Metrological performance of indoor-GPS in a simulated measurement assisted assembly process

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Abstract. This paper presents an experimental evaluation of the performance of an indoor-GPS (iGPS) system in a measurement assisted assembly process. A device was designed to simulate an assembly process with two rotational and one translational degree of freedom. The assembly of the device was performed with the assistance of iGPS and the result evaluated with a coordinate measuring machine. The results confirm the applicability of iGPS in assembly processes with production tolerances down to 1 mm.

1. Introduction
The assembly of large structures is a key challenge in the production of equipment such as wind- and water turbines, aircrafts, trains and ships. In modern shipyards, the construction of medium to large-sized vessels is performed block-wise. In one of the final assembly processes, called erection, previously manufactured blocks, often weighting hundreds of tons, are put into position by special vehicles, cranes and hydraulic jacks and welded to form the hull. Theodolites, laser levels, plumb-bobs and measuring tapes are used as measurement systems. The assembly is performed in an iterative fashion, intercalating positioning and measuring processes.

A paradigm shift in large-scale assembly is expected through the development of measurement assisted assembly (MAA). MAA consists in using advanced 3D measurement systems to enable direct, fast and sometimes even automatic part-to-part assembly without iteration. Quality and productivity enhancement and thus cost reduction is expected by implementing MAA processes [1]. The present work is part of a project that aims to evaluate the feasibility of MAA in ship construction. One of the measurement systems available for MAA is the Indoor GPS (iGPS).

Mosqueira et al. evaluated this system for the robotic alignment of fuselages, using a laser radar as reference measurement equipment [2]. Muelener et al. [3] and Schmitt et al. [4] assessed the overall performance of iGPS in 3D position measurement. They also identified the main sources of uncertainty of measurement processes using this system. However, to the best of our knowledge there are no results reported on the evaluation of the metrological performance of iGPS in assembly processes using an accurate calibrated reference measurement system.

The experiment we performed consists in assembling a special device with assistance of iGPS and checking the result with a coordinate measuring machine (CMM).
2. Materials and Methods

2.1. Indoor-GPS (iGPS)

The optical measurement system iGPS, also known as rotary-laser automatic theodolites (R-LAT) [3], operates according to the triangulation principle. On triangulation-based systems the position of a target point is determined based on azimuth and elevation angle measurements from at least two stationary measurement systems with known position and orientation.

The system consists of three basic components: transmitters, which act as measurement stations, detectors (or receivers) and position calculation engines (PCE). The transmitters are equipped with a rotary head that sweeps two fan-shaped laser beams and a LED ring that emits a strobe signal at the beginning of each second rotation. Photosensitive sensors in the receivers detect the light pulses and convert them to an electrical signal. This signal is amplified, digitized and processed in the PCE units that send receiver position and orientation data to a workstation. The rotation frequency of the rotors lies between 40 and 50 Hz. Each rotor operates with a slightly different frequency, enabling signal isolation [5].

The angle measurement principle is depicted in figure 1. Azimuth is calculated from the strobe time $t_1$ and the average of $t_2$ and $t_3$ and elevation is derived from the difference between $t_2$ and $t_3$ [6].

![Figure 1. Azimuth and elevation angle determination of a transmitter-receiver vector.](image)

The detectors are integrated in measurement tools. The measurement tools available in our system are the scale-bar, which is used in the system setup, the mini vector bars, used as static reference points (monuments) as well as in dynamic tracking tasks and the handheld vector bar probe (HHVB) which is the device used to capture single points. Each one of these tools is equipped with two receivers, enabling the determination of position and orientation in five degrees of freedom.

A six degrees of freedom tracking frame is created by fastening at least two mini vector bars to the object to be tracked. We used this kind of frame to assess the alignment and positioning movements during the assembly process.

The typical static length measurement uncertainty of the iGPS under good environmental conditions is 0.5 mm [5]. Our iGPS system is a Nikon Metrology (formerly Metris) model iSpace 6i, manufactured in 2008.
Dephental et al. state that the highest accuracy of an iGPS system with four transmitters can be obtained if the transmitters are placed on the corners of a rectangle and if the measurements are taken next to the centre of this rectangle [5]. The configuration we used in our experiments is depicted in figure 2. The transmitters were positioned at 1.8 m height in relation to the floor. We performed the assembly on a workbench of 1 m height located approximately at the centre of the rectangle formed by the four transmitters (T1 to T4).

![Figure 2. Transmitter configuration.](image)

**2.2. Experimental device**

We designed a simple experimental device to simulate an assembly process with two degrees of freedom of rotation and one degree of freedom of translation. This device consists of two triangular parts that can be aligned and positioned with aid of iGPS and then rigidly fastened to a base plate. The size of the device was chosen to fit the measurement volume of the available CMM.

The two triangular parts are made of aluminium profiles and are fastened to a 1000 mm x 1000 mm plate by three sets of screw/nut mechanisms (figure 3). This configuration allows three degrees of freedom: translation in ‘z’ and rotation around ‘x’ and around ‘y’.

![Figure 3. Screw/bolt mechanism.](image)
Two integrated detector units (IDU), including a mini vector bar and a PCE each, and three nests are placed on top of each part. A nest is a part with an inner cone (magnification in figure 4). The location of a nest can be measured with a probe (e.g. HHVB or CMM probe), featuring a spherical tip of appropriate size, by centering the probe tip in the cone. The triangular parts where designated ‘A’ and ‘B’. The nests of each part are numbered 1 to 3 (figure 4). The coordinate system was defined as follows: xy-plane defined by A1, A2 and A3; x-axis pointing from A1 to A2 and origin at A1.

![Experimental device](image)

**Figure 4.** Experimental device.

2.3. Procedure

Part A was kept stationary and fastened to the base plate. Part B was moved with the screw/nut mechanisms until its nests where brought to the xy plane, i.e., until z-coordinates of all nest where close to zero (we admitted a tolerance of ±0.3 mm). After the positioning process, we also fastened part B to the base plate and evaluated the result by measuring the position of all nests 10 times with the HHVB probe.

After the assembly and measuring processes, we took the device to a metrology laboratory where the positions of the nests where measured using a CMM (figure 5). A second measurement cycle with iGPS was performed after the return of the device to our laboratory to detect accidental misalignments during transport.

![CMM measurement](image)

**Figure 5.** CMM measurement.
3. Results

The results of the CMM measurement are listed in table 1 and the results of the iGPS measurements (average of 10 measurements) in table 2. The repeatability (two standard deviations) of the iGPS measurements is presented in table 3. The maximum expanded measurement uncertainty for the CMM measurements was estimated to be $U = 0.004$ mm, with $95.45\%$ coverage probability.

| x [mm] | y [mm] | z [mm] |
|---|---|---|
| A1 | 0.0 | 0.0 | 0.0 |
| A2 | 489.8 | 0.0 | 0.0 |
| A3 | 624.8 | 664.2 | 0.0 |
| B1 | 433.6 | 818.6 | 0.0 |
| B2 | -54.7 | 818.8 | 0.4 |
| B3 | -189.1 | 153.9 | 0.5 |

Table 2. Results of iGPS measurements.

| Results | Difference to CMM results (iGPS-CMM) |
|---|---|
| x [mm] | y [mm] | z [mm] | x [mm] | y [mm] | z [mm] |
| A1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| A2 | 489.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| A3 | 624.7 | 664.1 | 0.0 | -0.1 | -0.1 | 0.0 |
| B1 | 433.6 | 818.6 | 0.2 | 0.0 | 0.0 | 0.2 |
| B2 | -54.9 | 818.8 | 0.1 | -0.2 | 0.0 | -0.3 |
| B3 | -189.1 | 153.9 | 0.2 | -0.1 | 0.0 | -0.3 |

| Results | Difference to CMM results (iGPS-CMM) |
|---|---|
| x [mm] | y [mm] | z [mm] | x [mm] | y [mm] | z [mm] |
| A1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| A2 | 489.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| A3 | 624.5 | 664.2 | 0.0 | -0.3 | 0.0 | 0.0 |
| B1 | 433.3 | 818.5 | 0.1 | -0.3 | -0.1 | 0.1 |
| B2 | -55.0 | 818.7 | 0.3 | -0.3 | -0.1 | 0.1 |
| B3 | -189.1 | 153.8 | 0.4 | 0.0 | -0.1 | -0.1 |

| Results | Difference to CMM results (iGPS-CMM) |
|---|---|
| x [mm] | y [mm] | z [mm] |
| A1 | 0.01 | 0.03 | 0.04 |
| A2 | 0.03 | 0.05 | 0.05 |
| A3 | 0.16 | 0.13 | 0.04 |
| B1 | 0.09 | 0.04 | 0.05 |
| B2 | 0.07 | 0.07 | 0.05 |
| B3 | 0.06 | 0.06 | 0.06 |

Table 3. Repeatability of iGPS measurements.
4. Discussion
The CMM measurement results revealed a maximum residual difference of 0.5 mm between the z-coordinates of the nests of part A and part B. Although the device is much smaller than an industrial structure, we consider this result representative for the general performance of the system in an assembly process. Due to the measurement principle of iGPS, size-proportional error sources are expected to be less significant than effects such as triangulation condition and transmitter visibility.

The repeatability of the iGPS results ranges from 0.01 mm to 0.16 mm. This variation is probably related to the measurement condition (e.g. triangulation condition and transmitter visibility) at each specific point.

Although the length measurement performance evaluation was not within the scope of this experiment, it can be verified in table 3 that all the measured errors were smaller than 0.5mm, confirming the manufacturer’s specification for length measurement errors.

5. Conclusions
In this paper we reported the results of an experiment to evaluate the performance of an iGPS system in an assembly processes that includes alignment and positioning requirements. The quality of the assembly result was evaluated with a coordinate measuring machine.

The results show that it is possible to introduce iGPS as support to assembly processes. However, it is important to note that, due to metrological limitations of iGPS, the production tolerance should be in the order of one millimeter or larger.

A next project task is set to assess the system robustness in conditions typically found in a shipyard. The feasibility of outdoor measurements and the sensitivity to optical and electromagnetic interferences will be evaluated. Simultaneously, we’re aiming to integrate iGPS in a self-developed robotic platform for automatic assembly purposes.

6. References
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