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IPS – a vision aided navigation system

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Abstract: Ego localization is an important prerequisite for several scientific, commercial, and statutory tasks. Only by knowing one's own position, can guidance be provided, inspections be executed, and autonomous vehicles be operated. Localization becomes challenging if satellite-based navigation systems are not available, or data quality is not sufficient. To overcome this problem, a team of the German Aerospace Center (DLR) developed a multi-sensor system based on the human head and its navigation sensors – the eyes and the vestibular system. This system is called integrated positioning system (IPS) and contains a stereo camera and an inertial measurement unit for determining an ego pose in six degrees of freedom in a local coordinate system. IPS is able to operate in real time and can be applied for indoor and outdoor scenarios without any external reference or prior knowledge. In this paper, the system and its key hardware and software components are introduced. The main issues during the development of such complex multi-sensor measurement systems are identified and discussed, and the performance of this technology is demonstrated. The developer team started from scratch and transfers this technology into a commercial product right now. The paper finishes with an outlook.

Keywords: camera; computer vision; inertial measurement unit; localization; navigation.

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1 Introduction

Knowledge about position is essential for a huge number of tasks and applications – guidance (How do I get there?) strongly relies on self-localization (Where am I?), inspection of technical infrastructure always requires a spatial reference of a certain measurement in order to assign a finding to a spatial coordinate, autonomy depends on a known ego pose in order to interact without conflicts with human beings or other machines in a complex environment. For some of these applications, there are technical solutions available providing 2D or 3D coordinates in a local or global spatial reference system. The most important technologies available in this context are global navigation satellite systems (GNSS), e.g. GPS, GLONASS, or Galileo, in the near future. Although this technology is well established right now (including high-precision differential GPS) and beyond the improvements we can expect in the future w.r.t. availability and precision (e.g. real-time kinematics GPS), for some applications, GNSS does not provide a solution due to its physical principle based on radio waves transmitted from spaceborne satellites. GNSS' major drawback is its partly or complete unavailability in buildings, in mines, in industrial plants, or in forests. Its radio waves are not able to penetrate these objects; they are absorbed or reflected in a way that data processing fails, or data quality is not sufficient. A lot of possible (even new) applications relying on localization information cannot make use of GNSS. Autonomous forklifts cannot operate in industrial buildings, goods cannot be tracked in logistics companies, inspectors in ships or tanks cannot assign any finding to a 3D coordinate, unmanned harvesters cannot operate in the forest – all due to the absence of the signals needed for a determination of ego positions.

Of course, there are even other technologies available like laser trackers, WiFi, or pseudolite-based systems. They mostly have in common that a special infrastructure has to be a built up. Again, for some applications they solve the challenges and lead to practical and operational solutions.

To overcome even the remaining issues and to address further applications, an ego-localization system that can fulfill the following requirements is wanted:
- Provision of three position values
- Provision of three orientation values (optional)
- Data availability in real time
- Seamless applicability in indoor and outdoor scenarios
- Applicability without additional infrastructure
- Applicability without prior knowledge about the environment (e.g. maps)
- Scalability/adaptability to user-specific scenarios

There are several technologies tackling these challenges, e.g. [1–3] (see references). All systems were developed for various applications, different sensors, and data-processing algorithms are used. All the systems have only recently become available; no systematic comparison of their performance is on-hand right now.

The above-mentioned research question is also investigated by DLR for more than 10 years. A researcher team came up with a proposal to build a sensor system based on a technical copy of the human head. Human beings are able to navigate by using two sensors – the eyes and vestibular system in the ear. The brain processes the incoming data to localization and guidance information. Based on this approach, a 'technical head' was designed. A stereo camera substituting the eyes, an inertial measurement unit being an equivalent for the vestibular sensors, and a computing unit are its major components. In the next chapters, this system is described in more detail. Its working principle and the most important basic algorithms are illustrated. The requirements that have to be fulfilled to make such a system working is outlined. In the following chapter, a few application examples are described.

2 Integrated positioning system

The sensor system introduced above is given the name IPS – integrated positioning system[1], which illustrates its close functional relationship to GPS. It was developed in such a way that it can serve as a technology demonstrator for a large number of applications. This requires a certain degree of modularity for hardware and software in the early phases of the project. Figure 1 shows a block diagram of IPS. Figure 2 depicts two IPS at different technology readiness levels (TRL).

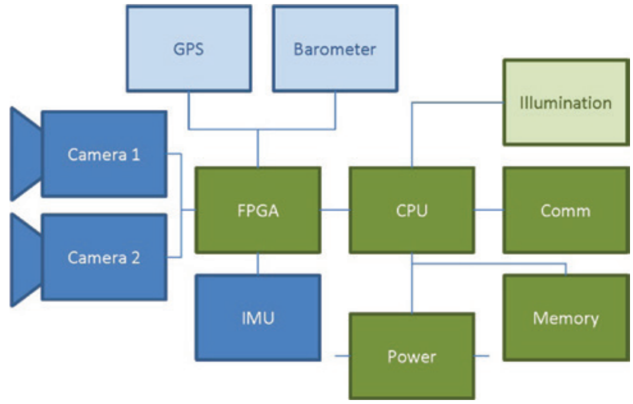

Figure 1: Block diagram of IPS. Dark-colored modules are indispensable, bright-colored modules are optional, blue boxes show sensors.

This modularity enables the developer team to add sensors (e.g., barometers, GPS) if needed and suitable. The main hardware components and software modules are introduced in the next paragraphs.

2.1 Hardware

As mentioned above, the main sensors are a stereo camera, an inertial measurement unit (IMU), and a computer. The sub-systems are described more in detail.

The stereo camera shall consist of two identical imaging 2D sensors. In general, the type of sensor is not relevant, even infrared systems or radar systems can be used. We use integrated CCD cameras, which are sensitive in the visible and near-infrared range of the electromagnetic spectrum. The imaging systems have to fulfill a couple of requirements, e.g. global shutter (meaning that the whole image is taken with a single snap shot) and system stability, for example, w.r.t. to thermal loads. The frame rate of the cameras limits the system's ability of modeling motion dynamics. Currently, IPS contains two CCD cameras (Prosilica GC1380H). Their main parameters are listed in Table 1.

Inertial measurement units (IMU), in general, are able to measure linear accelerations and angular velocities. By mathematical integration over time, a distance and an angle can be determined. However, this process is very sensitive to noise and biases of the sensors, resulting

1 In the last years, the aberration 'IPS' was more and more established as a new designation for 'Indoor Positioning System.' Our IPS is an indoor positioning system, but not limited to indoor scenarios and completely infrastructure independent (no dependence on WIFI or Bluetooth, etc., which is usually not considered as infrastructure in the indoor positioning community).

Figure 2: Integrated positioning system (IPS). Functional demonstrator (left), commercial prototype (right).

Table 1: Basic camera parameters of IPS.

Parameter	Value
Number of pixels	1360×1024
Radiometric range	8/12 bit
Frame rate	≤30 Hz
Focal length	4.8 mm
Field of view diagonal	98°

in large errors. Additionally, low-cost IMU's suffer from gravity-dependent and temperature-dependent effects. To overcome these issues, IMUs are coupled with aiding systems, e.g. GNSS or cameras. For such systems, complete theoretical models were developed dozens of years ago. IPS contains an IMU ADIS16488, its parameters are listed in Table 2.

IPS can be extended by any sensor that can provide information about position or orientation or their derivatives, e.g. barometers, compass, GPS. Maps can be included optionally, too, if they are available, but none of the mentioned sensors or information is required.

A computer based on an Intel® Core™ i7-6600U Processor (2.6 GHz, two cores) with a 4-GByte RAM is able to execute the data processing in real time.

Table 2: Basic IMU parameters of IPS.

Parameter	Value, gyroscope	Value, accelerometer
Range	450°/s	±18 g
Bandwidth	330 Hz	330 Hz
Random walk	0.3°/√h	0.029 m/s/√h
Bias stability	6.25°/h	0.1 mg
Scale-factor stability	10,000 ppm	5000 ppm
g-Sensitivity	0.009°/s/g	–

All data coming from the sensors are referenced w.r.t. to a common system time by assigning time stamps to each dataset. This part is currently taken over by a FPGA. This solution was chosen because the FPGA is thought to take over several additional tasks, e.g. image processing, in the future, too. Other solutions for taking over time stamping, e.g. by microcontrollers, are possible. Any synchronism between the sensors (except for the cameras) is not required; the knowledge of the different time stamps is sufficient.

IPS is equipped with an illumination system allowing operation in dark environments. The wavelength of the LEDs was chosen to be near infrared, such that they can be used as flashlights without confusing the human operators. Several electronic boards are part of the system, e.g. interface board, power board, as well as an interface unit allowing system control and monitoring. IPS system parameters are shown in Table 3.

2.2 Software

Several software modules are running on IPS. The current operating system is Windows, which can be substituted by Linux. The core element of IPS is the so-called navigation engine. Its inputs are the time-stamped, calibrated, and registered sensor data. A vector of six degrees-of-freedom pose data (three positions, three rotations w.r.t. to a local

Table 3: IPS system parameters.

Parameter	Value
Mass	0.6 kg
Dimensions	18×14×5 cm³
Power consumption	4 W

reference coordinate system) and a covariance matrix, being a quality measure of the estimated pose data, is IPS output.

The main steps of the data processing are a) visual odometry based on feature detection and tracking, and b) data filtering fusing the visual odometry with inertial navigation (and possibly other) data. The basic principles of both steps are described in the following paragraphs exemplarily and in Figure 3.

Visual odometry: it is assumed, that the images of both cameras are taken at the same time t_1, and the cameras are geometrically calibrated. Features are detected in the left image (process F). For this process, different corner detectors can be applied. For IPS, KLT [4] and AGAST [5] were implemented resulting in features, e.g. l_1. This feature is searched in the second image (process M) applying feature-matching operators, such as NCC (normalized cross correlation) or SAD (sum of absolute differences) leading to the feature's coordinates in the right image, e.g. r_1. Because of the known relative orientation of the cameras, the search area can be reduced to an epipolar line and results in a corresponding point in the second image. Both features are assumed to belong to the same object point; its three-dimensional (3D) coordinate is determined via triangulation (process R) assuming a known interior and relative (exterior) orientation of the cameras and resulting in a 3D point, e.g. p_1. Corresponding image points in the successive stereo frame at time t_2 are used to estimate the ego motion of the system. By using the inertial measurements, the correspondence problem can be reduced to a small area around a predicted feature position. To do so, the triangulated object point p_1 is transformed to the second stereo frame and projected to the two image planes. After applying a feature matcher (process M′) resulting in the image points l'_1 and r'_1, the relative ego motion (translation and rotation, process T) can be determined, e.g. by a non-linear least-square approach. An underlying RANSAC regime is used to find mismatched points to increase accuracy and robustness. The ego motion containing six degrees of freedom is an estimation of the movement of the sensor system during the capture of two successive images. By aggregation of these rotations and translations, a trajectory over the whole data acquisition period can be generated.

Filtering: the task of this software module is to fuse the data of all the different sensors with their measurements in their own spatial reference systems and time bases. The common time base is assured by a time-stamping concept. A common spatial coordinate system is acquired by sensor registration (see next chapter). Before filtering, some of the data needs to be pre-processed. As an example, IMU data, which are recorded in a body-frame coordinate system, are transferred into a navigation frame via strap-down mechanization. All relevant physical quantities, e.g. position, speed, acceleration, angle, and angular speed, define a state vector, which shall be estimated after each measurement update. For this task, several filter approaches can be applied, e.g. (extended) Kalman filter (IPS baseline) or particle filter.

All data processing is executed in real-time and provides an immediate estimation for ego motion. Post-processing steps can improve accuracy by running forward and backward filter algorithms and by introduction of additional information, e.g. spatial reference points. A more detailed description of the algorithms can be found in [6].

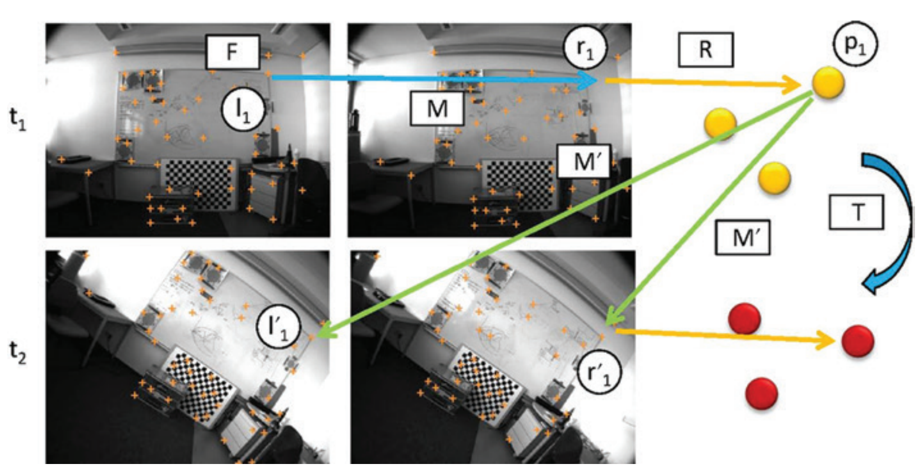

Figure 3: Basic principle of visual odometry based on a pair of stereo images taken at two different times.

2.3 Synchronization, calibration, registration

As mentioned before, a few requirements to the system and the data have to be fulfilled. First of all, camera images have to be synchronized to assure that images are taken at the same time. Second, all incoming data have to be time stamped in order to feed the filter correctly (as described above). Third, all sensors have to be calibrated. For optical sensors, the parameters of the interior and relative (exterior) orientation have to be determined applying well-known methods [7, 8]. For IMU's, noise, scale and bias have to be known from data sheets or have to be determined by own measurements. Finally, all sensors have to be spatially registered w.r.t. a common coordinate system, e.g. the origin of the IMU. This can be executed by measurements activating all sensors, e.g. by translations and rotations of the complete IPS system in front of a checkerboard.

3 Performance

Because of the data-processing scheme described above, an error is accumulated for all elements of the state vector. This means that the localization error increases over time and distance. Assuming a Gaussian distribution of all error sources, this leads to a random walk effect.

Accuracy is the most important performance parameter for IPS. Because of the absence of applicable competing technologies in indoor scenarios, it was difficult to obtain a high-precision ground truth for a complete data take. For IPS, a low number of discrete spatial reference points, such as an identical start and end point, were used to determine the accuracy. For a typical indoor scenario including a path of about 400 m length, a 3D error of 0.4 m is reached by IPS. The order of magnitude of the error was confirmed by dozens of measurement campaigns at different test sites over several years. The error depends on the distant and the time, so the appropriate error metric should be given as a power density function on or amplitude density function with units [m/√h] or [m/√m]. The evaluation of IPS is still ongoing; the team aims to retrieve these kinds of metrics soon. Of course, beyond calibration and registration, the reachable quality depends on a well-defined measurement process itself.

Figure 4 shows IPS accuracy compared to pure IMU localization and pure visual navigation for a typical indoor/ outdoor test run. For doing this, we defined a standard path to be walked by a human operator starting in an office, walking through a building including staircases, having an outdoor section, and finally, coming back to the office where we started. The length of the overall trajectory is about 400 m; it took about 6 min to walk the path. The trajectories resulting from different sensor combinations were laid over a building's cross section in Figure 4.

Figure 5 shows a very first comparison of several localization technologies for an outdoor scenario, when IPS was mounted on a car. It can be seen that IPS can support navigation if GNSS is not available or data quality is not sufficient. A qualitative analysis was not performed yet.

4 Application

During the last years, DLR identified a huge number of possible applications for such a system. In order to fulfill specific application-driven requirements, several IPS with different configurations and hardware components were built and used for measurement campaigns for concept proving; a few are described and illustrated in this chapter.

Ship inspection: currently, ship inspections, which are required regularly by insurance companies and governmental institutions, for example, are manual processes, which rely on camera images and text and/or audio descriptions. This process is highly prone to error

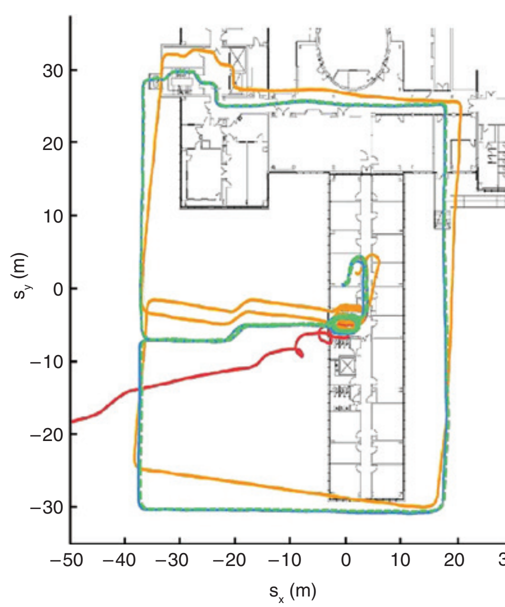

Figure 4: Comparison of the accuracy of different localization technologies in an indoor scenario (hand-held IPS). Reference trajectory (green), IMU-only trajectory (red), visual-odometry-only trajectory (yellow), and visual aided IMU trajectory (blue).

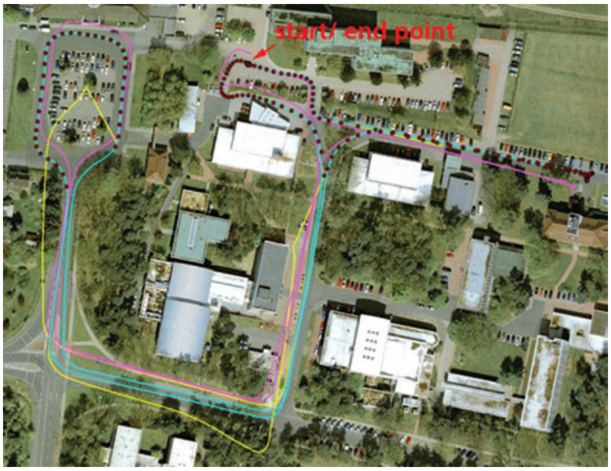

Figure 5: Comparison of the accuracy of different localization technologies in an outdoor scenario (IPS mounted on a vehicle, closed loop). DGPS reference points (red dots), IMU trajectory, fused with GPS if available (yellow, covered at some places with GPS measurements), visual-odometry-only trajectory (magenta), visual-aided IMU trajectory, fused with GPS if available (cyan).

– for example, there is almost no chance to check the inspector's path or to check the assignment of inspection photographs to a CAD model. IPS can bring much more reliability into this process by an automated assignment process (see Figure 6).

Mine inspection: as in the example mentioned above, also in mines, there is no GNSS signal available. Spatial registration of data, e.g. for inspection, is time consuming and expensive. For the inspection of shafts, tunnels, and adits, infrastructure-independent localization technologies are needed – IPS can close that gap and localizes inspectors and mining machines (see Figure 7).

Forest inventory: because of the absorption of radio waves in leaves, GNSS signals are heavily disturbed in forest areas. For inventories, planning and harvesting actions, information about the position of single trees, and machines can be an important benefit. So far, no mobile and real-time technology is available to fulfill the requirements. Again, IPS can support the application by its visual-aided inertial navigation approach (see Figure 8).

First responders: police, fire fighters, and other so-called first responders often do not have plans of buildings they need to enter. A GPS-independent localization and navigation system can help to find a way to a point of interest or the way back.

Vehicle localization: even if GNSS is available, its accuracy is not always sufficient. Several driver-assistance functions in cars need to rely on much higher precisions, e.g. turning-assistance function. The position of rail vehicles is determined by infrastructure-based localization technologies. To overcome this, GNSS can be a new technology, but its across-track accuracy is not sufficient. Again, IPS would be able to deliver additional, vision-based data.

5 From an idea to a product

IPS is an outstanding example that proves DLR's ability to develop high-tech products starting from scratch or, to say it in a more quantitative way, to go the complete way from TRL1 to TRL9. It is noteworthy that all applied single hardware and software components are well known, off-the-shelf, and not cutting edge at all. One-mega pixel cameras and low-cost IMUs are available for more than

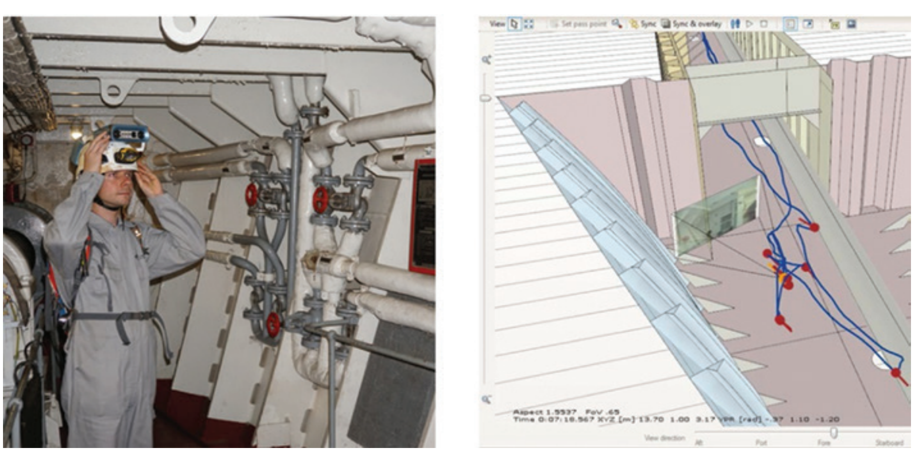

Figure 6: Ship inspection as an example for an IPS application, helmet-based system in operation (left), IPS trajectory and inspection photograph laid over a CAD model of a ship, visualized in ShipManager Hull © (right).

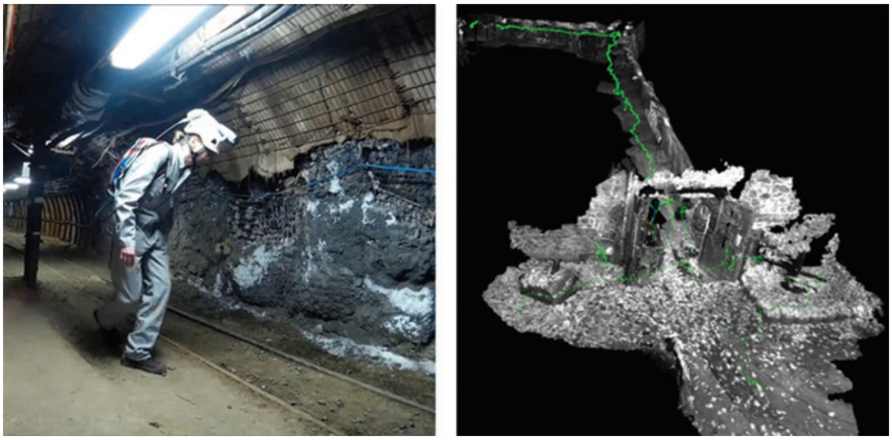

Figure 7: Inspection for a mining application (left) and derived data product showing a trajectory plotted over a 3D model generated by IPS data (right).

Figure 8: IPS outdoor system mounted on a forestry vehicle (left), automatically identified, labeled, and localized single trees based on IPS information (right).

10 years; Kalman filters were described in the 1960s [9]; feature detectors and matchers are well established for quite a while. The knowhow the DLR team gathered over years focuses on precise system modeling and accurate data handling for all sub-systems. IPS is not less and not more than an excellent piece of engineering.

Together with industrial partners und supported by DLR internal funding, the technology transfer process will be finished soon, and the production of IPS-based inspection systems will start in 2017.

6 Conclusions and outlook

In this paper, an IPS was introduced. By analogy with the human head, it determines its ego pose by fusing information from a stereo camera and an inertial measurement system. It works without any external reference, e.g. GPS, and can be a complementary navigation technology for a huge bunch of applications. Without additional information about absolute position, the localization error is a function of time. An accurate positioning relies on thoughtful system models and calibration.

For the future, with our partners, we will focus on operationalization, miniaturization of IPS, and further applications. Beyond this, there are still interesting research questions, e.g. can additional laser scanners or time-of-flight systems improve our technology? Additionally, mono-camera algorithms, e.g. SLAM, structure-from-motion, will be investigated to generate additional value. Because of the stereo-camera approach, IPS generates two images at the same time, which can be processed to a dense cloud of 3D points. These points can be used further to derive 3D models of the environment. This field is a promising extension of the current system relying just on add-on software modules. Furthermore, the images acquired during measurement campaigns can be used for scene interpretation and semantic modeling – being again a huge field of work.

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