IGPS – A NEW SYSTEM FOR STATIC AND KINEMATIC MEASUREMENTS

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Abstract: The research project Usofi is dedicated to the analysis of a new technology for surveying in industrial environments called iGPS (Metris, Belgium). The iGPS system is based on internal time measurements, related to spatial rays that intersect at the position of the sensor. iGPS is also employed for spatiotemporal position determination of moving objects. This new technology provides its own characteristic that depends on each application and can only be considered if knowledge about the systems measurements principle is at hand. First results of the research project are presented.

1. Introduction

The measurement system was developed in the late 90s under the name Constellation 3^{DI} and was renamed to iGPS later on. This name reflects some similarities in a figurative sense to the global GPS. An unlimited number of users can measure the position at same time, independent from each other but using the same infrared signals that are provided by several transmitters, also called satellites. But unlike GPS the iGPS was designed for local applications, the transmitters are installed in place and the position calculation is based on triangulation. Sub-Millimeter accuracy and flexibility enable the system to factory-wide localization of multiple objects, mainly used by industrial manufacturers, for example in aerospace, automotive or shipbuilding industries.

The characteristics of this new technology especially in kinematic mode are researched in the project USOFI[1] (investigation and system optimization of iGPS) at HS Karlsruhe in cooperation with University Karlsruhe (TH). Various effects caused by the geometric configuration of the transmitters and sensors or by reflections influence the system's accuracy and reliability. They have to be investigated, modeled and proven in praxis applications.

2. Concept of iGPS

2.1. Measurement Principles

At least two transmitters define the working volume of measurements. They sweep infrared signals throughout the area that are received by a theoretical unlimited number of sensors in

[1] Project partners: HS Karlsruhe, VMT GmbH and QBit (Bruchsal), funding by Federal Ministry of Education and Research, FH^3 programme

line of sight. Based on the arrival time of the infrared transmitter signals, each sensor determines independently the line from transmitter to sensor. Following the concept of triangulation, multiple lines can be used to determine the sensor position. The sensor itself consists of 32 planar photodiodes that are arranged as a facetted cylinder, enclosed by a protective glass casing. The sensors are connected to a digital-analog-converter and a pre-calculation unit, the PCE (Position Calculation Engine) that measures the arrival time of each signal with an internal clock and manages the communication with the PC.

Figure 1: Transmitters, Sensors and PCE [4]

2.2. Position Determination

Position determination is based on spatial intersection of straight lines, defined by spatial vectors from transmitter to sensor and the transmitter's position as starting point. When measuring with two transmitters, the sensor position is the closest point of intersection between two skew lines, the so-called rays. A connecting line can be established which represents the minimum distance between these two rays and the sensor position is then the mean point of this connecting line. Formulas to calculate the spatial intersection of skew lines can be found in [3]. With more than two transmitters a redundant number of observations can be obtained and different methods of adjustment can be applied, where each observation can be statistically tested and individually weighted.

Transmitter position and orientation are calculated in the setup process that has to be carried out before. In a free setup, multiple points are measured and a bundle adjustment is calculated with a free definable coordinate system.

2.3. Ray Determination

The determination of the ray from transmitter to sensor is based on the infrared signals of each transmitter and the individual geometry of the transmitter. Each transmitter emits two different types of signals, the so-called strobe signal and two fan beams. The frequency of the transmitter lies between 40 and 50 Hz and differs between each transmitter in the configuration.

Photodiodes in the body of the transmitter flash the strobe signal into the whole working volume at the beginning of every second rotation to distinguish precisely from fan beam signals. The fan beams are emitted continuously and rotate with the transmitter head around the vertical axis. The fans, with a beam width of ±30°, are arranged in a way that they are separated in a horizontal plane by an angle of about 90° and they are vertically inclined by an angle about ±30° (Fig. 2). As a result of this assembly, the angle between the two fan beams is greater than 90° above the horizontal plane and less below. Individual values for each angle, the rotation speed and the spin axis biases are quantified by a calibration method and stored in data files for each transmitter.

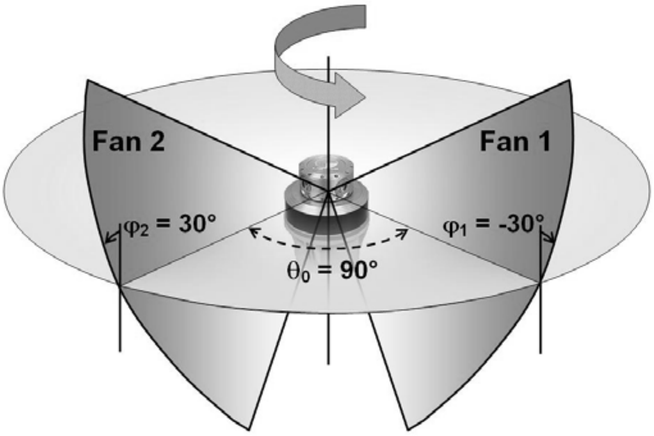

Figure 2: Fan beam geometry of the transmitter

Each sensor in the working volume receives signals from each visible transmitter and the arrival time is measured. The time of the strobe signal (t_{ref}) and the interpolated signal (t_0) define the beginning and end of each transmitter cycle (Fig. 3). t_1 and t_2 are time measurements when the two fan beams pass the sensor.

Based on these time measurements and the fan beams geometry, the angle values from transmitter to sensor are determined. With increasing time interval between the signal peaks of fan beam 1 in respect to fan beam 2 the elevation angle increases (Fig. 2). The Azimuth is determined using the reference time of the strobe and the mean between fan beam 1 and fan beam 2 in respect to one cycle rotation. See [3] or [6] for details.

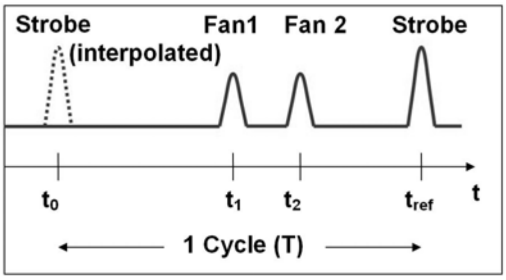

Figure 3: Signal sequence of one transmitter

2.4. Accuracy of Measurements

Due to [2] the measurement uncertainty of a single ray can be separated into multiple effects, for example:

- Transmitter Calibration: the accuracy of the values of the fan beam geometry of the transmitter, e.g. the inclination angle of the fan beams affect the accuracy of the ray directly.
- Transmitter Sources: other transmitter errors have been detected, for example beam symmetry or rotation noise that are not quantified in the calibration process and even can be affected by environmental conditions like vibration or dust.
- Sensor calibration and sensor sources: the most important error comes from the PCE's (Position Calculation Engine) internal clock.

In [2] an error budget is represented with single components. The values are based on two seconds of averaging and on the assumption of good environmental conditions. For a static measurement a measurement uncertainty of $U_{k=2}$=0.25 mm is indicated. A measurement uncertainty for kinematic measurements is not indicated. In [5] further investigations on azimuth angle accuracy are presented, this indicates a level of uncertainty for both azimuth and elevation angle that is at least as low as 1”.

3. Effects and Influences to iGPS

3.1. Multipath

Due to the rotation of the transmitter head, signals could be reflected by any material in the whole working volume. Reflections of the strobe signal can be disregarded. The reflected strobe signal and its origin arrive at the sensor at nearly the same time, therefore the time measurement of the strobe is almost unaffected.

In contrast to the strobe signal, the reflection of the fan beam signals leads to false time measurements and thus to a completely false ray. When the fan beam sweeps through the working volume, the reflection of this signal and also the arrival time of this reflected signal at the sensor occur to a completely different time than the arrival of the original signal. Due to the frequency of occurrence of the reflected signal, it can be assigned to the rotation frequency of the correct transmitter. Therefore all transmitters with more than two associated fan beam signal are flagged as multipathed. Because the amplitude of none of the signals is logged, the reflection and its origin cannot be distinguished from each other in a direct way. So both original and reflected signal pairs and all possible combinations are computed to rays and the false rays can be ignored afterwards as outliers in a statistical testing.

3.2. Effects on Signal Registration

3.2.1. Noise Floor Value

The noise floor defines the signal threshold for noise and signals. Only signals with amplitude higher than the level set by the noise floor value are treated as measurements and processed. Very low noise floor values are very restrictive and only signals with high amplitude will be accepted. This causes a decrease in measurement range since the signals amplitude decreases nonlinear with distance. Very high noise floor values accept signals with small amplitude, thus more measurement range is accomplished. But this can lead to more reflection and noise handling because overall more signals are accepted. Noise signals that occur sporadically cannot be assigned to a transmitter frequency and are filtered out easily. But reflection handling complicates the position determination process because they result in a nonlinear increase of possible rays and therefore to a huge overload in statistical testing. The noise floor value has to be set up carefully for each individual application and is often a trade-off between maximum range and reflection handling.

3.2.2. Sensor Position and Orientation

Since the sensor is not an infinitive small point, corrections have to be applied to the measured ray that is dependent of the sensors orientation with respect to the transmitter. The vertical angle of the sensor axis versus the transmitter is defined as pitch angle, and roll angle describes the angle with respect to the transmitter's rotation axis perpendicular to pitch angle. If pitch angle is zero, the correction of the measured ray is zero for all roll angles (Fig. 4). If the sensor is inclined towards the transmitter (Fig. 4), the measured ray, that is defined by the start and end of the signal is not the desired angle to the center of the sensor and has to be corrected. This correction can be described by equation (1), where *h* is the height of the internal cylinder of photodiodes.

$$correction = \sin(pitch) \cdot \sin(roll) \cdot h \qquad (1)$$

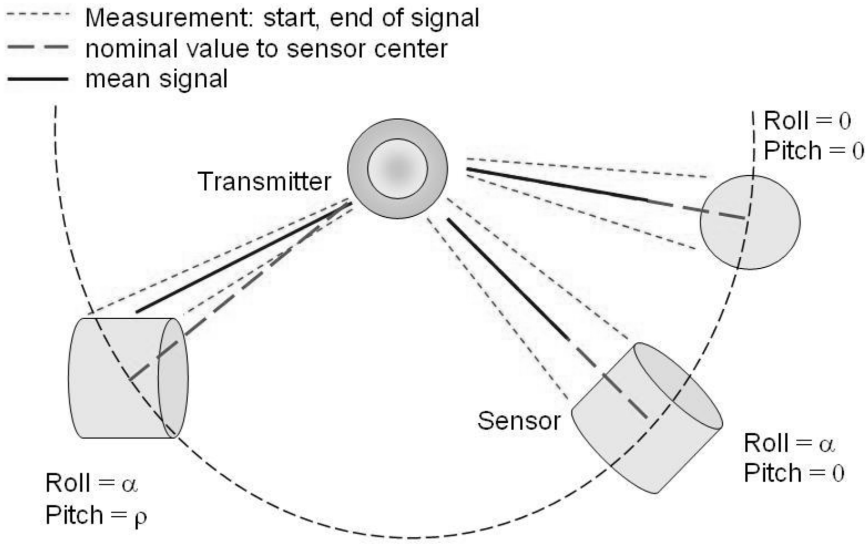

Figure 4: Sensor orientation in respect to the transmitter

The signal shape is mostly characterized by amplitude and signal width, that is defined in this context as time period between the crossing of the noise floor threshold at signal's rise and fall. Signals with a long signal width are more sensible to environmental error sources, for example because noise merges with the original signal and corrupts the falling edge. The strobe signal is almost invariant in width, because it is depending on the duration of the flashing itself and therefore independent from the distance to the transmitter. The signal amplitude decreases with increasing range.

The fan beam signal shape registered in the sensor is affected by the roll angle of the sensor. The simplified signal shape can be divided into three sections: signal rise, full signal and signal fall. Depending on the distance of the cylindrical sensor to the transmitter and its rotation speed, the inclined fan beam takes some time between the first strike on the photodiodes and full coverage that results simplified in a trapezoid signal curve (Fig. 5). The distance has an anti-proportional effect on the time period of all sections, because the fan beam passes a sensor far away faster. The individual length of each signal shape section is depending on the angle between sensor axis and fan beam inclination. If this angle difference is very small, that means the sensor is inclined by nearly -30°, the rising interval is short with very steep rising edge and the full interval long, because the fan beam almost immediately covers the full cylinder width. With increasing angle difference the rising edge is less steep and the time period of the section of rise is longer, while the time period of the full coverage is shorter. Due to the noise floor, the resulting signal width contains only a variable percentage of the length of the time periods of rise and fall.

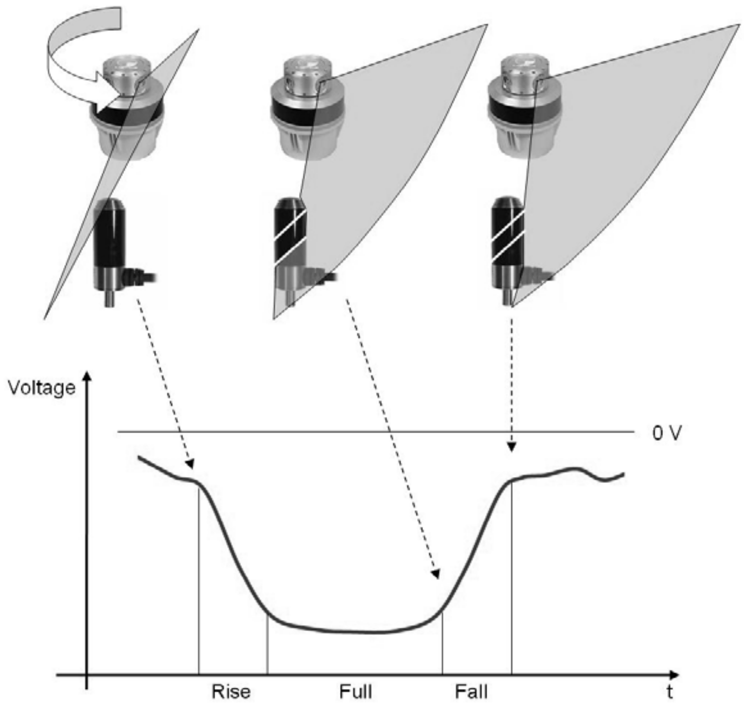

Figure 5: Signal sections on vertical sensor

All corrections concerning effects on raw time measurements or the ray are stored in look-up-tables along with individual corrections obtained by the transmitter calibration, thus measurements with inclined sensors should be accurate if the sensor orientation is known. Therefore only measurement tools or virtual combinations with more than 2 sensors can be used for precise measurements.

3.3. Kinematic Effects

Because the measurement principle of iGPS is based on time measurements, kinematic measurements can cause delay times for the azimuth and elevation determination [1]. In dependence of the object velocity, the sensor moves during a time measurement. A first delay time can arise between the time of data request and the time the strobe signal requires to reach the sensor. This delay time can be until less than 25 ms with a frequency of 40 Hz. The next delay times exist between the strobe signal and the first fan beam that passes the sensor and also between the strobe and the second fan beam. These delay times have a direct influence on azimuth and elevation determination. They can reach a range between about 5 ms and 20 ms.

Another delay time in kinematic measurements can be caused by the lack of synchronization of the different transmitters. This means that for a spatiotemporal position determination, the respective first fan beams of the transmitter arrive at the sensor not at the same time and the sensor has moved away.

4. Exemplary Examination Results

The 3D point accuracy of iGPS measurements is dependent of various effects, foremost the geometric arrangement of the transmitters, the so-called configuration. Since any configuration has its own weak points, an accuracy simulation is recommended. In the following two standard configurations are presented that were examined among other configurations with 2 - 4 transmitters.

As reference to the iGPS tests, a reference field with 17 control points was installed (Fig. 6). These control points were determined with an API lasertracker from 5 different positions. The adjustment of all lasertracker measurements resulted in a mean 3D RMS value of 0.02 mm and a maximum of 0.04 mm. Compared to the expected accuracy of iGPS, these coordinates can be used as reference.

4.1. Accuracy of Exemplary Configurations

Highest accuracy with four transmitters can be accomplished, if those are installed in an approximately rectangular box configuration. The accuracy is mostly depending on the accuracy of the setup, which means the determination of transmitter positions and orientations, and the intersections of the rays at the sensor position.

Best results were achieved when 8 bundle points were used in the setup, four of them in the middle of each side, halfway between the transmitters and four in the center of the test field. In this way a maximum spreading of the bundle points and good intersection angles on central points are combined, resulting in high accuracy of the bundle adjustment. Additional bundle points outside the transmitter rectangle, that improve the setup accuracy additionally, could not be measured due to the room's limitations. In this configuration, best 3D RMS value of about 0.05 mm is achieved in the centre (Fig. 6). The borders show a small decrease in accuracy to approximately 0.1 mm with a maximum RMS of 0.18 mm, mainly caused by the short distance to transmitter 1 that is below the recommended minimum distance of 3 m.

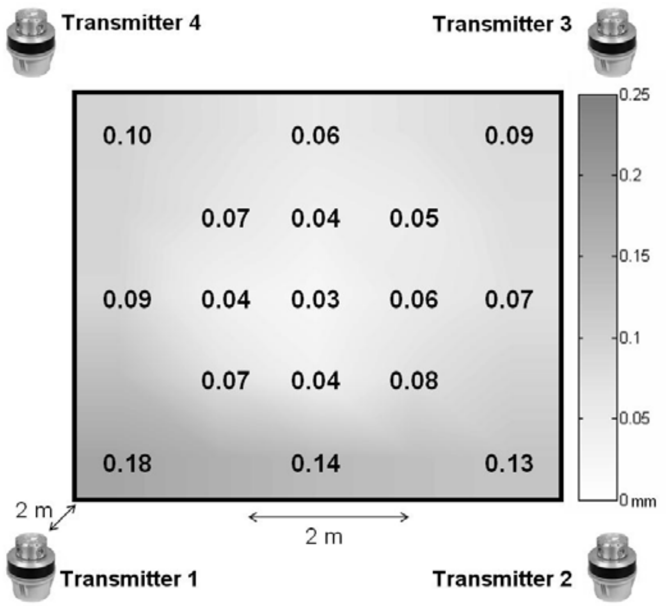

Figure 6: 3D RMS values of iGPS static measurements in box-configuration

Another standard configuration is C-Shape. It is most useful when measuring a large object that divides the working volume in two sections. This configuration places the transmitters in a half circle around the object. Measurements in the test field showed a circular accuracy distribution that can achieve RMS values of 0.08 mm in the area that is approximately the centre of the half circle (Fig. 7). When comparing measurement results that were created in different places of the configuration, the more inhomogeneous accuracy distribution than in the box-configuration must always be kept in mind.

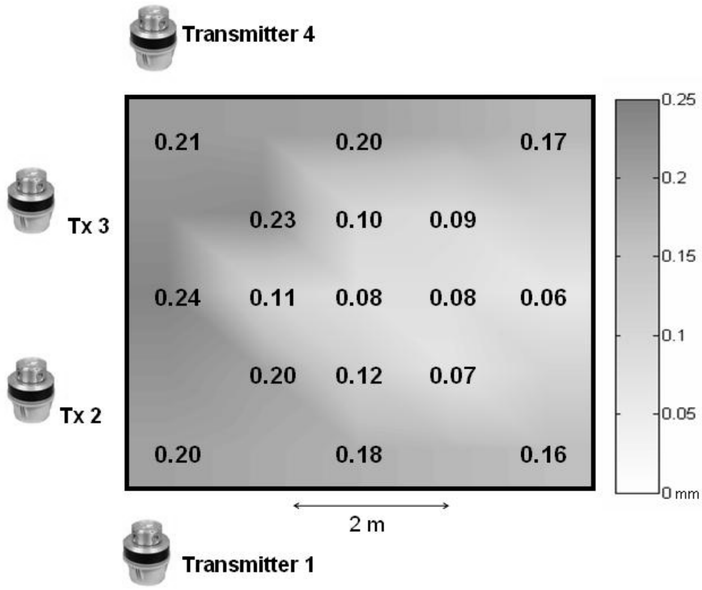

Figure 7: 3D RMS values of c-shape configuration

4.2. Multipath

In general, reflected signals are falsified to a great extend so that they are always ignored as outliers. To estimate the effect of multipath, several high reflective materials were placed in the working volume that reflected either signals from one transmitter multiple times or from multiple transmitters. Reference measurements were taken while these reflective objects were covered. In a configuration with just two transmitters it cannot be decided which rays are the right ones and the measurement is stopped automatically. In configurations with four transmitters, it was depending on the arrangement of the reflective objects, whether the measurement was stopped or whether it was completely unaffected by multipath, because all reflected signals could be ignored as outliers. More than three intensive reflections on the signals of one of the four transmitters could not be handled in the experiments, while single reflections on all four transmitters were uncomplicated. If too many reflections occur in a very reflective environment it is helpful to decrease the noise floor value.

4.3. Signal registration

The accuracy of a single ray is affected by the different influences on signal registration. Calibration parameters for the pitch and roll corrections are always based on a specific noise floor value, so that any change of noise floor without proper correction parameters results in measurement biases. These calibrations estimate the signal amplitude and signal width according to the orientation of the sensor and distance in respect to the transmitter. Environmental effects like dust or sunlight lower the signal amplitude so that the calibration parameters do not match to a small amount.

Measurements with a distance smaller than 2 or 3 meters, depending on the environment, for example overall brightness, create a bloom effect that complicates the detection of signal peak and increases the variance of time measurements. Therefore measurements close to one transmitter display a rotation because signals of this transmitter were registered too early.

Measurements with inclined sensors are directly affected by the quality of the calibration. In every configuration an inclination against one transmitter resulted in a reduced accuracy. Measurements of the reference field with 4 box-configuration and with a sensor that was inclined vertically by approximately 45° displayed an average 3D RMS of 0.25 mm and maximum RMS of 0.6mm. That is a loss of accuracy of about factor 2 with respect to vertical sensors. More examinations are planned to assign possible effects of the sensor orientation to angular biases.

5. Projected Examinations

Further examinations are planned for kinematic measurements of iGPS. In this context the delay times of the measurands will be of interest. In [1] a time-referenced 4D test and calibration system and an adequate modeling, based on quaternion-algebra, to determine delay times are described. Until now there is the problem of time-referencing with iGPS. It must be realized that iGPS is connected with the 4D test and calibration system to get a clear defined reference point for the measurements. Such a point can be the time of measurement request, because this is the time at which a complete measurement is expected. In this way the measurement system must have a trigger entrance or a connection about a serial line in order to connect it with the control system of the 4D test and calibration system. Afterwards the measurands, azimuth and elevation, can be integrated in the modeling and the delay times can be determined. First contacts could be established to Metris to solve the problems and the examinations can be started soon.

Another project that investigates the iGPS capability of the navigation of excavation machines is planned. The rear of the excavator will be equipped with several sensors to determine both position and orientation. Especially the orientation of the machine is important, because based on this the position of the excavation arm is calculated that is equipped with inclinometers on every axis. Although the desired level of accuracy is low, the environmental conditions, vibrations and quite fast moving machines provide difficulties that have to be estimated in further examinations.

6. Conclusion

One of the greatest advantages of iGPS is the possibility to measure multiple sensors with just one system. This is mostly needed in joint applications or tracking of objects and their orientation. Examinations of iGPS promised both good accuracy and reliability that has to be proven in practice currently. Depending on the application, maintaining the line of sight in a satisfying geometric arrangement of the transmitter can be difficult, nevertheless the system can be very valuable to many applications. In the next months it will be examined how far the system can be used for kinematic measurements and if the theoretical delay times exist.

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