Engineering Techniques Applied in Industrial Measurements Field

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Abstract: *This paper approaches the engineering techniques used at present within the close range measurements field for 3D positioning, techniques which cover a large industrial range, such as car and ship industries, air and space craft industry, chemical and atomic energy industry etc.*

Introduction

The necessity of positioning the objects on horizontal and vertical axis simultaneously (3D positioning) and in real time was acutely felt in the past few years, because of the even larger complexity of the objects which must be positioned and of the trend of performing the measurements in a shorter time, more accurately and with the possibility to verify the results on-site. The selection of an adequate system to sustain such a demanding task means taking into consideration a list of conditions and parameters such as: the system should be off-the-shelf, self-reliable, very flexible, rapid, accurate, lucrative and low cost.

Table.1. Classification of the instruments used in positioning measurements

Types of Measurements	**Types of Instruments**		
	Topo-geodetic		**Non-conventional**
Distance	Classical	invar band, theodolite with Bala rod	interferometers, extensometers
	Modern	*electro-optical instruments (EDM), laser instruments*	*laser interferometers*
Angles	Classical	theodolites	interferometers
		alignment telescopes, visual autocolimators	
	Modern	*total stations*	*laser interferometers*
		laser alignment telescopes, electro-optical autocolimators	
Level differences, inclination angles, vertical distances	Classical	levels, hydrostatic levels, theodolites	micro-levels, extensometers
	Modern	*digital levels, total stations*	*inclinometers, extensometers*
		micro-alignment telescopes	
Alignment verification	Classical	theodolites	-
		alignment telescopes, visual autocolimators	
	Modern	*total stations*	-
		laser alignment telescopes, electro-optical autocolimators	
Vertical transmission	Classical	theodolites, zenith telescope, vertical devices	-
	Modern	*laser devices*	

The current market offers a large range of instruments and conventional techniques (topo-geodetic and photogrametric) and specific instruments for special measurements (which are at the border between geodesy and physics) that can meet almost any requirement related to the positioning of the objects (see table 1).

A high novelty for this clasification is represented by the 3D scanners and the laser trackers, which alow the real-time determination of the 3D coordinates of a large number of object points. Also, a new technology that competes with the 3D scanners and laser trackers from the view point of the measurement speed compared to the high volume of data, comes from the field of close range terrestrial photogrammetry, and it is represented by the digital off-line and on-line CCD sensor systems.

1. Topo-geodetic technology

In order to face the more and more challenging current tasks for 3D positioning in a short period of time, or sometimes in real time, it is necessary to follow the process in a cycle of measurements comprising the stages of initial positioning, measurement and repositioning, and, if necessary, this cycle can be repeted until the designed position of the object is obtained. This can be maid by means of the new techniques: industrial total stations, laser trackers and 3D scanners.

a). Industrial Total Stations

These are modern topo-geodetic high accuracy instruments, which combine a device for measuring the horizontal and vertical angles, a distance measuring device EDM (**E**lectro-optical **D**istance **M**eter) and a software for data processing and registration.

The measuring principle of the EDM is:

$$D = (N \times \lambda + \Phi)/2$$

where: N – number of wave lengths recorded, λ – wave length, Φ – initial phase.

Table 2. Leica TDM 5000/TDA 5005

Technical Specifications		**TDM 5000**	**TDA 5005**
Angle measurement accuracy		0.5 ‘’	
Distance measurement accuracy		1mm+2ppm	
Distance range	corner-cube reflector	2-600 m	
	reflecting foil	1-180 m	
Speed of ATR tracking (for 10m distance)	longitudinal	-	4 m/s
	transversal	-	3 m/s

The ATR device (**A**utomatic **T**arget **R**ecognition) of the TDA 5005 is used for tracking the targets on the object to be measured, and it allows the automation of the entire positioning process.

Besides the common TDM 5000 and TDA 5005 characteristics, the TM5001 total station has an autocolimation device integrated in the telescope, which allows the measuring of every inclination that has a reflector target mounted on the object. The field of view is 2.08m/100m and 0.26/10m, the minimum aiming distance is 0.6 m and the magnification power is 32x.

The industrial total stations are, at present, very accurate devices for making the engineer’s job easier, regarding the shorter time loss in the process, reliability and accuracy.

b). Laser trackers

The laser trackers are instruments for measuring, in real time and with high accuracy, the 3D coordinates of the moving targets, based on polar measuring mode – angles and distance. The combination of the horizontal and vertical angles with the distance to the object point allows the calculation of the object position with an accuracy of several microns, for object volumes (diameters) up to several tens of meters. These instruments comprise a laser interferometer (IFM –

Inter**F**ero**M**eter) for measuring the distance to the object-point, and high precision sensors for measuring the horizontal and vertical angles; certain types of the laser trackers, like LTD 709 or LTD840 comprise an ADM device (**A**bsolute **D**istance **M**eter).

Although both devices are used to measure the distance with high accuracy, the laser interferometer is used to measure the distance only to one mobile point, provided that the connection between the instrument and the reflector was permanent, every interruption leading to the necessity to reset the coordinates system. The ADM device is used to measure the distance to the targets mounted on the object without the necessity of fulfilling this condition.

Table 3. Leica Laser Trackers

General Technical Specifications	
Tracking speed	4-6 m/s
Maximum measurement speed	1000 - 3000 points/ sec
Distance range	max 40 m
ADM measuring accuracy	25 µm/40 m
3D coordinate accuracy	10µm + 5µm/m

The advantages of these special instruments are: the high speed of data acquisition - each point being measured in a few seconds, the range of measuring with the laser - several tens of meters - that allows the measurement of high volume objects, the presence of only one operator, the possibility to use the system in difficult enviroments. Limitations: the interferometer's laser beam must not be interrupted during measurement (for the instruments that do not have an ADM device, like LT 640), and the high cost of the entire system.

c). 3D scanners

At the begining of this century, a new engineering concept has dramatically improved the possibility of fast measuring the spatial position of objects, and this is represented by the instruments based on 3D scanning, the so-called **H**igh **D**efinition **S**urveying technique – HDS. This technique is a very lucrative non-conventional method for several reasons: a short period of time is needed to perform the measurements, very high accuracy of the results, high detail level and low costs related to the objects volume which can thus be measured or positioned. Also it offers the possibility of visualizing the scanned object right after the measurement session and making 2D maps or cross sections through the 3D model.

These instruments measure the horizontal and vertical angles, and the distance to the object point. The possibility of measuring the distance classifies the scanning instruments in three categories: "time of flight" procedure based scanners – for measuring distances up to several hundreds of meters, scanners based on measuring the phase – used for medium distances up to 100 m, and scanners based on the traingulation method – for very short distances, with an accuracy of several microns (Vi 910 3D scanner from Minolta and GS 200 from Mensi).

Table 4. 3D Scanners Classification

Measurement Technique	**Measurement Range (m)**	**Measurement Accuracy (mm)**	**Producers**
"Time of flight"	< 1000	< 20	Leica, Mensi, Optech, Riegl
	< 100	< 10	Optech, Riegl
Phase measurement	< 100	<10	Leica, VisImage
Triangulation	< 5	< 1	Mensi, Minolta

Fig.1. HDS 3000 / HDS 4500 / Vi 190-Minolta / GS 200 - Mensi

Table 5. Leica 3D Scanners

Technical Specifications		HDS 3000	HDS 4500
Distance (measurement) range		< 100 m	< 53 m
Scanning field-of-view	horizontal plane	360°	360°
	vertical plane	270°	310°
Single point determination accuracy	distance	4 mm	≤ 3 mm
	horizontal and vertical angles	60 µrad	350 µrad
Scanning rate		1800 points/s	500 000 pcte/s
Measuring method		“time of flight”	phase

2. Short Range Digital Photogrammetry

Short range digital photogrammetry, also known as videogrammetry, was not sufficiently sofisticated at the begining to face the challenging tasks related to accuracy, which were very well resolved by means of industrial theodolites, laser trackers or classic film based photogrammetry. The last 10 years were the most active from the point of view of the innovations, integrating the photogrammetric techniques with CAD techniques (**C**omputer **A**ided **D**esign) or CAM (**C**omputer **A**ided **M**anufacturing) and developing high resolution multi CCD sensors systems even for dynamic measurements in real time.

Thus the high precision and fast measurement requirements lead to the development of different types of industrial photogrammetric systems, which can be used in off-line and on-line mode. Though both systems have as a comon feature the determination of the 3D object coordinates by means of the 3D object-space reconstruction using bidimensional images, they present differences in terms of accuracy, automation degree, flexibility, etc.

The *off-line systems* are implemented in certain sectors of the aircraft or maritime industry, where the real-time factor is not very important. They are caracterised by the differentiation of the data processing stage from the data acquisition stage through the measurement of all the images taken from all the net stations. Also, they are more flexible than the on-line systems as regards the improvement of the precision that can go up to 1:200 000 from the main dimension of the object.

The *on-line systems* are very useful for the measurement and registration of dynamic events, as for example in the automobile industry assembly lines, where the production rate is very high, or in the dynamic testing stage in the aircraft industry. They are caracterised by: real-time results of data processing from measurements, and system net made only of digital sensors, and not of film cameras. The measurement precision of the 3D coordinate is within 1 :50 000 and 1 : 70 000. The higher the resolution of the photogrammetric sensor, the higher the 3D coordinates determination (see Table 5).

Table 5. 3D Coordinates Precision

Image Dimension	Focal Length (mm)	Field-of-view $(^o)$	Precision for 1/30 pixels resolution	Precision for 1/3 pixels resolution
4k x 4k	40	48	1:200 000	1:20 000
3k x 2k	28	50	1:140 000	1:14 000
2k x 2k	20	48	1:100 000	1:10 000
1.5k x 1k	18	40	1:85 000	1:8 500
1k x 1k	14	36	1:70 000	1:7 000

INCA 3 (INtelligence CAmera) - Geodetic Services Inc. - is a high accuracy digital camera that integrates a high resolution CCD sensor (**C**harge-**C**oupled **D**evice) and a last generation computer for automatic industrial measurements proccesing.

Fig.1. INCA 3 Digital Camera

Fig.2. PRO-SPOT Projection System

This camera was designed for on-line and off-line measurement modes and it can be used in hostile and unstable industrial enviroments (high temperature, vibrations) for measuring and inspecting dynamic or static large volume objects in the aircraft, maritime and nuclear industries.

Table 5. INCA 3 Digital Camera

Technical Specifications

Accuracy	5µm+5µm/m
Focal length	21 mm
Sensor	8 MP

Right after the images are taken, the V-STARS software processes the images automatically and computes the 3D coordinates. This software has powerful tools for analysis during measurement, visualization and statistics, for transfering the data to other CAD environment or to another software package.

A limitating factor for the digital photogrammetric technique could be the fact that several thousands of targets must be attached to the measured objects, this action being a time and money consumer. A stroboscopic projector for projecting dot-targets on the measured object can be used in order to deal with this problem, such as a PRO-SPOT projector used with INCA camera (see fig. 2.)

Presently, the industrial photogrammetric methods and techniques can be defined as mature because of the high productivity, flexibility, accuracy, robustness and high confidence in results.

3. Unconventional Technology

Due to the necessity of working with special industrial objects and to the special working conditions, the geodetic engineers have been forced to utilize measurement instruments usually used in the automobile industry and physics laboratories, and use them in the surveying process. In time, just like the topo-geodetic instruments, non-conventional techniques developed thanks to the opening to various fields and to the necessity to automate the entire surveying process, from classic interferometry and alignment devices to modern laser devices.

a). Laser Interferometer

The interferometer is an instrument whose principle is older than one century, used to measure distances up to 100 m with high accuracy (max. 1 nm), knowing the length of the stable wave of the electro-magnetic radiation used. Also, it is used to verify the object geometry by measuring small angles, verifying the perpendicularity of two directions or the offset from rectilinearity and smoothness; it can determine speed and acceleration.

It is based on the light waves collision principle – Michelson principle – a coherent beam of light is split in two: the first is used as a reference, the second is reflected back from a reflective mirror, and it collides with the first beam. The number of the registered resulting fringes gives the distance between the interferometer and the mirror.

Changing the white light with a laser allowed the measurement of longer distances and improved the accuracy of determinations, because of the stability of the laser beam. A second inprovement of the Michelson interferometer is the changing of the reflective mirrors with corner-cube reflectors, which ensure the paralelism between the reflected and incident beams regardless of the incidence angle, and the third is the introduction of the photo-electrical cells which transform the fringes into impulses in order to obtain the offset and movement direction of the reflector.

The Zeeman laser interferometer, based on Zeeman principle, has a two-frequency He-Ne laser. This characteristic introduces a series of advantages: only 5% signal loss (50% for Michelson interferometers), there is no need for periodical electric and laser intensity adjustments, and it tolerates the signal variation induced by the reflector rotation.

Agilent 559A laser interferometer (Hewlett Packard) is an instrument based on Zeeman principle, and has the following parameters.

Table 7. Agilent 559A laser interferometer

Technical Specifications

He-Ne Laser Characteristics		
Vaccum wave length	632,991 nm	
Wave length accuracy	± 0.01 ppm	
Beam diameter	6 mm	
Distance Measurement		
Range	40 – 80 m	
Accuracy	20^0	±1.5 ppm
depending on the	15^0-$25^{\,0}$	±1.7 ppm
temperature	0^0-45^0	±3.0 ppm
Angle Measurement		
Range	$\pm10^0$ - $\pm20^0$	
Accuracy	± 0.2 % /angle ±0.05''/m	
Resolution	0.05 ''	
Minimum distance between laser and reflector	15 m	

The distance measuring principle is:

$$D = N_\lambda \times \lambda_{air}$$

$$D = N_\lambda \times \lambda_{vaccum} \times C_n \quad (C_n = 1/n)$$

where: N_λ – number of registered wave lengths, λ_{air} – laser beam wave length in the air, λ_{vaccum} – laser beam wave length in vaccum, C_n – atmospheric compensation factor, n – atmospheric reflective factor.

Measuring of small offset angles can be made using two frequency laser interferometer:

$$\Theta = \arcsin((L_1 - L_2)/S)$$

where: L_1 and L_2 - wave lengths and S – the reflector constant

b). Laser Alignement Telescopes

Laser alignement telescopes are instruments used to check the alignement, paralelism and perpendicularity of two directions, the surfaces plane geometry etc. They have a high stable laser transmitter with an integrated device for the precise alignment control of the transmitted beam.

The receiver is a high accuracy positioning device with an integrated software package for automatic processing and registration of collected data. An example of laser alignement telescope is a Taylor-Hobson product from Spectrum Metrology.

Table 7. Taylor-Hobson Laser Alignement Telescope

Technical Specifications	
Range of measurement (x,y)	± 5 mm
Measurement resolution	0.1 mm
Range of distance	0.1 – 10 m
Wave linearity accuracy	0.4 %

c). Electro-Optical Autocolimators

Electro-optical autocolimators are used to determine with high accuracy the small offset angles and to verify the parallelism between two directions.

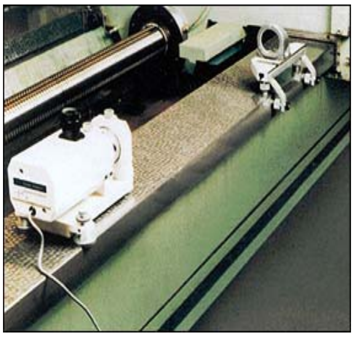

Fig.3. DA 400 - Taylor-Hobson Autocolimator

The measurement principle consists in projecting a light beam on a reflective target through the autocolimator telescope. The light beam intensity is very important because many applications need to measure long distances (up to tens of meters) and the convergent lenses ensure this quality. After the beam passes through the beamsplitter, it enters the objective lens, where it is collimated and then reflected back to the objective by a mirror (or reflector-target). The deviation of the mirror with Θ creates an offset of the returned image with a distance X, which can be automatically measured.

Table 8. Taylor-Hobson Electro-Optical Autocolimators

Autocolimators	Accuracy (“)	Measurement Range	Automatic Registration Interval (“)
TA 60	6	60x60 min	60
VA 900	1	± 900 sec	0.5
TA 51	0.5	10 min	0.2
DO 20	0.1	± 20 sec	0.01
DA 400	0.2	± 400 sec	0.1

Table 9. D-600 Autocolimator (David Optronics)

Technical Specification	
Accuracy	± ½ ’’
Sensitivity	1/10 ’’
Measurement range	120 ’’
Focal length	20 ’’

Conclusions

The industrial field is, by definition, a 3D positioning and measuring systems user, the car and ship industries, aircraft and spacecraft industries, physics laboratories, chemical and atomic energy industry being the larger consumers of special measurement techniques resources. The current challenging modern tasks for industrial measurements require the engineers to find the best solutions to fulfill the tasks in a shorter time, more accurately and verifing the results on-site. Nowadays, a geodetic engineer has a wide range of precise and highly precise conventional and non-convetional instruments and techniques at his disposal that helps him manage the tasks properly.

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