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Original article

Improved Georeferencing of a Wearable Indoor Mapping System Using NDT and Sensor Integration

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Abstract

Three-dimensional data has been used for different applications such as robotics, building reconstruction, and so on. 3D data can be generated from an optical camera or a laser scanner. Especially, a wearable multi-sensor system including the above-mentioned sensors is an optimized structure that can overcome the drawbacks of each sensor. After finding the geometric relationships between sensors, georeferencing of the datasets acquired from the moving system, should be carried out. Especially, in an indoor environment, error propagation always causes problem in the georeferencing process. To improve the accuracy of this process, other sources of data were used to combine with LiDAR (Light Detection and Ranging) data, and various registration methods were also tested to find the most suitable way. More specifically, this paper proposed a new process of NDT (Normal Distribution Transform) to register the LiDAR point cloud, with additional information from other sensors. For real experiment, a wearable mapping system was used to acquire datasets in an indoor environment. The results showed that applying the new process of NDT and combining LiDAR data with IMU (Inertial Measurement Unit) information achieved the best result with the RMSE 0.063 m.

Keywords : Georeferencing, Wearable Indoor Mapping System, LiDAR, Sensor Integration, Normal Distribution Transform

1. Introduction

With the development of science and technology, the quality of the 3D model plays an essential part in visualization or planning. Because of these reasons, increasing the quality of the 3D point cloud generation is the most recent topic for researchers. Besides, the number of researches focusing on the multi-sensor system is increased, because this kind of system can provide us a lot of useful information for 3D reconstruction purposes. A multi-sensor system consisting of optical and LiDAR sensors provides many benefits, coming from positional information such as 3D coordinates, depth values, and semantic information, with RGB color as an example. Among many types of the platform for holding the multi-sensor system, a wearable platform, such as a backpack or handheld system, is more flexible in a tricky environment and can be controlled directly by a human, with the fact that some places; such as a forest, inside of complicated buildings, construction sites, etc., are hard for acquiring datasets and surveying. When performing the wearable data acquisition system to generate 3D point cloud data, several steps should be carried out: sensor self-calibration, system calibration, and georeferencing. In particular, georeferencing is the most critical part when the system is moving. This is the process of converting all data into the same coordinate system for data integration. With a low-cost sensor system, when the

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accuracy of each sensor is not good as a more expensive one, improving the georeferencing accuracy is a core.

In the georeferencing process, when the system is moving or shaking because of the movements of a human, all data acquired from the system at different time belongs to different coordinate systems. Besides, without the control information, when the system goes further, the error is significantly increasing, this is so-called the error propagation. In an indoor environment, the GNSS (Global Navigation Satellite System) signal is ordinarily weak or unavailable (Chen *et al*., 2011). In this condition, the georeferencing process of the multi-sensor system is hard to perform, because it needs the control information from the GNSS signal to reduce the error when the system is moving. Therefore, finding a solution to improve the georeferencing quality in the indoor environment is a critical part when using the wearable multi-sensor system, especially the low-cost one. To do this, the components of the system or the methodology of the georeferencing process has to be concerned. Lagüela *et al*. (2018) developed the UVIGO wearable prototype including one LiDAR sensor (Velodyne VLP-16) and two webcams, and they used a SLAM method to deal with the GNSS-free environment. The authors proposed the extraction of edge and planar points from the point cloud after every 5 scans and used the ICP (Iterative Closest Point) for matching. This system is compared to the Zeb-Revo which has more information from IMU, and the results showed that there is more noise with the georeferenced data using the UVIGO prototype. J. Zhang and Singh (2014) generated a custom-built system with only one rotated LiDAR sensor (Hokuyo UTM-30LX) with the assistance from an IMU. To improve the accuracy, the authors used IMU information to align the point cloud before the georeferencing process. After that, edge and planar points are detected and used for motion estimation using the Levenberg-Marquardt method. The estimated errors prove that their method with IMU information declines the error twice compare to using the LiDAR data only, especially in the indoor environment. In their next research in 2015, when adding a monocular camera in the system, images data from the camera are used for the VO (Visual Odometry) process. For the georeferencing procedure, VO is applied first using the BA (Bundle Adjustment) method, and the LiDAR odometry is then performed to reduce the error propagation from the VO process. In case when the environment is lack of features or the light condition is weak, the image matching process might fail. A dataset from a LiDAR sensor is not affected by the weather condition, so it can help the georeferencing process. In the paper of Wen *et al*. (2016), with the system of an IMU and three laser scanners, the rotation angles from the IMU sensor are directly used as the initial rotation for the ICP process in the direct georeferencing procedure, but the error accumulation still occurs. To solve this, the SLAM method with loop closure is proposed, with the EKF (Extended Kalman Filter) based method. In their conclusion, the indirect georeferencing expresses the finer plane patches in the result.

In summary, LiDAR data is mostly used for the georeferencing step with the scan matching, instead of using the observations directly from the positioning sensors in the multi-sensor system, such as an IMU or GNSS receiver, especially in an indoor environment. Nevertheless, information from these sensors can be used to enhance the quality of the georeferencing process.

After this introduction, Section 2 illustrates the design and performance of the mapping system used in this paper. Especially, Section 3 focuses on the georeferencing process of this system, and several methods of improving the accuracy are explained. The experiments, results, and the evaluation process are discussed in Section 4, and finally, the conclusive remarks are addressed in Section 5.

2. Wearable Indoor Mapping System – Backpack System

2.1 Configuration of the backpack system

In this paper, to perform the georeferencing process in a specific case, a wearable geospatial data acquisition system – a backpack system - is introduced as a cluster of 3 fish-eye lens cameras, 2 LiDAR scanners, a GNSS antenna, an IMU, and a computer system. All sensors are attached to a platform that has the shape of a backpack so that the whole system can be worn by a human (Fig. 1). In the body of the system's platform, all sensors are installed rigidly to avoid the relative positional changes when the system is moving.

The sensor arrangement is designed while considering data acquisition without blank areas, and without interference between sensors.

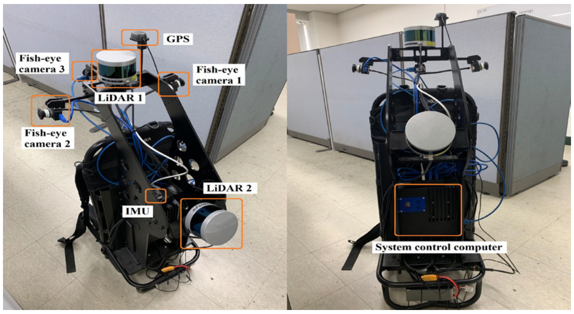

Fig. 1. Design of the backpack system

Three fish-eye lens cameras are allocated in three perpendicular directions on top of the backpack system, heading to the left, right, and the front direction. One LiDAR sensor (i.e., LiDAR 1) - the horizontal LiDAR sensor - lies among three cameras on the top and the other one (i.e., LiDAR 2) - the vertical LiDAR sensor - lies on the back and locates in an inclined direction. Two LiDAR sensors are placed vertically and horizontally to scan the surrounding environment completely and avoid direct contact between the beams of light from two sensors. The specifications of the fish-eye lens camera and LiDAR sensor are shown in Tables 1 and 2, respectively.

Table 1. Specifications of the fish-eye lens camera

	Fisheye-lens	Camera
Model name	Sunex DSL315	Chameleon3 5.0 MP Color USB3 Vision
Projection	Isometric projection (equisolid angle projection)	
Resolution (pixel)	2448×2048	
Pixel size (mm)	0.00345	
Focal length (mm / nominal value)	2.67	
Field of View	135o~190o	

Table 2. Specifications of the LiDAR sensor

Model name	Velodyne VPL=16	
Number of channels	16	
Field of View	Horizontal	360°
	Vertical	30° (±15°)
Resolution	Horizontal	0.1° (5Hz) 0.2° (10Hz) 0.4° (20Hz)
	Vertical	2°
Range	Up to 100 m	
Accuracy (nominal)	± 3 cm	

The GNSS receiver lies on top of the system, next to the horizontal LiDAR sensor. An IMU sensor is a combination of accelerometers, gyroscopes, and magnetometers, that provides the velocity, orientation parameters for the ground coordinate system (Deilamsalehy and Havens, 2017). In the backpack system, the IMU sensor gives the rotation angles from this sensor to the ground coordinate system. After the system calibration process, the relationship between the IMU sensor and the backpack system is estimated. Therefore, with the rotation variations from the IMU sensor, the rotation from the current backpack system's coordinate system to the ground coordinate system can be given. The IMU sensor is allocated at the back, near the computer system. The accuracy of the IMU sensor of the backpack system is shown in Table 3.

Table 3. Angular Accuracy of the IMU sensor

IMU sensor	
Roll & Pitch Accuracy (Dynamic)	0.2°
Heading Accuracy (Dynamic)	0.2°

2.2 3D point cloud generation process

The overall process of generating 3D point cloud data from the backpack system is shown in Fig. 2. Firstly, with the backpack system and sensors attached to it, the sensor self-calibration process has to be taken care of first, in this case, is for the fish-eye lens camera, to calculate the IOPs (Interior

Orientation Parameters) of these sensors. After that, the geometric relationship between all sensors in the backpack system, expressed by the ROPs (Relative Orientation Parameters), is estimated during the system calibration process. Self- and system-calibration for the backpack system were already conducted in this paper (Choi, 2018). For more detailed explanations of the calibrations, please refer to Dr. Choi's papers.

With the translation and rotation parameters between all sensors acquired from this process, all data extracted at one position can be combined for the 3D data generation. However, when the backpack system is moving, the georeferencing process is the final critical step to integrate all data groups from all the positions separated by a time step. Finally, all datasets can have a common coordinate system for a complete 3D model of a whole surveying trajectory.

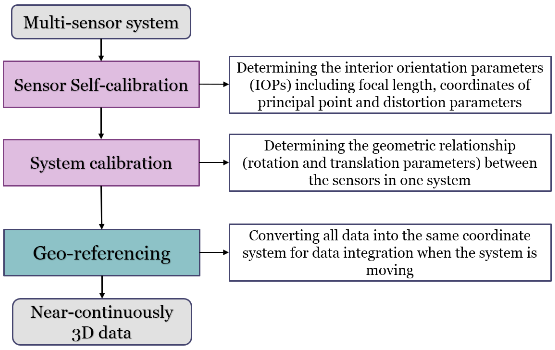

Fig. 2. 3D point cloud generation process of the backpack system

3. Georeferencing Process of the Backpack System Using LiDAR Data

After the system calibration process, the ROPs will be used to transform the coordinates of the LiDAR point cloud into the same coordinate system of fish-eye lens camera by the Collinearity equations, this is so-called the data fusion process. However, when the backpack system is moving, each estimated data acquired from the data fusion process belongs to an independent coordinate system of each epoch. Because of that reason, the georeferencing process is needed to combine all the data into the same coordinate system. In general, georeferencing approaches can be categorized into three groups: direct georeferencing, indirect georeferencing, and data-driven georeferencing (Schuhmacher and Böhm, 2005).

In direct georeferencing, the position and orientation of the multi-sensor system can be calculated directly using additional sensors; such as a GNSS, an IMU sensor, a total station, etc., in case the environment is suitable for these sensors to acquire accurate results. By contrast, the indirect georeferencing approach does not use precise information from additional sensors. This approach is based on the matching process between the observations acquired from the sensors attached to the system. The observations may include the feature points of the images taken from optical cameras, the point cloud data from the LiDAR sensor, the orientation angles from the IMU sensor, etc. (Vogel *et al.*, 2019). This approach requires high-quality image data, point cloud data, and the improvement of the matching process between image points or LiDAR points. The algorithms considered for this approach are the ICP proposed by Besl and McKay (1992), or the SLAM (Simultaneous Localization And Mapping) method (Durrant-Whyte and Bailey, 2006). The final approach, data-driven georeferencing, is based on reference datasets that have already been georeferenced such as digital surface models or virtual city models. However, the quality of such datasets will affect the georeferencing results considerably.

In this research, the direct georeferencing process only is unavailable because of the GNSS-free environment when the backpack system is used in an indoor scenario. Moreover, a reference dataset is not provided for the data-driven georeferencing procedure. Consequently, the chosen approach in the experiments is the combination of indirect and direct georeferencing, which used the LiDAR dataset as the input data, and the information from the IMU sensor of the backpack system is used additionally. The detailed methodology for the georeferencing process using the LiDAR sensor will be discussed in the following sections.

3.1 Indirect georeferencing methods using LiDAR data

Since the data from the LiDAR sensor is a point cloud, the georeferencing process of the backpack system using LiDAR data is based on the scan registration process between point clouds extracted from two consecutive positions. There are many point cloud registration methods. Among them the point-based distance method; ICP, and the point-based probabilistic method; NDT, are the most popular ones. A comparison between ICP and NDT is briefly discussed to choose the most suitable method for the georeferencing process of the backpack system.

ICP is the method to minimize the difference between two point clouds, is proposed by Besl and McKay (1992). The concept of this method is to iteratively find the shortest distance between one point of the source point cloud to a fixed point cloud, calculate the transformation and apply to the source point cloud until the solution is converged. However, the relationship between corresponding points from two consecutive scans of the LiDAR sensor is not clear, leads to the matching problem (Fan *et al*., 2015). Moreover, in ICP, the points from point clouds are directly used for the matching process, so the computation cost is very high, causes a slower performance (Magnusson *et al*., 2007).

On the other hand, the NDT has a different concept comparing to ICP. In the case of matching the 3D point clouds, space is divided into a grid of voxels which are cubes with constant size. After that, all of the points in the clouds are represented by a group of local normal distributions. In more detail, in each voxel including at least three points, the mean and covariance matrix of a point can be calculated. Finally, the probability of belonging to the voxel is formed (Biber, 2003; Magnusson *et al*., 2007).

The iteration process of the NDT method is to optimize the transformation matrix between two point clouds using a standard numerical optimization method: Newton's method (Magnusson *et al*., 2009; Pang *et al*., 2018). Because points are not used directly in NDT, the computation cost might be reduced. With these benefits, the NDT method is chosen for the georeferencing process of the backpack system in this research.

3.2 Suggested NDT process

In the traditional process of the NDT method for the georeferencing of the backpack system, a point cloud is matched with a previous point cloud when the system is moving. The flowchart of this method is expressed in Fig. 3. At the current position, the NDT method will calculate the transformation between the coordinate system at the current position and the previous one. Similarly, the next step will be estimating the transformation between the next position and the current one. This method can reduce the processing time because each NDT step is independent, but the error propagation can happen quickly. The starting position often is the most reliable, especially in an indoor environment, the starting position can be controlled using prior measurement or has the GNSS signal. Therefore, when the system is going further without relating to the starting position, the error can increase dramatically.

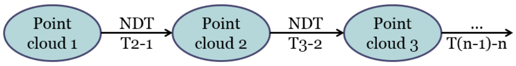

Fig. 3. Traditional NDT method in georeferencing

To decelerate the growth of the georeferencing error, a suggested NDT method is introduced. The concept of this method is that the current point cloud will be matched with the merged previous point clouds. Fig. 4 illustrates the flowchart of this method. At the current position, all the point clouds of the previous positions will be aligned to the first position using the calculated translation and rotation matrices from NDT, and the result point cloud is used for the next registration step. With this concept, all positions can have an indirect relationship with the first position. This can be control information to reduce the error when the system going further.

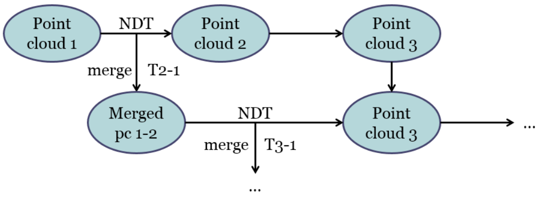

Fig. 4. Suggested NDT method in georeferencing

3.3 Georeferencing process of the backpack system

The georeferencing process of the backpack system is expressed in Fig. 5. When the system is moving, at two consecutive positions, two point clouds are extracted from the LiDAR sensor, and the problem becomes estimating the transformation between two point clouds. After estimating the translation and rotation matrices, the current point cloud is transformed into the same coordinate system as the previous one. Information from other sensors can be applied to help the transformation matrix searching process become more accurate.

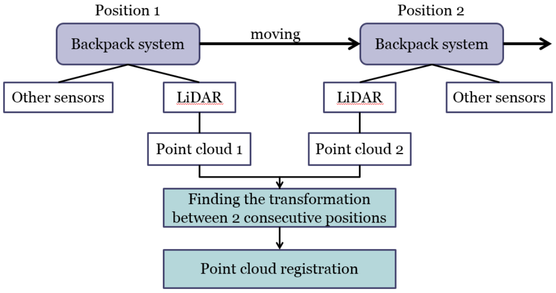

Fig. 5. Georeferencing process of the backpack system using LiDAR data

In this paper, there are two cases of georeferencing:

1. Georeferencing using NDT and LiDAR data only

In this case, the horizontal LiDAR sensor is used as the major sensor for the point cloud registration process. A suggested NDT process is also tested and compared to the traditional one, to find a better procedure.

2. Georeferencing using NDT and LiDAR data with IMU information

As mentioned in the specifications of sensors in the backpack system, the IMU includes the rotation angles to rotate all output data to the Ground coordinate system, based on the estimated relationship between sensors in the system calibration step. In the georeferencing process, the IMU information is used to align the original point cloud from the LiDAR sensor before applying the NDT method. With this constraint, the errors of rotation angles can be reduced, and the amount of improvement depends on the accuracy of the IMU sensor.

4. Experiments and Results

4.1 Experiments

The real dataset is collected using the backpack system in an indoor environment includes many lecture rooms, laboratories, a 20-meter corridor, and one way in the center which leads to the stair. During the experiment, the backpack system is worn and moved continuously with a normal walking speed.

The backpack system started at a lecture room, went out from the back door through the corridor, and then came back to the same lecture room to the front door. The output dataset was tested with the traditional NDT and suggested the NDT process, with or without the IMU information.

After the processing part, results are shown and evaluated using qualitative and quantitative methods. The qualitative evaluation is defined in science as any observation made using the five senses. In this case, the processed point clouds are expressed by images and compared using human eyes. On the other hand, the quantitative evaluation method uses scientific tools and measurements. An accurate sensor is used to make observations.

4.2 Qualitative evaluation

Using the visualization inspection process, the qualitative evaluation was carried out. The results are shown and evaluated by comparison. Firstly, the results of using the traditional and suggested NDT method (with/without IMU information) are illustrated in Fig. 6.

The top and side views of two cases on the left side of Fig. 6 shown that matching a point cloud to one previous point cloud leads to the error of the heading angle. By contrast, in the case of the traditional and suggested NDT methods seeing on the right side of Fig. 6, matching a point cloud to the merged previous point clouds expressed a big improvement. There's no rotation error along the z-direction, and the shapes of the lecture room, corridor, some parts of the stair, and laboratory can be seen clearly.

Especially in Fig. 7, it can be seen that using the additional IMU information for the suggested NDT process also shows a nice result, on the right side of the figure. Besides, the utilization of the IMU enhanced the quality of the output point cloud with a thinner boundary.

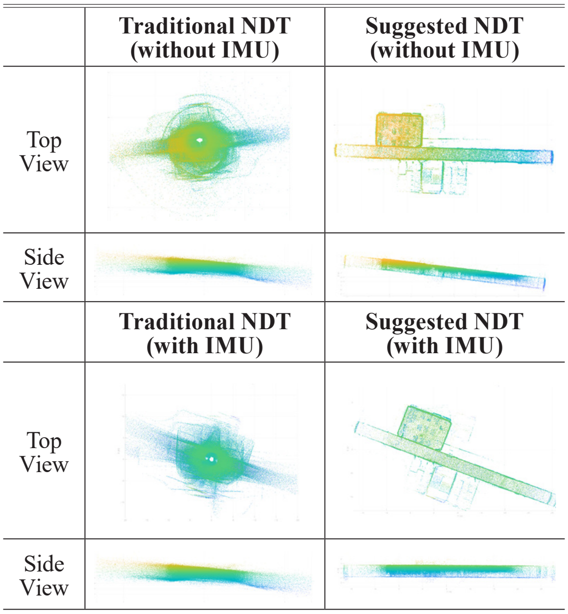

Fig. 6. Results of traditional and suggested NDT method (with/without IMU)

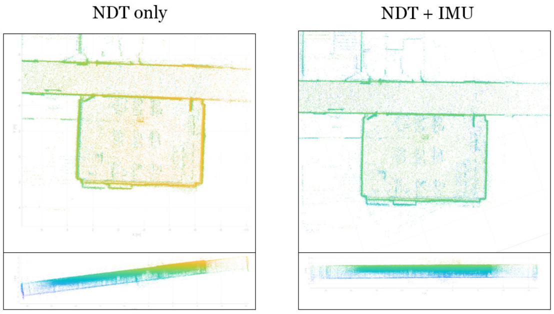

Fig. 7. Results using the suggested NDT process with and without the IMU information

4.3 Quantitative evaluation

In this paper, the quantitative evaluation was done by two methods:

1. Evaluation by the matching accuracy (relative accuracy): the RMSE values of the NDT process are used to compare the improvement of the proposed georeferencing methods.

The RMSE from the NDT method compares the improvement of the proposed georeferencing methods. After the NDT process, the transformation matrix between two consecutive point clouds is estimated, this matrix can be used to apply to the moving point cloud, and use the result to compare with the fixed point cloud. In this research, RMSE value is derived from the Euclidean distance between the aligned moving point cloud – using estimated transformation – and the fixed point cloud. This distance is calculated based on the point-to-point correspondence of the pairs of points that are searched using the K-nearest neighbor (Peterson, 2009).

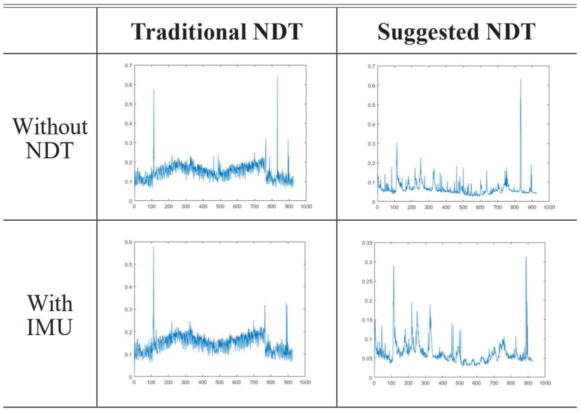

Fig. 8. RMSE values of NDT method in four cases (line graphs)

Fig. 8 shows the RMSE values from the NDT method of four cases in the experiments by line graphs. It can be seen that the RMSE values fluctuate constantly during the experiment and reach a peak when the backpack system is turned suddenly.

Table 4. RMSE values of relative accuracy

Method		Average RMSE (m)	Min RMSE (m)	Running time (min)
NDT	+ IMU			
Traditional way	No	0.1489	0.0632	22.9403
	Yes	0.1486	0.0643	16.6951
Suggested way	No	0.0658	0.0267	19.4991
	Yes	**0.0626**	0.029	**14.3677**

Table 4 shows the average RMSE values of the experiment in four cases. It is clear that the suggested NDT method gives better results with the RMSE values decreasing twice compared to the traditional NDT method. Moreover, when using the addition IMU information, the average RMSE value is the lowest one with the figure of 0.0626 m. The running time also reduces significantly when the input data is already aligned by the rotation parameters from the IMU sensor, with the shortest time is 14.3677 minutes.

2. Absolute accuracy evaluation using a total station:

A total station is an accurate sensor that can be used in the case of an indoor environment with a good line of sight and simple structure without complex elements. In this evaluation method, the data from the total station is the reference to check the accuracy of the generated point cloud. Several edges in the experimental place are chosen and measured. The reference distance is directly measured by setting up the total station on the experiment place. At the same time, with the evaluating distance, the georeferenced point cloud is fed into the CloudCompare software to manually calculate the same edge from the reference one. Finally, the RMSE values are calculated based on the differences between the acquired distances. However, due to the bad results of two cases using the traditional NDT method (Fig. 6), it is impossible to measure some specific distances using CloudCompare. So the quantitative evaluation focused on comparing the accuracy of two cases using the suggested NDT method, with or without the IMU information.

The evaluation result of the experiment using the absolute accuracy is expressed in Table 5. In this case, only the suggested NDT method are concerned, because the results of the traditional method are unqualified for evaluation. The RMSE values of the suggested NDT method with and without IMU information are 0.238 m and 0.131 m, respectively. These figures show that using an additional IMU sensor can improve the accuracy twice than using the horizontal LiDAR sensor only.

5. Conclusion

This paper proposed several methods to improve the accuracy of the georeferencing process of a wearable indoor mapping system using LiDAR point data. In the case of an indoor environment, where the GNSS signal is weak or absent, the important step is decreasing the misalignment of the point cloud georeferencing process. The first solution is finding the best point matching method, and a suggested NDT process is introduced in this paper. Another solution is the integration between LiDAR data with additional data sources to enhance the quality of the output results. The IMU sensor is used to preprocess the original data before applying the NDT method. The experimental results and the evaluation process show that the suggested NDT reduces the RMSE value about 2.3 times, and using the information from the IMU sensor can improve twice in the case of a small area with the same height value. In conclusion, the proposed solutions can increase the accuracy of the georeferencing process,

Table 5. RMSE values of the absolute accuracy evaluation

Measurement	Direction	Measurement from total station (m)	Error (m)	
			NDT	NDT + IMU
Room 1	Length	6.156	0.056	0.015
…Room 7	Height	2.462	0.01	0.013
Corridor 1	Length	2.363	0.005	0.017
…Corridor 4	Height	2.46	0.357	0.227
Total: 11 lines		RMSE	**0.238**	**0.131**

especially with a low-cost multi-sensor system. However, in a larger and height-changing area, only horizontal LiDAR data is not enough. Hence, for future work, the integration between LiDAR data and image data from the fish-eye lens cameras or point cloud data from the vertical LiDAR sensor will be focused.

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