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Novel inspection system, backpack-based, for 3D modelling of indoor scenes

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***Abstract*— This work presents a novel system for indoor positioning and data acquisition based on LiDAR sensors and inertial Units. Data are processed with SLAM techniques in order to perform an accurate computation of the trajectory followed by the system in any working environment. The quality of results obtained with the presented system is analysed through its application to two case studies, by comparing geometric measurements to the point clouds obtained with FARO FOCUS 3D Terrestrial Laser Scanner, which has good performance regarding precision.**

Keywords—SLAM; LiDAR; backpack; indoor; 3D keypoints

I. INTRODUCTION

The generation of digital 3D models of existing buildings is a field of study with increasing interest during the last years, especially regarding the representation of indoor scenes in order to be used as basis for refurbishment and design tasks. What is more, the availability of the digital model of the interior of the building is essential for the implementation of indoor positioning systems to complement evacuation procedures for emergency cases, or for the guidance of blind people.

Advances in the reduction of size and weight of laser scanning sensors, together with the increase in their acquisition speed, present the possibility of acquiring data with mobile systems. These systems are equipped by one, or more, 2D or 3D laser scanner, and their trajectory is measured by different positioning systems, according to the characteristics of the system: GNSS, IMU, odometers [1]. The main advantage of these systems is their capacity to acquire data from large areas in a short time interval, with high accuracy. These mobile systems present a wide application in outdoor scenes, while indoor scenes present the complexity of lacking GNSS coverage. This fact implies a challenge for the accurate computation of the trajectory.

Mobile systems for point cloud acquisition of indoor scenes (Indoor Mobile Mapping Systems, IMMS) currently in the market can be classified, depending on the platform, in 3 groups: cart, backpack and manual. Backpack-based mobile systems consist on a platform fixed to the back of the human-operator, where sensors are positioned. These systems allow the inclusion of more weight than the manual system, which can be in the form of sensors and / or of higher autonomy as a function of the size of the battery.

The majority of these systems apply the technique of Simultaneous Localization and Mapping, known as SLAM, which consists on the construction of an incremental map of the unknown environment and the simultaneous positioning within it [2].

The SLAM algorithms that use laser scanners are very focused on the type of LiDAR used, with two main alternatives: one that uses high-performance 3D laser scanners, with high cost and weight. This alternative uses Stop&Go techniques, characterised by measuring in controlled stops during displacement in which the 360º scan is performed. The second option is destined to low-cost laser scanners, with low precision and weight, which are of common use in robotics. These systems do not need to stop for measuring, but the quantity of data acquired is lower than in the first case, since the systems are usually destined to the computation of the trajectory and the generation of a 2D point cloud of the scanned area. There is the option of incorporating one more LiDAR sensor to acquire a higher amount of points, and thus generate a 3D point cloud with low density compared to the point clouds generated by the Stop&Go technique.

There is a third alternative for SLAM systems that combine the characteristics of 2D and 3D systems based on new systems with high rotation speed and several infrared rays that are able to acquire a higher number of points than classic 2D systems. In addition, the orientation of the rays allows the generation of 3D point clouds with complete information of the environment [3]. Consequently, new SLAM algorithms [4] are focused on the detection of 3D characteristics in the point cloud at high-speed, towards their use in systems that work online.

This work presents a backpack-based system for positioning and mapping of indoor scenes. Its structure provides ease of use in different scenarios. The system uses measurements performed by a laser scanner Velodyne VLP-16 with an IMU sensor to correct deviations from the trajectory.

II. INDOOR INSPECTION SYSTEM

A. *Sensors*

The core sensor of the system is a laser scanner from Velodyne, model VLP-16. It can be described as a 3D LiDAR that offers data acquired in real time, with 30º vertical coverage due to the 2º separation between its 16 rays. Horizontal coverage is 360º. Angular resolution is between 0.1 and 0.4º, with 3 cm accuracy. The weight of the sensor is 830 g, not constituting a significant overweight to the backpack-operator. Its acquisition speed, together with the fact that data acquired is 3D and its low weight in comparison with classic 3D laser scanners makes this sensor optimal for the project.

The other sensor installed is an Inertial Measurement Unit (IMU) from Advanced Navigation, used for the alignment of the relative position of the system to the global coordinate system during displacement. Its high acquisition speed allows the association of each IMU measurement with the one from the laser scanner, thus computing and adjusting the trajectory. The precision of the IMU is 0.1 – 0.2º for Roll and Pitch, and 0.5 – 0.8º for Heading.

B. *Mechanical integration*

The platform of the system is a backpack, trecking style, with 40 L of capacity in order to have space for all the components required (**Fig. 1** left). The backpack has an internal structure formed by 2 fluted metallic bars, in vertical position within the backpack and supported by a rigid plastic cover that eases the installation of the sensors.

Sensors are attached to the backpack with a specifically designed structure, and made with a 3D printer. The structure allows the correct attachment of the sensors to the backpack, in such way that they move jointly. This joint movement is necessary to use data from the IMU to correct the position of the laser computation. The 3D printer uses PLA (Polylactic Acid), which is a low-cost plastic material that allows the creation of a rigid structure with reduced weight (**Fig. 1** right).

Fig. 1. Acquisition system (left), and detail of the sensors (right)

C. *Electronical integration*

The application of SLAM techniques to data acquired in real time is performed in a PC with reduced dimensions, storing also the trajectory and the resulting point clouds from the displacement. The PC is placed inside the backpack, and its portability is possible by the use of a power source DC-DC, 120W that allows the use of batteries. The PC consists of an Intel Core i5-4460 processor, 3.2Ghz, 8Gb RAM DDR3 of 1600MHz and a SSD hard disk of 500GB.

The whole system is powered by a Lipo 4S battery (approximately 14.8V) of 20000mAh with a discharge rate of 10C. In addition, software control and result visualization includes a BQ Edison Tablet, which communicates with the PC through a WiFi connection.

The computation of consumption includes the independent consumption of the different sensors and devices, resulting in approximately 101.62W, with an accumulated power of 296W for the battery. Dividing the power of the battery by the consumption of the system results in an estimation of 2.9 hours of autonomy in full performance.

III. SLAM ALGORITHM

The algorithms used for positioning and mapping are based on the work described by [5] with modifications for its application to data from laser scanner Velodyne VLP-16.

The steps followed by the algorithm are the following (**Fig. 2**):

1. Acquisition of a scan, S, consisting on a revolution of the laser configured with an angular resolution of 0.1º, with the 16 rays providing approximately 57600 points per revolution.
2. Simultaneous data acquisition with the IMU, I, storing data closer to the central point of the laser scan. This way, the error performed by displacing and rotating the laser during each measurement is minimised.
3. Roll and Pitch values are used to correct the position of the system with respect to the last calculated position, that is, the position of the system in the previous revolution. This results in the new position of the scan, Si.
4. The reduction in computation time and generation of a robust result is performed by the search of characteristic points in the scan Si, resulting in a group of points Ki. The methods used for the search of characteristic points are based on the extraction of planes and corners within the scan (point cloud). With this aim, the normal vector is computed for each point using its closest neighbours, and they are grouped according to the geometry formed by each point neighbourhood.
5. The registration between the new scan Si and the stored point cloud is performed using techniques based on the Iterative Closest Point (ICP) algorithm, first introduced by [6]. The algorithm search for the reduction in the distance between characteristic points, Ki, of both point clouds, through iterative translations and rotations of the point set Ki. It must be highlighted that the search of corresponding points between point clouds includes only those points close to the last position calculated by the system, establishing as 100 m the distance between the points considered and the last position of the system.
6. When the algorithm reaches an adequate result, the rotated and translated set of points is stored, increasing the size of the resulting point cloud. The position and orientation of the system is updated with the transformation required for the last operation of registration.

The developed software uses the framework Robot Operating System (ROS) as basis, in order to accelerate the programming related to sensor control and data storage in standard format.

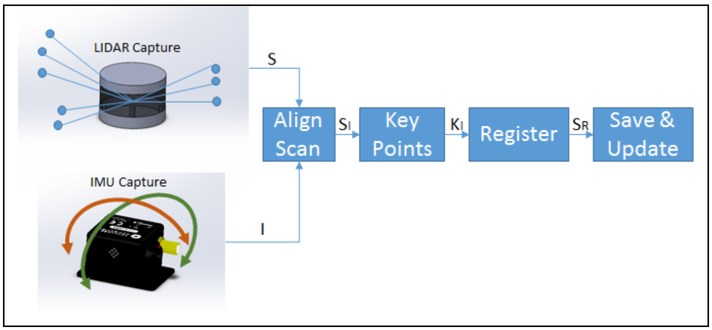

Fig. 2. Algorithm workflow.

IV. SYSTEM ANALYSIS

The system is used in the modelling of two case studies in order to validate its performance and results. Both cases are indoor scenes, with different configurations, construction elements and furniture, allowing for a more robust test of the system. Case study A is a corridor with 55 m length, and a high number of windows and doors leading to rooms and courtyards (**Fig. 3** top). The trajectory followed started at the entrance of the corridor, displacing the system along it in its entirety, and rotating 180º at the end of the corridor in order to scan the end wall. Acquisition time was approximately 40 seconds. Case study B is the hall on the third floor of a building (**Fig. 3** bottom), characterised by big windows in the different orientations of the hall. The path followed by the system starts in one side corridor, going through the hall in a curve, and leading to another corridor. Acquisition time in this case was 16 seconds.

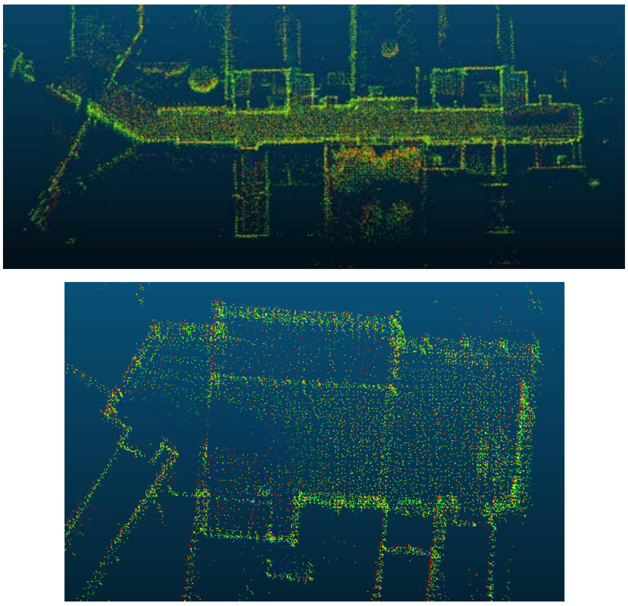

Fig. 3. Plan view of the point cloud acquired by our Backpack Indoor Mapping system for case study A (top) and B (bottom).

For both case studies, the point clouds acquired by the Backpack system are compared with those measured by the Faro Focus 3D X330 laser scanner. The latter are considered as ground truth given the high precision of the Faro laser and of the registration techniques for different scan positions; 3 scan positions were needed to cover case study A, while 2 were needed for case study B. Registration techniques consist on the use of 3 artificial targets, visible from the different positions. The targets are automatically selected and identified by the software, and used for the basic registration between point clouds with trigonometric techniques. Next, fine adjustment methods are applied based on ICP algorithms, which compute the transformation with the highest distance reduction between point clouds. Acquisition and point cloud registration time for case study A is 40 min (**Fig. 4** top), while 25 min are required for the acquisition and registration of the 2 case study B point clouds (**Fig. 4** bottom).

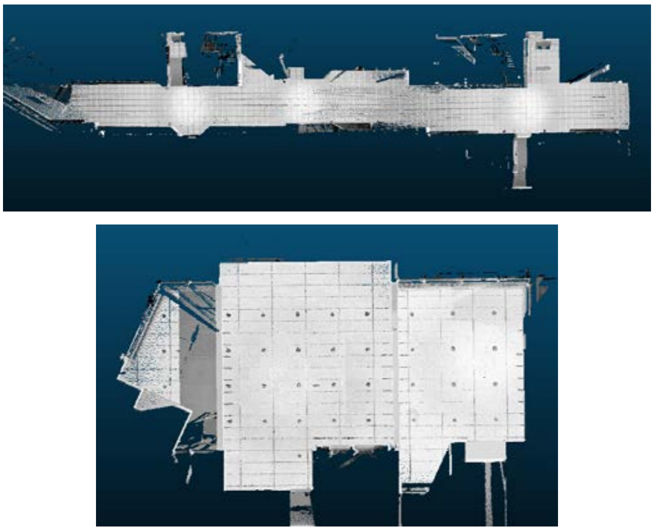

Fig. 4. Plan view of the point cloud acquired by FARO for case study A (top) and B (bottom).

V. RESULTS

The evaluation of the results of the system is performed through the measurement of distances inside the point clouds from both systems. These points can be considered as corresponding between point clouds, although the little deviation provoked by the human interaction must be taken into account.

For the comparison of distances between points, 6 distances are measured for case study A, and 5 distances are selected for case study B, as shown in (**Fig. 5** top) and (**Fig. 5** bottom) respectively. For each distance, we compute the difference between the results obtained in the Backpack point cloud and the Faro, in absolute value, as well as the percentage of the difference with respect to the distance. The percentage gives a clearer view of the error, since their absolute values are usually in the order of the total measured distance. **TABLE I** shows that case study A presents error percentages between 0.71% and 2.77%. Visual analysis of the point clouds does not show any evidence for this variation, so we finally attribute it to the manual selection of the points to measure distances. In order to avoid the consideration of the manual part of the error, we compute the mean error, resulting in 1.7%, with a mean absolute difference of 0.06 m. Both percentage and absolute value can be considered as acceptable.

Regarding case study B, differences measured both as absolute values and as percentages are shown in **TABLE I**. They are lower than for case study A, with a percentage variation of 0.48%, and a mean difference of 0.26%. The cause of the improvement of the results can be the shorter length of the followed path, minimising drift error, as well as the structure of the building, since case study B presents less symmetry than case study A. Symmetry is a characteristic that introduces complexity to the generation of quality results by SLAM algorithms.

TABLE I. Measurements and computations performed for the dimensional comparison of case studies A and B.

No. Distance	FARO(m)	Backpack Indoor Mapping(m)	AbsDif = ABS(FARO-BIM) (m)	AbsDif * 100 / FARO (%)
Case study A				
D1	4.09	4.02	0.07	1.71
D2	1.75	1.77	0.02	1.14
D3	3.36	3.43	0.07	2.08
D4	1.4	1.39	0.01	0.71
D5	3.25	3.34	0.09	2.769
D6	5.08	4.99	0.09	1.77
Mean			0.058	1.698
Case study B				
D1	5.14	5.14	0	0
D2	2.08	2.08	0	0
D3	9.26	9.3	0.04	0.43
D4	2.68	2.67	0.01	0.37
D5	8.27	8.23	0.04	0.48
Mean			0.018	0.257

VI. CONCLUSIONS AND FUTURE WORK

This work presents the current development state of an indoor mapping backpack-based system, equipped with a 3D laser Velodyne VLP-16 and an IMU. The system is analysed through its application to 2 case studies, showing interesting results for mapping, as well as for 3D model generation

Regarding classic terrestrial laser scanners, our system presents a homogeneous point density, since points are measured during displacement, with no incidence in any position. In contrast, terrestrial laser scanners present higher point density near the stations used for measurement. For this reason, the Backpack Indoor System acquires a higher number of points from the exterior of the building through the windows of the scene. These points, although useful for the reconstruction of the model, increase the noise in the final point cloud and are deleted for the modelling process.

The next step in the development of the Backpack Indoor System is the incorporation of a RGB image sensor, which will be used for image acquisition during displacement. Images will be subjected to algorithms for the search and detection of closed loops in the trajectory, in order to minimise the error obtained in its computation.

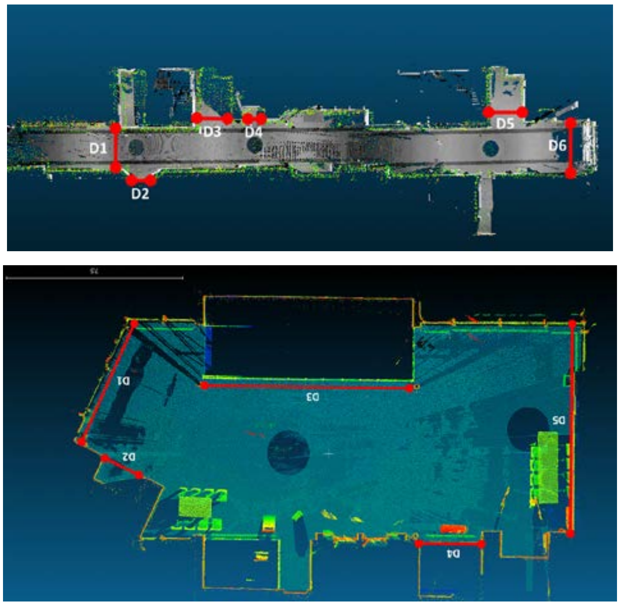

Fig. 5. Plan view from Faro (no ceiling), with the distances measured for the evaluation of the quality of results of the Backpack Indoor System (in green) for case study A (top) and B (bottom).

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