July 2021

Evaluating indoor & outdoor mobile mapping accuracy

An assessment of NavVis VLX data quality compared to a terrestrial laser scanner, including indoor and outdoor scenarios.

Introduction

As the number of mobile scanning systems on the market grows, the need for an industry standard to evaluate the accuracy of these devices in indoor and outdoor environments is increasingly apparent. This document is a practical and reliable method to assess the accuracy of mobile laser scanning systems in indoor and outdoor environments. It's part of an ongoing initiative at NavVis to establish a reliable method for evaluating the accuracy of mobile laser scanning systems.

Do you need a mobile scanning system?
Laser scanning has made it possible to capture many environments in full 3D – but using conventional static scanners can be slow and cumbersome. Numerous scanning positions are required to ensure no details are missed, reducing the total area which can be captured per day. As a result, using a static scanner to document buildings and industrial facilities is a highly labor-intensive process.

In contrast, mobile laser scanning devices are next-generation surveying tools with the ability to rapidly cover large, complex areas.

But while mobile laser scanning solutions promise faster, easier data capture, in many cases the data quality is not comparable. Moreover, there are no industry standards to measure the accuracy of mobile scanning devices.

This leads to a lack of confidence in mobile solutions among laser scanning and AEC professionals who might need to deploy these devices.

In the past, NavVis products were developed especially for indoor operation. The lack of an official industry standard for mobile mapping in this scenario is what we sought to address in our accuracy white paper for indoor mobile mapping*. With the launch of NavVis VLX 2nd generation, which includes hardware and software optimizations for outdoor scanning, we will now expand the scope of our accuracy evaluation to include the exterior of buildings.

The accuracy assessment criteria described in this document is therefore aimed at providing laser scanning professionals who have a need for mobile systems with a reliable means of choosing the right tool to deploy – both indoors and outdoors.

Use cases for mobile scanning systems
The following use cases will help you decide if you need a mobile scanning system in your projects:

- Large commercial and industrial properties which would take too much time to capture with static scanners.
- Manufacturing environments, where disruption must be kept to a minimum.
- Construction verification purposes, where BIM (Building Information Modeling) models and point clouds are compared in third-party software to have complete transparency before construction has started or during construction.
- As-built documentation or models and scan-to-BIM/CAD.
- Public buildings which are heavily used by people, where disruption of ongoing operations must be kept to a minimum.
- Projects with a tight deadline where scanning must be completed quickly or only when the area is not in use.

**Evaluating the accuracy of a wearable mapping system – https://navv.is/accuracy*

Key difference between mobile and static scanning systems

When evaluating the accuracy of mobile scanning systems, it is important to consider a key difference in how data is captured. Terrestrial laser scanners (TLS) capture data by scanning at a single position, while mobile devices continuously capture data at multiple positions while being moved through an environment.

Therefore, when we refer to the accuracy of a TLS, we are talking about the accuracy of discrete measurements at a single position. For one scan position, the specification sheet of a TLS usually refers to certain confidence levels associated with standard deviation, often 1-sigma, which equals 68% confidence, and sometimes 2-sigma, which equals 95%. A standard deviation of 5 mm with a confidence level of 1 sigma, or 68% means that 68% of all measurements must be within a range of 5 mm accuracy.

Meanwhile, the accuracy of a scan using a mobile mapping system is based on a vast number of discrete measurements taken continuously. This path of very dense scanning positions is otherwise known as the mapping trajectory.

Just how accurate is the data captured with NavVis VLX for indoor and outdoor locations?

When it comes to mobile mapping devices, absolute accuracy is dependent on the project geometry, which means we cannot make a general statement at this point. Instead, we analyzed the accuracy in two different scenarios, followed by a mapping and modeling example:

- The first scenario represents a typical indoor example: an office consisting of small rooms, connected through a hallway with some additional doors between the rooms, which require only a few loop closures to minimize drift.
- The second scenario is the outdoor mapping of a facade which is 20.3 m tall and 30.3 m wide. The selected facade is part of a L-shaped street of houses with a length of 400 m in total. This type of environment is an ideal test for outdoor mobile mapping since many artificial objects can be recognized by the NavVis VLX and loop closures can be conducted by crossing the street.
- The mapping and modeling example features a complete three-story residential building, including the interior, the outer shell of the building and the garden. The whole property is captured in one data set and demonstrates how fast and simple a potential modeling workflow from scan-to-BIM can be.

Accuracy benchmarks

NavVis has established a rigorous approach for evaluating the relative (local) and absolute (global) accuracy of a mobile laser scanner in earlier publications*.

The assessment criteria that were set relied on two industry-standard devices as benchmarks for accuracy: a total station and terrestrial laser scanner. These devices were chosen based on the premise that to assess the accuracy of a mobile scanning system, the reference data must be of greater accuracy than the test data. For the purpose of this paper, we will briefly summarize the TLS as a benchmark for accuracy.

Global cloud-to-cloud metric based on a TLS
The most significant metric for comparing mobile and static laser scanning accuracy is one that detects deviations in a mobile point cloud by comparing it to a point cloud from a TLS. It is also a benchmark for the absolute accuracy of the system. This assessment is conducted by running a full comparison of TLS point clouds and mobile point clouds computationally. To compute the deviation between the TLS point cloud and NavVis VLX point cloud, we use points and their normals to obtain an unbiased estimate of the distance between the two scanned surfaces. To account for changed conditions in the environment, such as cars or pieces of furniture which are present in only one of the scans, we include deviations up to 50 mm in the analysis – everything above that we consider as outliers. In the tests described in this document, we compared both clouds as a whole.

Because this type of comparison is fully automated, it can be based on a few million measured points. This approach therefore provides the most comprehensive insights into absolute accuracy.

*Evaluating the accuracy of a wearable mapping system – https://navv.is/accuracy

Two ways to increase accuracy with a mobile mapping system

Mobile mapping is inherently prone to accumulate measurement error along the mapping path (or mapping trajectory).

There are two ways to reduce this error when using NavVis devices:

1. Conducting “loop closures”: by returning to a point where the mapper has been before during the same scan, the error can be minimized. In such cases, NavVis mapping software recognizes overlapping points in the trajectory and uses these to minimize drift error.
2. Using “control points”: control points (CPs) are surveying targets that have already been measured with high precision (e.g., using a total station). These can be used as fixed points to minimize drift error with NavVis mapping software.

Both NavVis M6 and NavVis VLX allow for capturing the coordinates of control points during a mapping session. NavVis M6 can be used with ground control points, while NavVis VLX is compatible with both ground and wall control points.

In principle, there are three available options:

1. No control points: Here, a point cloud in an arbitrary coordinate system is the result.
2. Control points for (geo-)registration: Here, at least three CPs should be used per scan, to allow for registration of the point cloud in a local or global cartesian coordinate system.
3. Control point-based optimization: Here, CPs are used to both register the point cloud and to increase the absolute accuracy. The latter is achieved by doing an additional global optimization on the mapping trajectory that takes the CPs as constraints into account.

In the following scenarios, we will touch upon all three approaches.

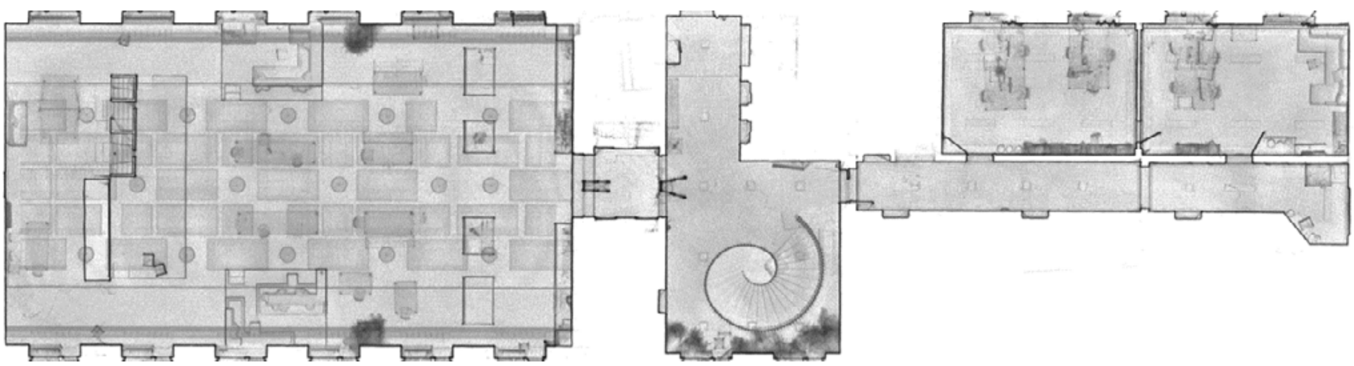
Scenario 1: Mid-size Office

Point cloud of the office floor test scan (ceiling removed for illustration only)

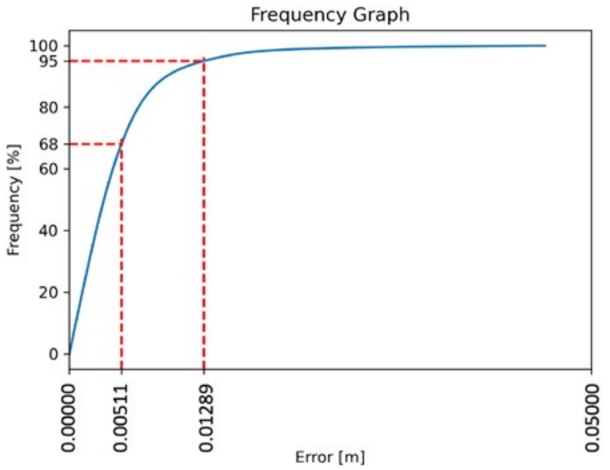
This scenario represents a typical layout for mid-size offices or residential projects – small rooms aligned along a corridor and connected with a few additional doors. The size of this project is around 500 sqm and was scanned in 20 minutes as one dataset, including capturing six control points and several loop closures. The scan includes panorama images every 1-2 m, this contributes to the highly realistic coloring of the point cloud (see the image above).

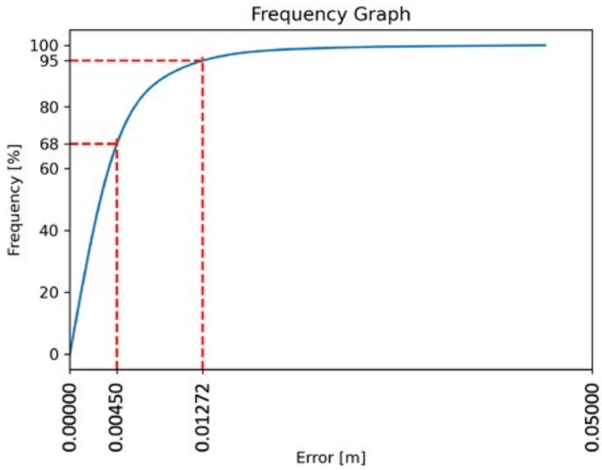
The data from NavVis VLX was processed twice: a) using the CPs for registration only, without CP-based optimization, and b) using the CPs for global optimization of the point cloud geometry and for registration.

As ground truth, an external laser scanning provider was commissioned to scan the office with a highly accurate terrestrial laser scanner. For both test models a) and b) we conducted a full cloud-to-cloud comparison using an in-house tool. Below, the cumulative distribution of the deviations between the TLS point cloud and the NavVis VLX point cloud is shown in two graphs.



Horizontal section through the office environment





Cumulative distribution of deviations resulting from the global cloud-to-cloud comparison: a) point cloud without CP-based optimization (left), b) point cloud with CP-based optimization (right)

Absolute Accuracy Global cloud-to-cloud	**a) Point cloud without CP-based optimization**	**b) Point cloud with CP-based optimization**
68 % of measurements are below	5.1 mm	4.5 mm
95 % of measurements are below	12.9 mm	12.7 mm

From this evidence, we can state that the absolute accuracy for test model a), which represents the point cloud without CP-based optimization, is 5.1 mm at 68% confidence and 12.9 mm at 95% confidence. For test model b), which represents the computationally optimized point cloud geometry, the absolute accuracy is 4.5 mm at 68% confidence and 12.7 mm at 95% confidence.

Model a) is particularly interesting because it represents the accuracy that can be achieved when no control points are used. In this concrete test model, CPs were used for registration only, and not for global optimization of the point cloud. Especially remarkable is the fact that the absolute accuracy for model a) is only 0.6 mm higher than the absolute accuracy for model b). Therefore, it represents the accuracy that can be achieved without using CPs at all in this environment. The small difference represents the capability of the NavVis SLAM (Simultaneous Localization and Mapping) algorithm in indoor scenarios, which enables a high-accuracy documentation of buildings without the survey of CPs.

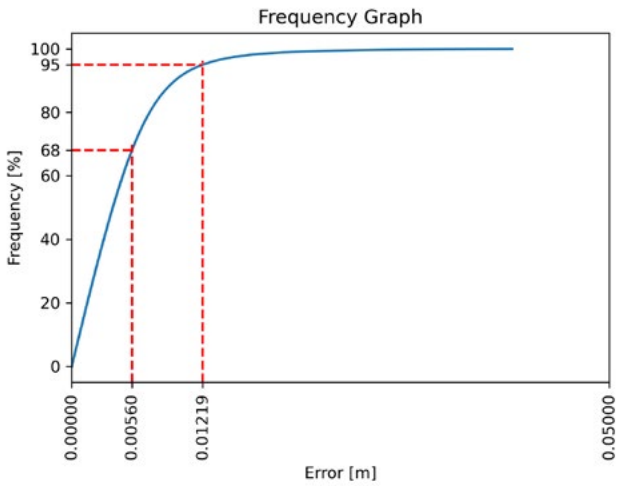
Still, the usage of control points depends on the environment being mapped. It cannot be assumed that reality capture of indoor locations without control points will always have such great accuracy. Furthermore, for the alignment of several data sets and the (geo-)registration, it may still be necessary to install and measure control points.

Scenario 2: Scanning a 20 m high facade

This scenario represents a selected facade that was part of a mapping of a residential street with houses. The facade has an extent of 31.3 m (width) by 20.3 m (height), resulting in 635 sqm facade area in the urban outdoor environment.

As ground truth, one scan position with high resolution was acquired with a highly accurate terrestrial laser scanner. The area between 0 m and a height of 1.55 m was left out for the analysis in both point clouds to remove the occlusion created by parked cars in front of the building. For the test scenario e) we conducted a full cloud-to-cloud comparison using an in-house tool. Below, the cumulative distribution of the deviation between the TLS point cloud and the NavVis VLX point cloud is shown.

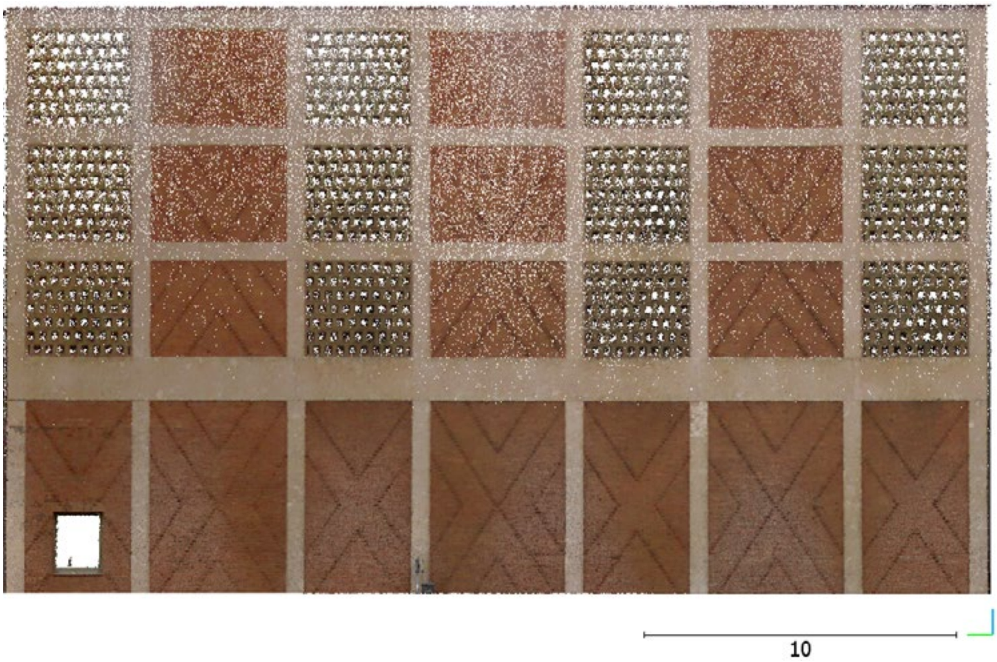
From this evidence, we can state that for the test scenario e) 68% of the points are within 5.6 mm deviation from the ground truth and 95% of the points are within a deviation of 12.2 mm from the ground truth. The example proves that urban environments are feasible for fast and accurate data capture using NavVis VLX, even if they include narrow streets with high facades.



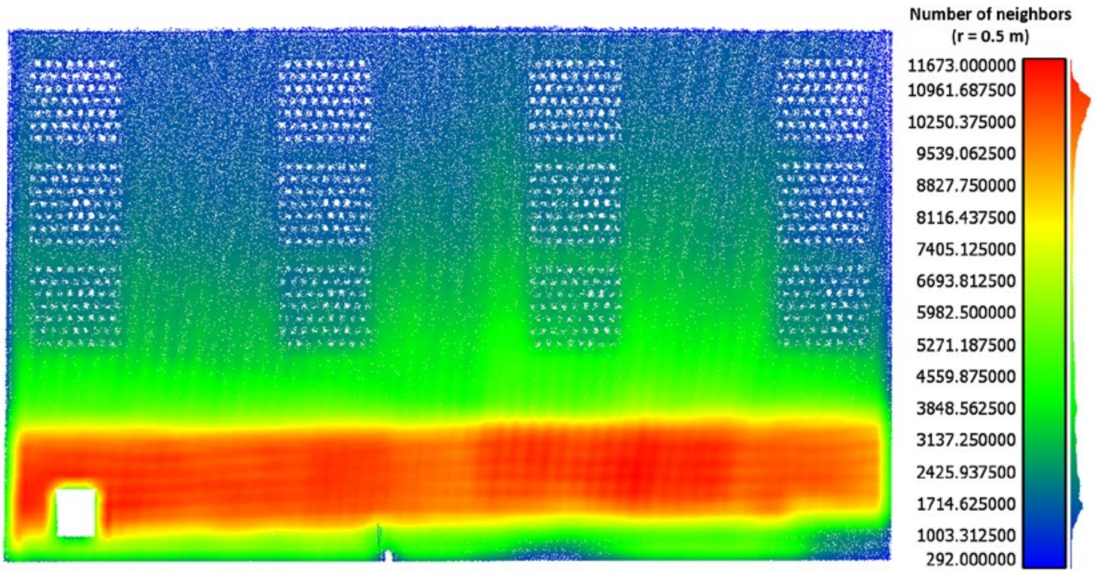
Cumulative distribution of deviations resulting from the global cloud-to-cloud comparison.

Absolute Accuracy	e) Global cloud-to-cloud Comparison
68 % of measurements are below	5.6 mm
95 % of measurements are below	12.2 mm

Point cloud of the urban environment scan (front view)



Visual impression of the NavVis VLX point cloud

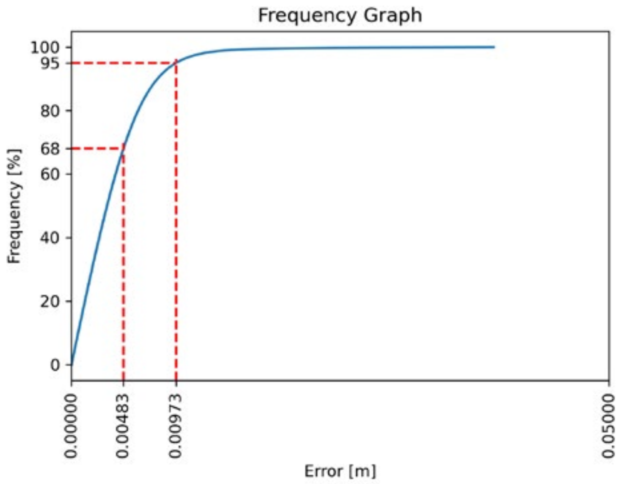


Point density of the point cloud of the NavVis VLX, represented by number of neighbors in a 50 cm radius

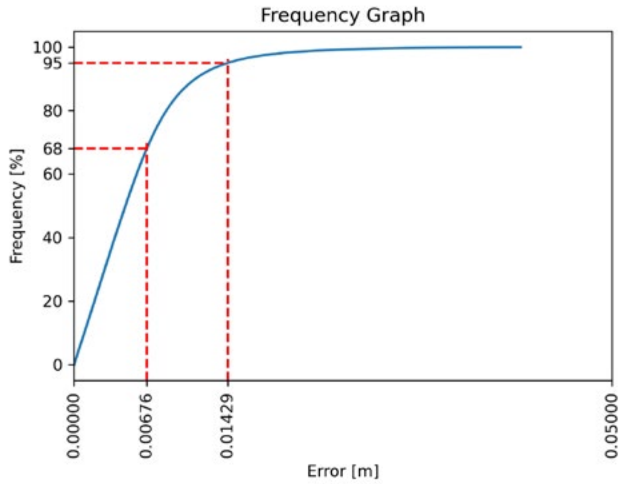
For deeper analysis, we cut the described facade into three equal parts with respect to height to analyze if the accuracy changes with increasing distance between the device and the object. As shown in the frequency graphs below, the results acknowledge our assumption that with increasing distance between scanner and object the measurements get less accurate. Still, as shown in the graph on the right, even for the highest area we can state that 68 % of all measurements are below 7.5 mm and 95 % of all measurements are below 16.9 mm.

Additionally, we show the point density for the high facade processed with a resolution of 5 mm. As shown in the figure below, the point density decreases with increasing distance between the NavVis VLX and the area of interest. This results in a high point density (~ 5 mm distance between two points in the point cloud) within a height of the facade between ~1 m and ~5 m, colored in red. Between the floor (0 m) and ~1 m and ~5 m and ~10 m facade height, the point distance increases to 12 mm in average, as colored in green. The area represented by a mixed colorization of green and blue (10 m to 15 m facade height) shows point distances of 18 mm. The highest part of the object (15 m to 20 m) still is represented with a point density of 21 mm in average between two points.

This analysis leads to the conclusion that facades as shown in this example can be modeled in LOD200 based on NavVis VLX data. A real-world use case might be the calculation of the energy efficiency of buildings based on the opening proportion of the facades.

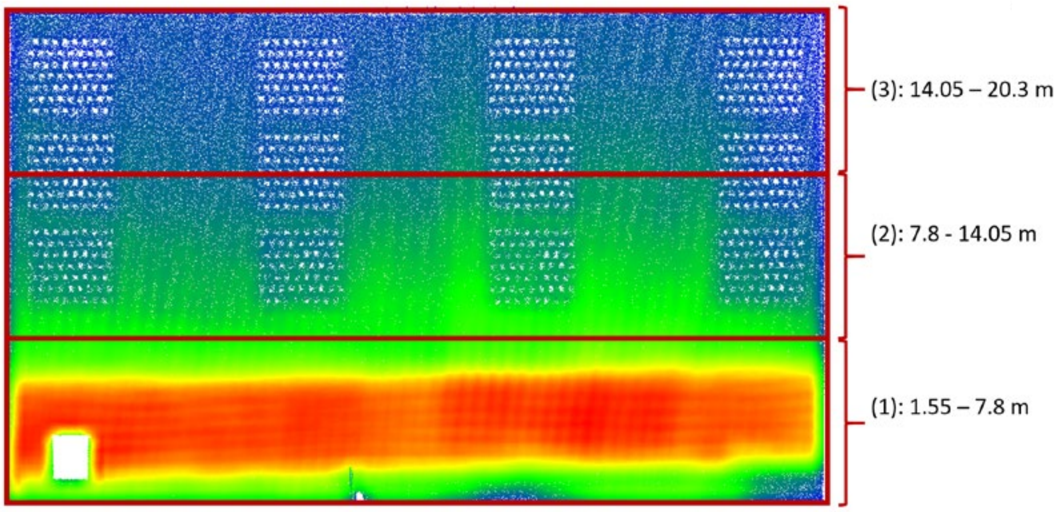


Absolute Accuracy in three heights	1.55 – 7.8 m
68 % of measurements are below	4.8 mm
95 % of measurements are below	9.7 mm

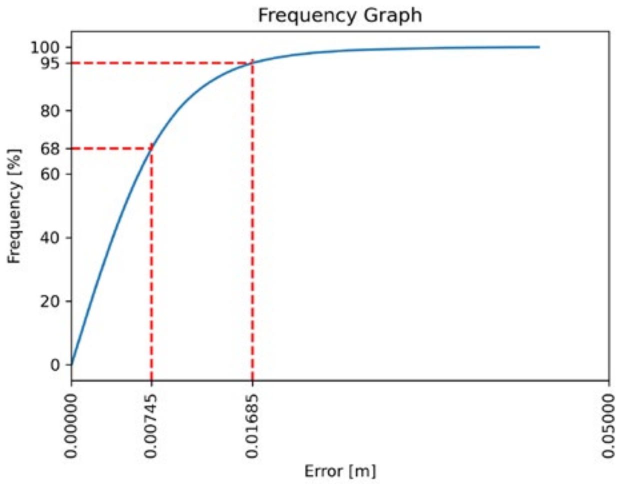


Absolute Accuracy in three heights	7.8 - 14.05 m
68 % of measurements are below	6.8 mm
95 % of measurements are below	14.3 mm

Point cloud of the urban environment scan (front view)



Subdivision of the facade for the detailed analysis of three defined heights



Absolute Accuracy in three heights	14.05 - 20.3 m
68 % of measurements are below	7.5 mm
95 % of measurements are below	16.9 mm

Mapping and modeling a large family house

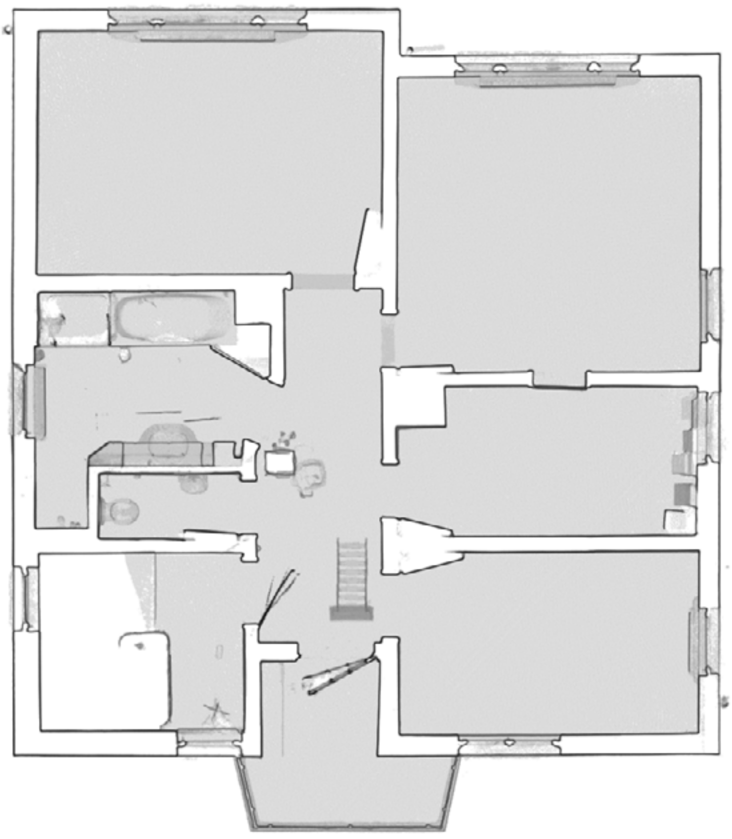
This example shows a three-story residential building including an indoor area of approx. 250 sqm, property, and garden with a land area of approx. 400 sqm. The project was scanned in a single session in 30 minutes, from the inside to the outside, without the capture of control points. Indoors, panorama images were captured every 2 m, while the distance increased to 5 m during capture of the outer shell. We demonstrate the simplicity and speed of a scan-to-BIM workflow from as-built capture to BIM model.

The example shows how quickly and easily a large family house is comprehensively mapped (including the garden area), resulting in one data set complete with color information. The NavVis SLAM algorithm is robust enough to facilitate the connection between the three stories of the inside of the house and the surrounding property outdoors. The point cloud enables the creation of BIM models in LOD300 in third-party software. The panorama images further support a detailed and fast modeling process. Additionally, the 2D layout creation can be achieved in third-party software based on the dense and sharp point cloud.

Rendering of the BIM model

Overlay between point cloud and BIM model

Vertical section through the large family house



Horizontal section through the large family house

Conclusion

The concrete results from the two scenarios and one example provide a good basis for laser scanning professionals to decide if NavVis VLX is suited to indoor and outdoor projects with specific accuracy requirements, and to decide if and how many control points measured with a total station should be used.

Key findings

- For indoor environments comparable to the mid-sized office shown in the first scenario, the usage of control points is of small importance for accuracy, if sufficient loop closures can be conducted during the mapping.
- The mapping of urban outdoor environments and buildings facades works well, in use cases comparable to the second scenario.
- For a facade of 20.3 m height, we achieved an overall accuracy of 5.6 mm and an accuracy of 7.5 mm in the higher regions above 12.5 m at 68% confidence.

If the required deliverable is as-built CAD or BIM documentation for construction or refurbishment, NavVis VLX is the perfect device for most indoor spaces, even without using control points. In outdoor projects where no larger loop closures can be achieved, control points are recommended for global optimization and additionally might be used for registration of multiple scans.

If the required deliverable is a registered as-built survey with an accuracy level up to LOA30, NavVis VLX together with a total station to measure control points is very well suited for most indoor cases and outdoor cases where adequate structures or objects are visible. We cannot guarantee an accurate mapping in forests, caves, tunnels, or other environments where manufactured objects within 60 m are missing.

Moving forward, we will continue to conduct research into other built environments and, in the long term, extend the scope of this accuracy evaluation towards challenging outdoor scenarios as forests, parks, and open areas with fewer artificial structures. Moreover, we welcome feedback and any suggestions on how to extend and standardize the evaluation of mobile mapping systems.

About NavVis

Bridging the gap between the physical and digital world, NavVis enables service providers and enterprises to capture and share the built environment as photorealistic digital twins. Our SLAM-based mobile mapping systems generate high-quality data with survey-grade accuracy at speed and scale. And with our digital factory solutions, users are equipped to make better operational decisions, boost productivity, streamline business processes, and improve profitability. Based in Munich, Germany, with offices in New York and Shanghai, NavVis has customers worldwide in the surveying, AEC, and manufacturing industries.

For more information, visit www.navvis.com.

NavVis has the most accurate mobile mapping systems on the market. Used together with NavVis IVION, professionals in the laser scanning, surveying and AEC industries have an end-to-end reality capture solution.

Glossary of terms

AEC *stands for* ***Architecture, Engineering and Construction****, a collective term for three associated industries.*

BIM *stands for* ***Building Information Modeling****, the methodology of creating a smart 3D model that offers a holistic view of a building to enable stakeholder collaboration. It enables a single stakeholder to make decisions at various stages in the building lifecycle, and update the central model so other stakeholders can always have the latest information.*

CAD *stands for* ***Computer-Aided Design****, the use of computers for the creation, modification, analysis, or optimization of a design. CAD software can be used to increase productivity, improve the quality of design, improve communications through documentation, and to create a shared database.*

CP *stands for* ***Control Points****, targets on the ground or walls which have known coordinates. They should be measured with high precision, e.g. using a total station. Integrating them into a mobile mapping workflow minimizes the phenomena of drift error.*

LOA *stands for* ***Level of Accuracy****, the acceptable tolerance range for the building measurements gathered during the capture process – as well as the tolerance range for how those measurements are represented in the model.*

LOD *stands for* ***Level of Detail****, the depth of the information included in the model.*

Scan-to-BIM *is the process of using laser scanners to capture dimensional information for an existing building or location, and then using that information to create a BIM.*

SLAM *stands for* ***Simultaneous Localization and Mapping****, an algorithm that fuses data from a mapping system's onboard sensors to determine its trajectory at the same time as it moves through the environment. This calculation is performed a huge number of times every second.*

TLS *stands for* ***Terrestrial Laser Scanner****, a device which captures data as discrete measurements by scanning at a single position.*

NavVis

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Version 1.0 | July 2021