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Indoor GPS: system functionality and initial performance evaluation

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Abstract: *Indoor GPS* (iGPS) is a newly developed laser based measuring system for large scale metrology. The relative portability, reconfigurability and ease of installation make the iGPS suitable for many industries manufacturing large scale products. The system performance depends on both the components characteristics and their physical configuration. Hence, an important consideration for the iGPS is to characterise its real capabilities, pointing out how they can be influenced by the system's configuration and setup.

In this paper, the system is introduced and the technical aspects are briefly described. Then, an initial test is performed to establish its repeatability, reproducibility and accuracy.

Keywords: dimensional metrology; large-scale metrology; distance measurements; Indoor GPS; iGPS; metrological performance.

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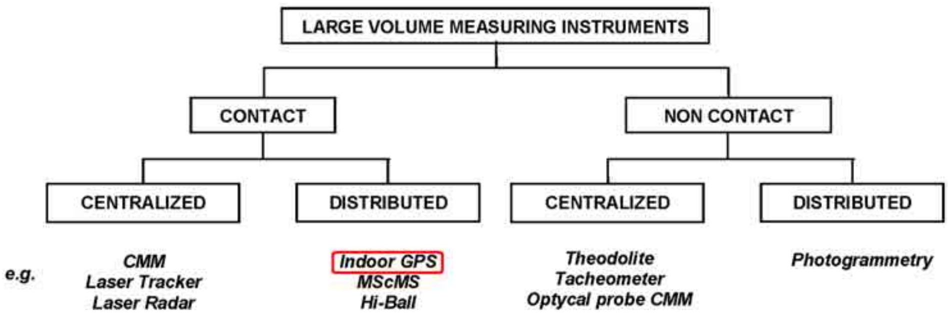
1 Introduction

The field of large-scale metrology can be defined as the metrology of large machines and structures, that is, "the metrology of objects in which the linear dimensions range from tens to hundreds of meters" (Puttock, 1978). There is an increasing trend for accurate measurement of length, in particular, the 3D coordinate metrology at length scales of 5 m to 100 m has become a routine requirement in industries such as aircraft and ship construction.

Recent advances across a broad range of technologies have led to some innovative measurement solutions such as laser interferometry, absolute distance metrology, and very high density Charge-Coupled Device (CCD) cameras that were previously difficult or impossible to implement (Estler et al., 2002). Figure 1 shows a classification scheme of large volume measuring instruments for various applications. Here, the measurement systems are classified into *centralised* and *distributed* systems. A centralised system is essentially a stand-alone unit which can work independently to provide the measurement of a spatial coordinate on the object surface, e.g., a laser tracker. In some cases, a number of centralised systems can be simultaneously used with the aim of improving the measurement accuracy. On the other hand, a distributed system needs a series of measuring stations that work cooperatively to collect information for determining the coordinates of a point on the object's geometry. In general, the individual stations associated with a distributed system cannot measure coordinates. For instance with each iGPS transmitter only the angular information of a sensor can be measured

(Metris, 2007), which will be used in relation to the angular data from the other transmitters in the iGPS network to calculate coordinates of a point. Distributed measurement systems, due to their topology and the light weight of each of their units, are portable and can be easily transferred to the measurand.

Figure 1 Classification of large volume measuring instruments (see online version for colours)

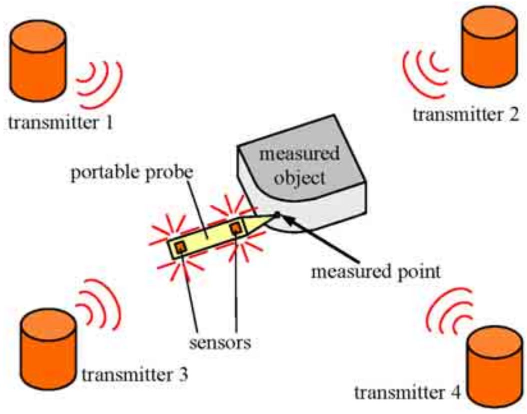


The other distributed contact measuring instruments shown in Figure 1 are Mobile Spatial coordinate Measuring System (MScMS) and Hi-Ball. MScMS is a new system, composed of a number of distributed wireless devices, utilising ultrasound technology. A mobile probe, which implements a time-of-flight approach, is able to calculate the distances from these devices and to locate itself by trilateration (Franceschini et al., 2007, 2008). Hi-Ball is a system composed of a number of infrared LEDs, arranged around the measuring area, which can be viewed by an optical sensor probe measuring the object surface. The probe is able to locate itself by measuring the angles from the LEDs and performing a triangulation (Welch et al., 2001).

The iGPS is a modular, large volume tracking system enabling factory-wide localisation of multiple objects with metrological accuracy, applicable in manufacturing and assembly. The system components of the iGPS are a number of transmitters, a control centre, sensors and receivers (Kang and Tesar, 2004). The distributed nature of the system eases handling and provides scalability for coverage of the measuring area. For this reason, the iGPS is more suitable for particular large scale types of measurement. For instance, some large-sized objects cannot be transferred to the measurement systems due to their dimensions or other logistical constraints. Therefore, it is required that the measurement system to deployed in situ for the measurement of such components. For the system operator, iGPS can potentially be considered as a faster and easier solution compared to conventional systems such as CMM, theodolite or Laser Tracker.

Transmitters use laser and infrared light to determine the relative angles from the transmitters to the sensors. The sensors, used for measuring the workpiece, have photodiodes inside their modules that can sense the transmitted laser and infrared light signals (see Figure 2). Based on the known location information of the transmitters, which is normally obtained in an initial *setup* phase, the position of the sensors can be calculated. The signal is transferred through a wireless network connection providing mobility to the operator. Similar to a satellite-based GPS, a one-way signal path is created from the transmitters to each sensor. This approach allows an unlimited number of sensors to continuously and independently calculate positional data.

Figure 2 Representation scheme of an iGPS measurement and its portable probe (see online version for colours)



Measurements are taken by touching the required points on the object's surface with a probe that is equipped with double sensors. Points are defined on a Cartesian coordinate system; the coordinates are then processed by specific algorithms, in order to determine geometric features. Such measured features are then used to extract the desired dimensional information such as feature positions and angles between two features.

In an initial testing, in which the measurement is achieved by averaging a number of samples obtained in 2 seconds scanning, the uncertainty related to the position of the single points was reported as being lower than 0.6 mm (ARC Second, 2004). To carry out an initial test of the system's metrological performance and to identify the most important factors affecting it, several explorative laboratory tests were performed. For the experimental work described in this paper, an iGPS system equipped with four transmitters was used. The description of the specific testing conditions and the results of these tests are presented at the end of the paper.

There are several standards for conventional dimensional metrology systems (ISO 10360, 2001; ANSI/ASME, 2006). However, currently there are no international standards or best practice guides for distributed metrology systems such as the iGPS.

The remainder of this paper is organised into three sections. Section 2 provides a brief introduction to the iGPS technological features and *modus operandi*. Section 3 analyses in detail the most important factors affecting measurements. Section 4 reports on the system performance as evaluated by a number of initial tests. The results of the experiments are then given and described in more detail. Finally, the conclusions and future direction of this research are given.

2 iGPS technology and operating features

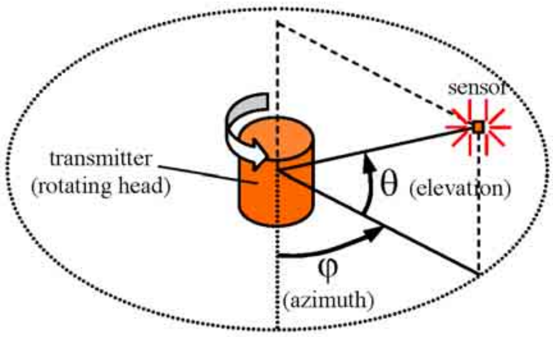
Typically, the system components of the iGPS are: three or more transmitters, a control centre and a number of wireless sensors. Transmitters operate as reference points (with known position) continually generating three signals: two infrared laser fanned beams rotating in the head of the transmitter and an infrared LED strobe (Arc Second, 2004). Sensors are passive elements which can be placed on the surface of the object to be measured to receive the transmitters' signals.

iGPS is a *scalable* (or modular) system since the number of transmitters and sensors can be increased depending on the requirements of the measurement environment. Such characteristics, however, do not compromise the network's communication or slow down the setup activities and measurements (ARC Second, 2004).

Before starting measurements, the location of transmitters has to be determined. This phase should be fast and automated to prevent any conflict with the system adaptability to different working environments.

During measurements, the position (x, y, z) of each sensor is calculated. Each transmitter presents two measurement values to each sensor: the horisontal (azimuth, φ) and the vertical (elevation, θ) angles (see Figure 3). Sensors can calculate their position whenever they are located in the line of sight of two or more transmitters. The principle used is triangulation (Niculescu and Nath, 2003).

Figure 3 Azimuth (φ) and elevation (θ) angles from a transmitter to a sensor (see online version for colours)



This is a description of how sensors measure angles from the transmitters. Each transmitter generates two rotating infrared laser beams and an infrared LED strobe. These optical signals are converted into timing pulses through the use of a photo detector. The rotation speed of the spinning head in each transmitter is deliberately set to a different value in order to differentiate the transmitters. Additionally, the transmitter speed is continuously tracked and used to convert the timing intervals into angles. As shown in Figure 4, the two fanned beams, radiated from the rotating head of each transmitter, are tilted with respect to the rotation axis (the vertical axis of the transmitter), nominally at –30° and +30°. This angular method is used to calculate the elevation angle by:

- knowing the angles of the fanned beams (ϕ with respect to vertical as shown in Figure 4)
- determining the difference in timing between the arrival of laser 1 and laser 2 to the sensor
- knowing the speed of rotation of the transmitter, which is continually tracked.

The measurement of azimuth angle (φ) requires a horisontal index, which is created by firing an omnidirectional LED strobe at a fixed direction in the rotation of the transmitter's head. Referencing the timing diagram at the bottom of Figure 4, the azimuth angle is determined by:

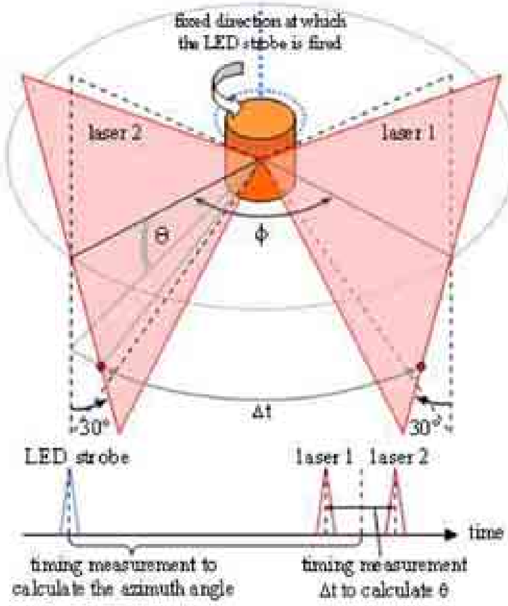
- knowing the angles of the beams
- making a timing measurement between the strobe and the laser pulses
- knowing the speed of rotation of the transmitter.

In addition to the azimuth and elevation angles from the transmitter to the sensor, more information is needed to perform a sensor position calculation, which is the relative position and orientation of the transmitters.

The transmitters make a *constellation* of reference points that are located through a system setup process. The relative position and orientation of the transmitters are determined using an advanced algorithm, which is known as bundle adjustment (Chen et al., 2003). In this algorithm the angular information of each transmitter with respect to the other transmitters in the network is calculated via measuring a few points between the transmitters. Then the absolute coordinates of the transmitters are calculated by defining a scale, which is the absolute distance between two known points such as the length of a reference bar (the inter-sensors distance is about 202 mm). The scaling factor can be improved by using larger reference lengths later on in the process. iGPS provides a relatively rapid and semi-automated localisation procedure, requiring relatively few manual measurements (Akcan et al., 2006).

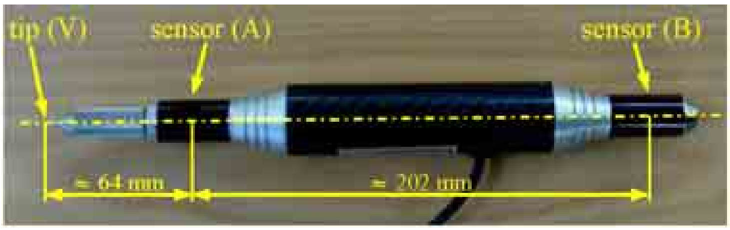
Once the setup has been completed, the measurements can be performed using a portable handheld measurement probe, known as a Vector bar (V-bar). This probe is equipped with two sensors (Figures 2 and 5) that should be carried by an operator in order to measure the coordinates of the points touched by the probe tip. To be stable and insensitive to thermal expansion, the portable probe is mainly made of composite material.

Figure 4 Representation scheme of the transmitter's fanned beams (see online version for colours)



Source: Metris (2007)

Figure 5 iGPS portable hand-held measurement probe (see online version for colours)



In summary, the measurement procedure is made up of three main steps:

- The spatial location of each sensor is achieved using a triangulation technique. To uniquely determine the relative location of a point in a 3D space, at least two transmitters are needed (Chen et al., 2003; Akcan et al., 2006). All information needed for the location calculation is sent to a computer for processing.
- As shown in Figure 5, the probe tip (V) lies on the line that connects sensors A and B. Therefore, the location of the point touched by the probe tip can be calculated using the coordinates of points A ≡ (x_A, y_A, z_A) and B ≡ (x_B, y_B, z_B) and the geometrical features of the probe (distances $d_{V–A}$ and $d_{A–B}$).
- Similar to CMMs and Laser Trackers, it is possible to determine or create new shapes and geometries of objects using the relevant software. The geometries include cylinders, planes, circumferences, cones, spheres, and any other standard features. This is achieved based on a set of measured points from the part surface. Such points are collected using the portable probe, and processed using the classical optimisation algorithms (Overmars, 1997).

3 Factors affecting measurement

During the tests performed many factors affecting the quality of measurement were identified and analysed. The most significant factors include:

- number of transmitters
- movement of the sensors during measurement
- location of transmitters (setup)
- environmental factors.

These will be individually analysed in the following paragraphs.

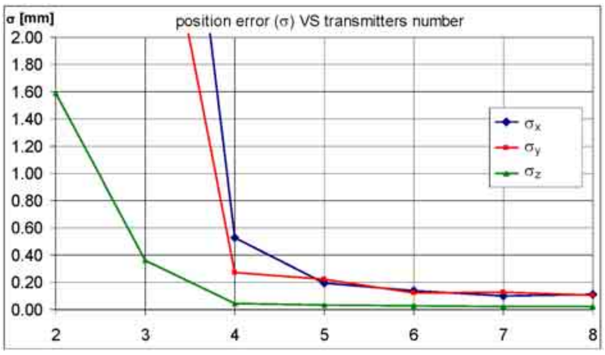
Number of transmitters. The number of transmitters is strictly related to their communication range and the measurement volume. Since the communication range of each transmitter is around 25 m, the transmitters' density within the measuring volume does not have to be high. For this experiment four transmitters are used, which cover a relatively large working area (about 300 m^3, considering a plant layout).

The influence of the number of transmitters 'seen' by a sensor on its position error is analysed, using exploratory tests combined with simulation. These tests are useful to obtain preliminary indications. In the future, this effect will be studied in more detail, by means of a structured Design of Experiments (DoE). Actually, 30 points – with a priori known positions – were measured (repeating the measurement 150 times per point) while the number of transmitters for the desired points was deliberately changed from 2 to 4 transmitters. Coordinates position errors (residuals) were determined considering the difference between the 'true' coordinates' position, and the coordinates' position of the points, as calculated by triangulation. Then, the coordinates position errors related to all the 30 points were put together, showing a normally distributed pattern.

In the simulation experiment the effect of the number of transmitters is studied by varying the transmitters' number from two to eight. The result showed that when only two transmitters are used, the uncertainty in the measured points is very high. This uncertainty decreases to a great extent (for instance by a factor of four for *Z*-axis), when the third transmitter is used for measuring the same point. When the fourth transmitter is added the improvement in the accuracy reduces, although it is still significant. By adding the 50 or more transmitters, the improvement is shown to be small and negligible. This behaviour is shown in Figure 6, in which the standard deviations (σ_x, σ_y, σ_z) related to the coordinates positional errors are plotted based on the number of transmitters (from 2 to 8).

This means that during the measurement by four transmitters, if the path between a transmitter and a desired sensor is accidentally blocked, and the sensor can only see three of the transmitters, the measurement quality will drop. This can happen when the line of sight between a sensor and one or more transmitters is obstructed by the operator or the workpiece body. Consequently, the transmitters should be arranged around the measuring area in suitable positions to gain maximum coverage (e.g. near the ceiling, to reduce the risk of obstructions). Regarding the future, trials will be carried out in order to study the best way of positioning the transmitters, depending on the measured object and the measuring area.

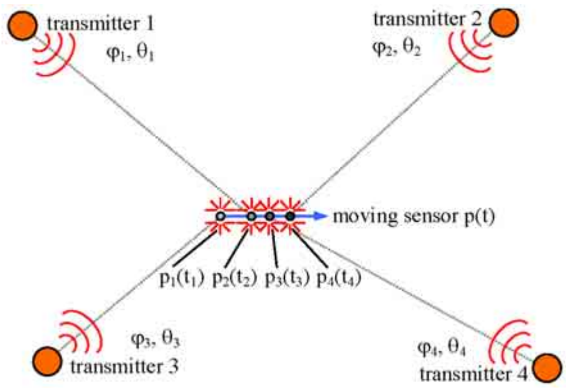
Figure 6 Influence of the transmitters' number on the position error (see online version for colours)



Sensors' movement during measurement. iGPS can be used to perform either static or dynamic measurements. In particular, during aircraft assembly operations, it can be useful to perform dynamic measurements. However, the system performs best in static measurement. This is due to the positioning method used. The position of each sensor can be calculated by triangulation using the two angles (φ and θ) from each transmitter.

The transmitters' sampling rate depends on the angular speed of their rotating heads. As explained above, the spinning speed is unique for each transmitter to be differentiated. Assuming that the rotation speed is around 3000 rev/min, each transmitter will be able to communicate with sensors about 3000/60 = 50 times per second. Even though the transmitters sampling rate differences are small, it is impossible to receive concurrent data from all transmitters. The inevitable difference in data streaming is in the range of a few hundredths of a second. This effect does not create any problem for static measurements; however, it will affect the dynamic measurement. Figure 7 shows such a scenario, in which sensors are moving in time (t). For any sensor, the position at time period ($t_4 - t_1$) is calculated by triangulating data collected in very close, but for different instants (Moore et al., 2004). It can be assumed for the purpose of discussion that the data collection occurs by sensing information received firstly by transmitter-1, secondly by transmitter-2, thirdly by transmitter-3 and finally by transmitter-4. At time t_1, a moving sensor's position is read when it is located in position p_1, at time t_2, when it is in position p_2 and so on. Even if the difference consists of a few tens of a second, it produces a location error. Therefore, the faster the sensor moves, the larger the error becomes.

Figure 7 If a sensor moves, data from transmitters are inevitably received in different instants (see online version for colours)



In this paper the experiments for the system metrological performance were performed in static conditions, in order to avoid errors caused by the movements of the sensors.

Transmitters' location setup. iGPS provides the opportunity of arranging transmitters in different ways, depending on the desired measuring area and the workpiece geometry. Every time the position of the transmitters is changed, a setup should be performed. Obviously, this step needs to be completed before performing measurements and its accuracy has strong effects on the accuracy of the measurements results (Patwari et al., 2005). For this, iGPS software provides a semi-automated setup procedure that requires a few initial measurements that can be done manually or automatically for example by a robot. During the setup procedure, the system scale is determined by placing two sensors at a known distance within the measuring area, in at least 8 different positions and orientations. To that purpose, a reference bar of an *a-priori* known length can be used.

When reference bars with different lengths, but similar uncertainties are used, longer reference bars normally generate better results in the above mentioned setup process

(Zakrzewski, 2003). However, the use of too long a reference bar is not practical and may produce other errors, which may inversely influence the position accuracy of the transmitters (e.g., flexing or thermal expansion of the bar).

Environmental factors. iGPS, like most measuring instruments, is sensitive to several environmental factors, in particular temperature, light and vibrations. It is well known that laser signals are sensitive to changes in air conditions, especially in terms of temperature, which can exhibit both temporal and spatial variations within large working volumes. Light typically has a 'go, no-go' effect; that is to say, if sensors are exposed to light, the laser beams can be 'obscured' and consequently measurements cannot be performed at all. To avoid this problem, for the experiments in this paper, the lights in the laboratory are kept at minimum, especially in the area near to the sensors and transmitters. Vibrations are another source of error that can produce little movements of the measured workpiece or of the measuring equipment. This effect can be large, and it should be considered when analysing the results.

To filter bad points from the measurement due to external factors such as light, temperature or vibrations, the iGPS software provides several diagnostic controls. The reliability of measurements increases significantly by using auxiliary sensors, which are placed in fixed positions at *a priori* known distances. With these sensors, the system can correct the initial setup in real-time, by compensating the changes in the environmental conditions of the measuring field, and determining whether the system is conforming to the desired tolerance (Kang and Tesar, 2004).

4 Experimental work for iGPS' preliminary performance analysis

Explorative tests were performed to evaluate the iGPS metrological performance in the following conditions:

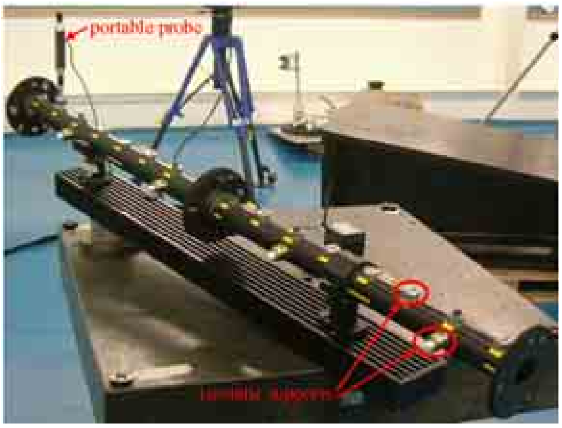
- use of four transmitters
- measuring area of about 60 m^2 (6×10 m)
- the system was setup using the mobile probe as a reference bar.

The iGPS performance has been initially estimated through three tests:

- *Repeatability test*. Repeatability is defined as. "closeness of the agreement between the results of successive measurements of the same measurand, carried out under the same conditions of measurement" (GUM, 2004; VIM, 2004). A point within the working volume was measured repeatedly, about 150 times, to benefit from the high sampling rate of the instrument. During these measurements, the probe was left in a fixed position. The test was repeated for 30 different points in different areas of the working volume. For each point coordinate, the residuals between the single measurements and their average value were calculated. Then, for each Cartesian coordinate (x, y, z) all the residuals from all the 30 points were put together.
  The residuals show a normally distributed pattern. The repeatability indicator is given by the standard deviations (σ_x, σ_y, σ_z) related to each Cartesian coordinate residual as shown in Table 1.

- *Reproducibility test*. Reproducibility is defined as: “closeness of the agreement between the results of successive measurements of the same measurand carried out under changed conditions of measurement” (GUM, 2004; VIM, 2004). This test was similar to the previous one, with the only difference being that the probe was replaced before each single point measurement. Hence, each point was approached from a different direction, using different orientations of the probe. Reproducibility gives a preliminary indication of the system’s accuracy, whereas repeatability gives a preliminary indication of the target system’s accuracy. This is based on compensating for the most important causes of systematic errors. Table 1 shows the standard deviations related to each Cartesian co-ordinate. As expected, the standard deviations are higher than the repeatability tests.
- *Accuracy test*. Accuracy of measurement is the “closeness of the agreement between the result of a measurement and the value of the measurand” (GUM, 2004; VIM, 2004). This test was performed using a calibrated reference artefact with known dimensions (Cross et al., 1998). The reference artefact consisted of two one meter bars assembled to create a two meter long reference bar. The reference bar was made of composite materials with different isostatic supports on which the mobile probe can be placed during measurement (see Figure 8). The nominal dimensions of the artefact (points’ nominal position and nominal distances between points) were calibrated using a laser interferometer and a CMM, which are at least two orders of magnitude more accurate than the iGPS. These distance measurements were repeated by placing the artefact in 30 different positions and orientations within the measuring area. To reproduce a common measuring strategy, each point position was calculated by averaging 150 single position measurements. The standard deviation related to the distance residuals (σ_{DIST} in Table 1), that is to say, the differences between nominal distances and distance measured with iGPS, was also calculated. Moreover, for each point coordinate, the residuals between the measured and the nominal position Cartesian coordinates were calculated. Then, the standard deviations related to the coordinates (σ_x, σ_y, σ_z) were calculated. The residuals have been verified to be normally distributed. Based on these results, the iGPS uncertainty (referring to a $\pm 2\sigma$ interval) can be roughly estimated to be less than 1 mm.

Figure 8 National physics laboratory artefact (Cross et al., 1998), used for iGPS experiments (see online version for colours)



The results of these preliminary tests are summarised in Table 1. Considering the different testing conditions, these results are reasonably consistent with the results of some tests carried out by iGPS constructors (ARC Second, 2004). In general, the σ_z value is lower than σ_x and σ_y, for the repeatability, reproducibility and accuracy tests. This is due to the geometric configuration of the constellation devices as transmitters were mounted on tripods, which were set more or less at the same height. Therefore, they can be considered as approximately placed on a horizontal plane (*XY*) perpendicular to the vertical (*Z*) axis (Patwari et al., 2005).

Table 1 Results of the iGPS preliminary tests, performed in the specific testing conditions described in Section 4

Test	*Repeatability*			*Reproducibility*			*Accuracy*			
Standard deviation (mm)	σ_x	σ_y	σ_z	σ_x	σ_y	σ_z	σ_x	σ_y	σ_z	σ_{DIST}
	0.057	0.056	0.036	0.157	0.162	0.081	0.165	0.172	0.096	0.211

5 Conclusions

This paper firstly makes a brief description of the architecture and operating principles of the iGPS, which is a recent laser based, large volume measurement system. The system has several modules that are lightweight, portable and adaptable to different working environments and can be rapidly installed and used. The system contains a number of transmitters that can be positioned and reconfigured in the desired layout. However, prior to performing any measurements, the new position and topology of the system should be known. This is done by performing a setup known as bundle adjustment, in which a number of points are digitised and used to calculate the relative angular position between the transmitters. This information is then integrated with a scale factor that is obtained by digitising a known distance such as a length reference bar. The main issues and factors affecting the results of iGPS measurement are reviewed. The outline system performance in terms of repeatability, reproducibility and accuracy was studied by initial experiments. According to the results that are obtained by averaging 150 readings for each point's measurement, the accuracy results are within 0.2 mm. This is achieved over a two meter length, however for real large scale metrology similar experiments should be repeated for larger lengths, for instance 10 to 20 m.

The result of measurement improves by increasing the number of transmitters although such improvement becomes negligible from adding the fifth transmitter onwards. Further accuracy improvement can be achieved by controlling the environmental affects like temperature gradients, vibrations or direct light. Also, the quality of the initial system setup is a fundamental aspect.

It is also shown that with the existing technology, the iGPS may not be completely suitable for dynamic measurements. However, by predicting the direction of movement and by using error compensation methods, this limitation may be resolved and the iGPS could potentially be utilised for slow dynamic measurements.

Future work will deal with the detailed analysis of the effects of the reference bar length used for the initial setup on measurement performance. This should lead to finding an optimal length of reference bar for bundle adjustment to minimise the error in the transmitters' location. Also more detailed experiments will be carried out in order to accurately characterise the system, depending on different types of setup strategies, and external conditions.

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