate distances at very high sample rates to a single retro- or prism reflector.

More recent systems such as the Leica Smart 310 (Schertenleib, 1995), originally badged as a Kern system and now updated as the LT500, and the Spatial Metrix Tracker4000 have overcome many of the initial disadvantages of laser ranging. Principal amongst the advantageous changes has been improved portability and a simplification of the set-up process, enabled by miniaturisation and advances in computer technology respectively. In turn this has reduced the influence of non-optimal geometry, as multiple set-ups for a measurement project are now a practical mechanism for ameliorating poor surface incidence angles and producing better measurement reliability. The design of the measurement geometry for laser trackers is quite straightforward, as compared to theodolites and photogrammetry, and the visible laser beam is an unequivocal signal that the system is working correctly. As a consequence, the penetration of laser ranging systems into the industrial measurement market has been quite pronounced during the last few years and shows no sign of the plateau which is currently affecting theodolite-based systems. User preference for the estimated 300 laser ranging systems in use in the aerospace and manufacturing industries today centres around the convenience of setting up and operating a single measurement device, the high level of automation and impersonal nature of the measurement process, and the user friendliness of the software.

PHOTOGRAMMETRIC SYSTEMS

Shortis and Fraser (1991) describe in detail the changes to close range photogrammetric systems which have occurred during the previous few decades. In summary, advances in a number of areas of the technology, algorithms and procedures have allowed industrial measurement systems based on photogrammetry to become, like theodolite and laser ranging systems, an off the shelf tool for the aerospace and manufacturing sectors of industry.

Prior to the introduction of systems based on video and digital still cameras, three main factors contributed to the increased adoption and use of photogrammetric systems for industrial measurement. The first of these factors was the use of more versatile and sophisticated medium and large format camera systems which incorporated continuous focusing, reseau grids and stable base roll film. Prior to the 1970s, close range cameras were metric (fixed interior orientation), fixed focus and could only accept glass plates as the emulsion medium. The second factor was the introduction of multi-station, self-calibrating network solutions which allowed much greater freedom in the design of photographic coverage and simultaneously realised substantial improvements in the accuracy and reliability of the object space coordinates. Furthermore, the use of internally constrained solutions for the close range photogrammetric networks, also known as free network solutions, removed the requirement to provide independently measured, accurate control data whilst also producing the optimum precision for the photogrammetric network. The third factor was the semi-automation of the measurement processes. The use of retro-reflective targets in conjunction with flash photography, automated comparators with integrated vision systems, and “resection drive back” algorithms allowed much greater efficiencies in the measurement process and consequently improved turn around times dramatically. Although the resection drive back process still required an operator to identify known target positions to initiate a measuring sequence, advantage could be taken of predicted locations of known targets, line following for strips of target tape and repeated measurements in production line environments to maximise the proportion of automatic measurement of target images.

The combination of these three factors allowed non-specialists to be rapidly trained in photogrammetric network design, measurement and computation, producing highly accurate results within, in some cases, a few tens of minutes. A comprehensive review of film-based industrial photogrammetric systems is given in Fraser (1988).
Digital Photogrammetric Systems

Although proportional accuracies of better than 1:250,000 are still largely the province of large format film cameras, the most recent revolution in industrial measurement systems based on photogrammetry has been the introduction of high resolution digital still cameras. Building on techniques pioneered in machine vision, there were many examples of successful use of CCTV and standard video camcorders for industrial measurement in the 1980s. However, it was not until 1991 and the release of the Kodak DCS100 that vision metrology systems were feasible. The 1524 by 1028 pixel CCD sensor was packaged into a standard 35mm SLR camera, which allowed a range of high quality lenses and flash equipment to be used in conjunction with the camera. Initially released with a separate hard disk for image storage, the DCS200 quickly followed with hard disk storage for 50 images within the base of the camera. The DCS series and similar cameras transfer the image digitally, avoiding synchronisation errors and noise inherent in video systems based on analog signals, and allow unlimited portability. The latest revisions of these very popular cameras are the DCS420, and now the DCS460 with a 3072 by 2048 pixel array. These and similar cameras have been applied to many industrial and engineering applications, such as industrial inspection (Beyer et al, 1995) and large scale engineering metrology (Fraser and Shortis, 1995).

The single, roving camera mode of operation is now known as “offline” mode, and in essence is the traditional method of photogrammetric measurement using retro-targets, free network solutions and self-calibration. Locations of circular targets within the digital image can be computed using intensity-weighted centroids, edge detection and ellipse fitting, or template matching. Centroids and ellipse fitting require the elimination of background or noise by the removal of a local threshold. Whilst template matching may be independent of high contrast targets, for non-targeted points the technique requires an initial template to be defined. All measurement location scenarios require the coarse location of the target images to be defined to position the local window within the image space, and digital images have provided the opportunity for an even higher level of automation of the measurement process.

![Figure 1. (a) Various coded target types and (b) an orientation device.](image)

Whereas automated comparators used by film based systems were limited in their ability to automatically search for target images, there is no such restriction on digital images and the current generation of powerful computer systems. All high contrast targets can be located within all digital images of a photogrammetric network and subjected to a battery of geometric tests to eliminate false targets. Specific targets can be identified and labelled by the recognition of any of a number of coding schemes (van den Heuval et al, 1992) or unambiguous patterns (figure 1). This has led to the concept of orientation devices (figure 1) and automatic orientation of digital images. An orientation cross using coded targets or a grouping of circular targets in a known and fixed relationship is introduced into every digital image of a network, or coded targets are placed at pre-determined locations such as key points of the design coordinate system of a tool or jig. A robust, closed form resection solution (Zeng and Wang, 1992) is then employed to enable automatic orientation.

Once the images in the photogrammetric network are oriented, techniques to determine target correspondences, such as epipolar or epiplane searching (Chen et al, 1994), are used to identify and match all possible uncoded targets remaining in the images. Poor correspondences are ignored at this
stage and a self-calibrating, free network solution is computed. The refined camera calibration and orientation data is then used to update the target correspondences and provide additional data for another network solution. This iterative process continues until all target correspondences are resolved, or a pre-set criterion is reached. A number of industrial measurement systems based on high resolution CCD cameras and portable computers (Beyer et al, 1995; Brown and Dold, 1995) have taken advantage of these innovations to produce industrial vision metrology systems which have very high levels of automation, accuracy and flexibility. Within the category of optical measurement systems, vision metrology has perhaps the highest level of automation for general purpose operation.

Online Systems

The limitations of the offline mode of operation of vision metrology systems are a finite delay between measurement and results, increased processing time for complicated objects which may require many images, and the inability to target or image all points of interest. To overcome these restrictions, the concept of a optical measurement work cell, now known as online or real time systems, was introduced in the early 1990s (Pettersen, 1992). Although photogrammetric work cells and 3D digitisers based on analog video cameras and retro-targets pre-date this concept, online systems using two or more digital cameras are now well established in the automotive and aerospace industries.

The fundamental component of online systems is the hand held probe (figure 2), comprising a retro-reflective or LED grouping of targets and a measuring tip similar to that found on CMMs. The tip is positioned over the point of interest and the measurement process is triggered by the operator. The trigger will light the LEDs and remotely fire the cameras, or remotely fire the cameras and flash units for retro-targets. The captured images are downloaded to the system computer and the probe is located by scanning the images for the distinctive pattern of targets. The orientation and location of the probe are computed with suitable checks on the integrity of the coordinate data, and the offset to the probe tip is added to complete the measurement. Typical online systems link the cameras to the host computer via cables containing fast digital or LAN interfaces, plus synchronisation lines and electrical power.

![Figure 2. Online system measurement probes.](image)

Online systems also feature a high level of automation, as many of the advances found in offline systems can be also implemented for online systems. Specifically, coded targets or orientation devices can be used to establish the initial exterior orientation of the cameras. The probe or a scale bar can be subsequently used to strengthen the solution by moving it throughout the working volume. Fixed targets within the field of view can be continuously monitored to assuage any concerns with regard to the stability of the cameras during the period of online measurement. Cameras are typically pre-calibrated, although there are strategies which can be used to self calibrate the cameras in situ (Shortis and Beyer, 1997). The control software for online systems commonly has a direct link to a CAD application and, like theodolite based systems, allows a “build” mode where geometric objects can be accumulated from sequential probe measurements.
The most recent development for vision metrology systems is the introduction of “intelligent” cameras (Dold, 1997). The GSI INCA series, as used in their V-Stars industrial metrology systems, includes an onboard processor which searches images as they are captured. Using a LAN interface, the local processor can communicate the status of an image to the host computer immediately, identifying flash failures, lack of coded or uncoded targets or both, or lack of an orientation device. Rather than transmitting the image, the camera can send a status message, the location of a hand held probe or the entire image. Although this development is more pertinent to online systems where there are clear advantages for the speed of processing, it does have application to all uses of vision metrology systems.

Although the industrial measurement market for offline and online digital photogrammetry is not growing as strongly as that of laser trackers, it is nevertheless growing and a reasonable estimate is that more than one hundred systems have been sold to industry during the last five years. A detailed review of recent advances in digital photogrammetric systems is given in Fraser (1997).

COORDINATE MEASURING MACHINES

Coordinate measuring machines (CMMs) were developed as a mechanical solution for accurate 3D measurement, based on industrial measurement and manufacturing techniques. CMMs are effectively very accurate 3D mechanical digitisers which use encoders to track rotation and translation stages. These systems have universal penetration into industry because they are seen as an essential measurement tool, and hence are the major competition for optical systems based on geodetic and photogrammetric principles. CMMs have very tight integration with industry standard CAD systems, are capable of automated measurement and repetitive procedures, have a wide range of touch probes which enable “impersonal” measurement, and can achieve accuracies of the order of a few micrometres. Whilst conventional CMMs are well known, there are a number of recent innovations which are providing an increased level of competition within the industrial measurement market.

Portable CMMs

One of the severe disadvantages of CMMs is that they are large, fixed installations. There is a maximum size limit for objects which can be measured and the object must be transported to the CMM, rather than vice versa. The largest CMMs can measure objects up to a few metres in size with an accuracy of tens of micrometres, but such systems require a capital outlay of millions of dollars, a controlled environment and considerable resources for maintenance and support of the system.

Portable CMMs have been available for more than a decade and overcome some of the limitations of fixed CMM installations. Systems such as the Romer and FaroArm are based on an articulated arm connected to a base unit which can be stand mounted or clamped to the object to be measured. The arm comprises three or more universal joints (shoulder, elbow and hand) with encoders to track the position of an interchangeable probe tip. The reach of such systems ranges from 1 to 3 metres whilst the accuracy of the point positions is of the order of 0.1 millimetres.

The systems require a set up process to reference the CMM to the design coordinate datum of the object. The effective measuring volume of the systems can be extended by multiple set-ups within the same reference coordinate system. Once more there is tight integration between the CMM and the CAD application, including a build mode and the ability to manually select design locations. Portable CMMs have found wide acceptance, particularly in the automotive industry, as a very portable and flexible technique which is simple to set up and operate.

Optical CMMs

Most online vision metrology systems are based on the components of, and can be used as, offline systems. One alternative is the somewhat mis-named “optical CMM”, with three cameras in a single, mobile unit connected by cable to a LED type probe. The units are typically sealed and have fixed focus cameras to prevent interference and particularly variation in the camera calibration or orientation.
The outer cameras are convergent to improve the intersection geometry and three cameras are utilised to provide some redundancy of measurement and better reliability in the epipolar searches for target correspondences. Such devices are a direct competitor for portable, mechanical CMMs. Optical CMMs have the advantage that the conical measurement volume can be larger, but the variation in the accuracy across the volume is more variable.

This concept can be extended into the “optical tracker” category, where sealed, modular units can be positioned and calibrated to continuously track LEDs within a predefined volume. Two cameras with orthogonally mounted linear CCD arrays and cylindrical lenses are often used, rather than a single camera with an area CCD array and a conventional lens. The advantage gained is very fast processing of the image data, as two 10000 element linear arrays generate an order of magnitude less data than a standard camera. Optical trackers have found niche markets in biological movement studies, robot tracking and virtual reality, but their use in the aerospace and manufacturing industries has been limited to model tracking in wind tunnels and some dynamic alignment problems for component assemblies.

HYBRID SYSTEMS

Practical and commercially viable industrial measurement systems are generally foreshadowed by the development of prototype systems for research, or investigations into innovative techniques of industrial measurement. Although not all research and investigation results in feasible solutions, the hybrid systems currently under development do show potential for future use, at least in niche markets.

CMM Developments

A further limitation of CMMs is the touch probe, which is required to contact the surface. Much research and development has been conducted on the use of touch probes to increase their efficiency, accuracy and versatility (Nasham, 1993), however the fundamental restriction of positioning and contacting the surface is unavoidable. The combination of lasers and CMMs has been a topic of research since the 1970s, and the use of laser profiling in conjunction with CMMs has been recently revived (Ramanan et al, 1995) due to technological advances in laser diodes, such as miniaturisation, and decreasing cost. The system operates by scanning the laser across the part to be measured, dramatically increasing the efficiency of the system for routine quality control tasks and the measurement of highly complicated pieces.

For identical reasons to the integration of the laser profiler, the combination of CMMs and machine vision has also been under investigation for some years. The typical system incorporates a single CCTV camera attached to the measuring probe at a known offset. The emphasis here has been on the automated identification and inspection of parts, typically by associating the CAD model with the part through the detection of edges (Nasham, 1993). Whilst the laser profiler and the integration of vision will never replace the touch probe completely, the combination of the techniques provides a further advance in efficiency and versatility of CMMs.

Integration of Vision and Motorised Control

A promising development in vision metrology systems is the concept of a mobile measuring unit which is capable of “flying” around an object to be measured (Malz, 1996). The location of the measuring head is tracked by robotic control or by photogrammetric transfer of the design datum. The photogrammetric measurement is derived from either a single camera and light stripe projector, or a stereo-vision system with a random dot projector to provide surface texture. There are already a number of systems, such as the Steinbichler Comet, which are capable of very accurate measurements within a relatively small working volume. The potential for further development of such systems is enormous and there are several research projects developing integrated systems which combine digital cameras, robots and CAD systems for industrial inspection and manufacturing control.
There is also current research under way on more general integration of vision systems and motorised theodolites. The first innovation is the extension of the simple target recognition previously discussed in the context of automated theodolite measuring systems. Motorised video-theodolites are being adapted to be used for general feature point recognition (Mischke and Kahmen, 1997). Multiple video-theodolites could be used as an automated industrial measurement system which is independent of high contrast targets, although such a system would still be limited to well defined key points for an acceptable level of accuracy. A second, novel solution uses a linear CCD array to scan objects (Hovenbitzer and Schlemmer, 1997), with the eventual aim of industrial inspection and architectural mapping driven by an interface to a CAD model.

CONCLUSIONS

The end result of the improvements to the technology of 3D measurement systems is greater competition between the different techniques. All of the competing technologies are progressing toward a simple “red light-green light” type of automation wherein the system makes virtually all the decisions with regard to the quality of the 3D data, and the knowledge and skill of the operator becomes less important.

The continuing development of optical measurement techniques will allow these systems to continue to compete successfully with the more traditional mechanical systems. The improvements in ease of use and automation, in conjunction with greater flexibility and reliability, realises a significant competitive advantage which is currently being very well exploited by laser tracker systems. However, it could be expected that CMMs will remain one of the dominant techniques in the aerospace and manufacturing industries due to innovations such as portable systems, the integration of laser profiling and the use of machine vision. In particular, thousands of portable, mechanical CMMs have been sold to the industry over the last several years and there is every prospect that use of portable systems will continue to expand.

Despite the high levels of competition, there is an emerging trend of cooperation between vendors of complementary techniques. For example, offline digital photogrammetry can provide control networks for portable CMMs to enable the efficient inspection of large and complicated fixtures. However, true hybrid systems, such as vision metrology combined with robotic control, also show great promise and a maturation of this technology will certainly lead to a broader utilisation within industry.

REFERENCES


