Title: **Intelligent 3-D Elevator Shaft Mapping**

Author: Christian Studer, Head, New Technologies, Schindler

Subjects: Construction
IT/Computer Science/Software
Vertical Transportation

Keywords: Construction
Elevators
Technology

Publication Date: 2021

Original Publication: CTBUH Journal 2021 Issue I

Paper Type:
1. **Book chapter/Part chapter**
2. Journal paper
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished

Intelligent 3-D Elevator Shaft Mapping

Christian Studer

Raphael Bitzi

Philipp Zimmerli

Authors

Christian Studer, PhD, Head, New Technologies
Raphael Bitzi, New Technologies Team Member
Philipp Zimmerli, New Technologies Team Member
Schindler Elevators Ltd.
Zugerstrasse 13
6030 Ebikon
Switzerland
t: +41 414454830
f: +41 414454830
e: christian.studer@schindler.com; raphael.bitzi@schindler.com; philipp.zimmerli@schindler.com

Christian Studer studied civil engineering and holds a PhD in multibody dynamics from the Swiss Federal Institute of Technology (ETH). He has held various positions on Schindler's innovation teams, including as technology expert to the Solar Impulse mission, the first around-the-world trip with a solar airplane. Today he is the head of Schindler's New Technologies department, which develops breakthrough innovations for the vertical transportation industry.

Raphael Bitzi has a master's degree in robotics from the Swiss Federal Institute of Technology (ETH). Since 2011 he has worked for the Schindler New Technologies Team, developing and industrializing robotic installation systems and camera-based measurement and localization devices.

Philipp Zimmerli studied mechanical engineering at the FHNW Windisch. He worked in various engineering consulting companies for many years, before he started in Schindler's New Technologies department in 2013. With his deep mechanical background, he supports the team on several projects.

Abstract

Laser and camera scanning, as well as mapping solutions, are increasingly used to create accurate 3-D models of the built environment. This paper presents a prototype of an intelligent camera system for automated elevator shaft scanning and mapping. It aims at assessing whether elevator shafts are built within admissible tolerances. The system works in four steps. First, time-synchronized cameras with a 360-degree view are lifted within the shaft by a small rope winch or a drone. In the second step, a precise digital 3-D model of the built elevator shaft is derived from the camera images. In the third step, the positions of the shaft door openings are identified in the 3-D model, by using computer analysis. In the fourth step, the digital elevator CAD model is placed into the real shaft 3-D model, based on the positions of the door openings. Using this system the elevator can be digitally installed, prior to the start of physical installation.

Keywords: Construction, Digital Twin, Imaging

Introduction

Elevator shafts are key structures in buildings. They essentially form one room, from the basement of a building up to the top. Elevators must be constructed in close conjunction with overall building erection. In spite of the large size and long construction time of the elevator shafts, they need to be within close geometric tolerances to allow for proper elevator installation.

First, elevator shafts need to be straight, in order to guarantee good elevator ride quality. Any kinks or curves in the elevator rails due to out-of-plumb shafts can lead to oscillations of the elevator car as it travels at high speed along the rails. Required tolerances in shaft straightness also include the positioning of the elevator shaft door openings, which must be all in line with each other.

Second, cross-sections of the elevator shaft must be made over its entire length to the admissible tolerances in order to assure the elevator fits. This is especially crucial, as today's elevator systems maximize space utilization in elevator shafts, leaving only a small amount of room for adaptation to geometric irregularities.

Detecting tolerance issues in the elevator shaft during elevator installation leads to corrective actions on the construction site, namely the ordering of new shaft material or partial removal of concrete (see Figure 1). Advance knowledge of whether and where corrective actions must be scheduled is essential, in order to prevent potentially costly delays and disturbances on construction sites.

Special attention has to be paid at handover of the elevator shaft from the builder to the elevator company. Common practice today entails elevator companies making a rough manual measurement with plumb lines in the shaft and measuring the wall and door distances on each floor with respect to the plumb lines. This is an error-prone and time-consuming task that only allows spot checks in the shaft, and not a comprehensive measurement. This paper presents the latest research on how to obtain accurate 3-D models of the entire built elevator shaft, and how to digitally install the elevator model prior to physical installation, in order to detect any geometric tolerance issues.

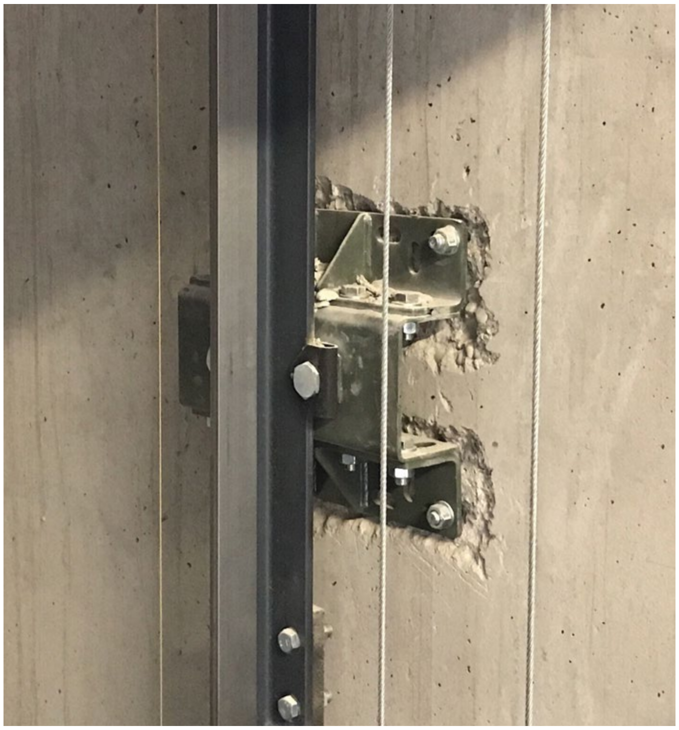

Figure 1. Corrective action at elevator wall bracket, due to shaft walls being out of tolerance.

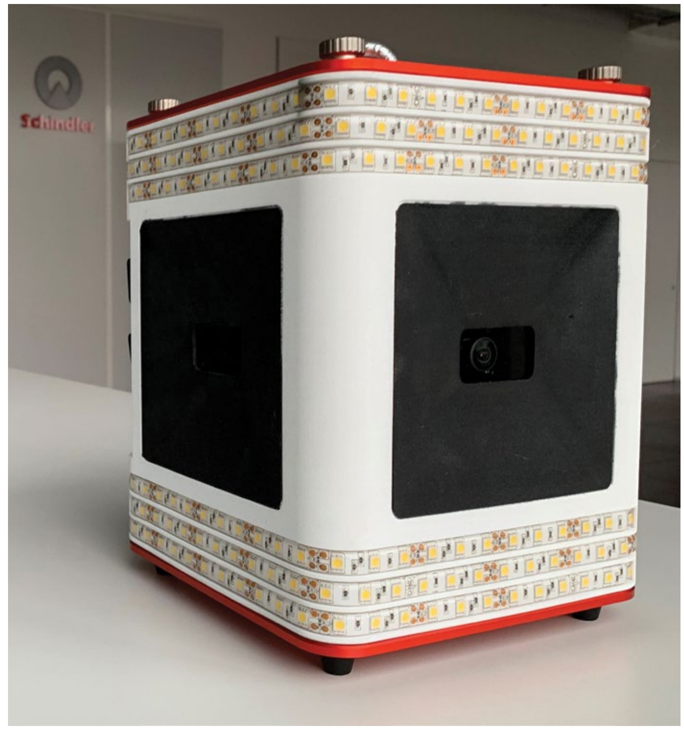

Figure 2. Camera unit consisting of four cameras, LED lighting system, and a computer for data processing.

State of the Art

Today 3-D laser scanning of buildings is a state-of-the-art practice. These widely available, but rather expensive scanners can be placed in a room and output a highly accurate 3-D model of the built geometry to millimeter tolerances. However, using these scanners in an elevator shaft is tricky, because the shaft is narrow horizontally and long vertically. To illustrate this, if a 3-D laser scanner is placed only in the elevator pit, the angle of reflection of the laser beams on the shaft walls becomes too small for accurate results as the height of the shaft increases. As a consequence, laser scans of the shaft would need to be made every few meters, and these scans would then need to be stitched together. In addition, laser scanners need a solid base during their scanning, i.e., scaffolds would need to be installed in the shaft every few meters, which is not practical with today's scaffold-less progressive elevator installation processes.

Another state-of-the-art real-world imaging technology is the mapping of landscapes by drones. Drone-derived images are stitched together and converted into models, making a three-dimensional landscape based on global positioning system (GPS) information. However, this cannot be easily translated to elevator shafts, as GPS positions are not available in buildings, and thus the position of the drone and associated camera must be otherwise obtained.

Today there are also many applications of simultaneous localization and mapping (SLAM) algorithms, such as in smartphone-based room measurement apps and autonomous vehicle navigation, as well as in robotics applications. However, most SLAM positioning systems dependent on consumer hardware do not usually deliver sufficient position accuracy required for elevator shaft mapping. Therefore, special attention has to be paid to fine-tune SLAM to application use cases, in order to achieve suitable measurement accuracy.

Elevator Shaft Scanning

The following outlines a new prototype-stage camera-based measurement system for elevator shaft measurement. The application of the system consists of the following steps:

1. A multiple-camera system is moved along the elevator shaft by a drone or a winch as it continuously takes images.
2. The camera images are transformed into a 3-D point-cloud model of the elevator shaft.
3. An algorithm automatically detects the elevator shaft door openings in the 3-D model and creates virtual reference lines.
4. Based on the virtual reference lines, the elevator rails and brackets are virtually placed in the shaft. By doing so, it can be automatically checked whether all brackets and shaft doors can be mounted within the given tolerances.

Each step is further explained in detail below.

Step 1: Camera Imaging of the Shaft

The system consists of four time-synchronized cameras, which can take images with a frame rate of 10 Hz and resolution of 1.6 megapixels. In addition, the system has an onboard inertial measurement unit (IMU) which measures linear acceleration as well as angular velocity. A picture of the camera system is shown in Figure 2. The camera system is moved up and down the shaft with a small winch and a rope, as it continuously makes images. See Figure 3 for an impression of the system in action. In principle, it could also be mounted on a drone to fly up and down the shaft. The images are associated with position information to enable the construction of a precise real-world-based 3-D shaft model afterwards. See Figure 4 for an illustrative example.

The positions of the images are obtained using SLAM technology. The camera takes one set of images at time t1 and another set of images at time t2, as the camera has moved in the shaft between time t1 and t2. The quantification of this relative movement of the camera between times t1 and t2 can be derived by integrating the accelerometer and gyroscope data of the IMU. The algorithm also detects so-called "natural features" like distinct optical wall structures in the images taken at t1, which can again be found in the images taken at t2.

By comparing the position of these features within the images taken at t1 and the images taken at t2, the algorithm can calculate the relative movement of the camera between t1 and t2, see Figure 5. It must be highlighted that this process requires some minimal texture to be present on the elevator shaft walls for use as reference points, i.e., raw shafts with visible concrete structure are preferable to white-painted shafts. Attention must also be paid to proper lighting, which is

Figure 3. Camera unit in use in the shaft.

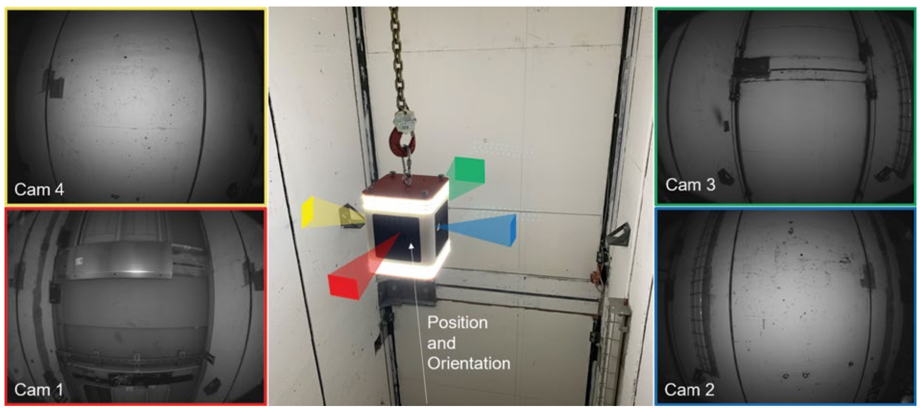

Figure 4. Illustrative example of images taken by the cameras, including their positioning.

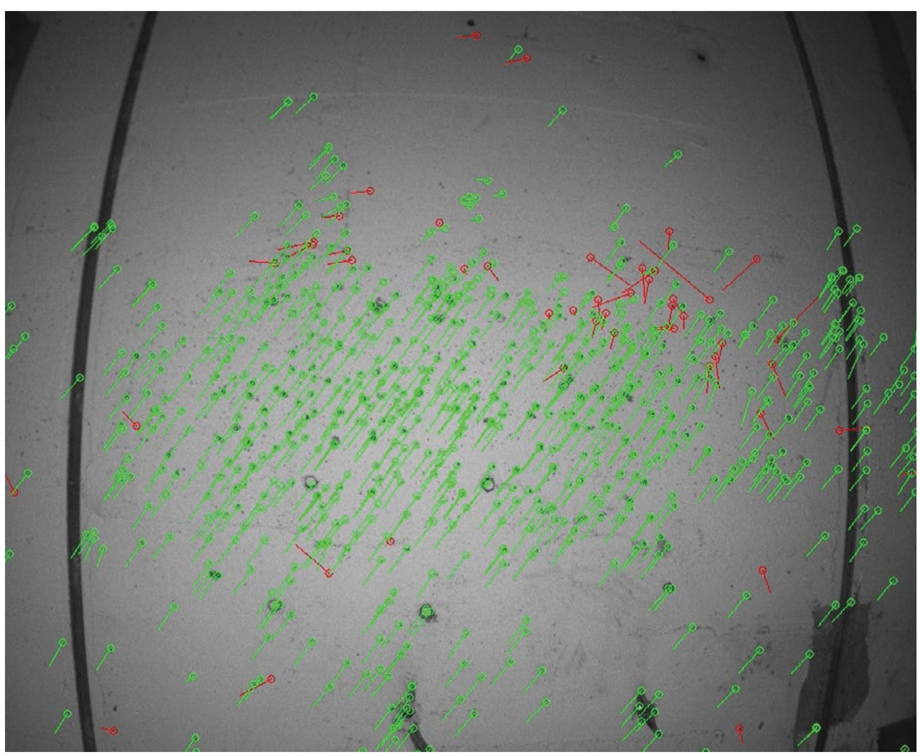

Figure 5. Images made by the camera, including features (green: tracked features; red: rejected features; lines: features tracked from previous image).

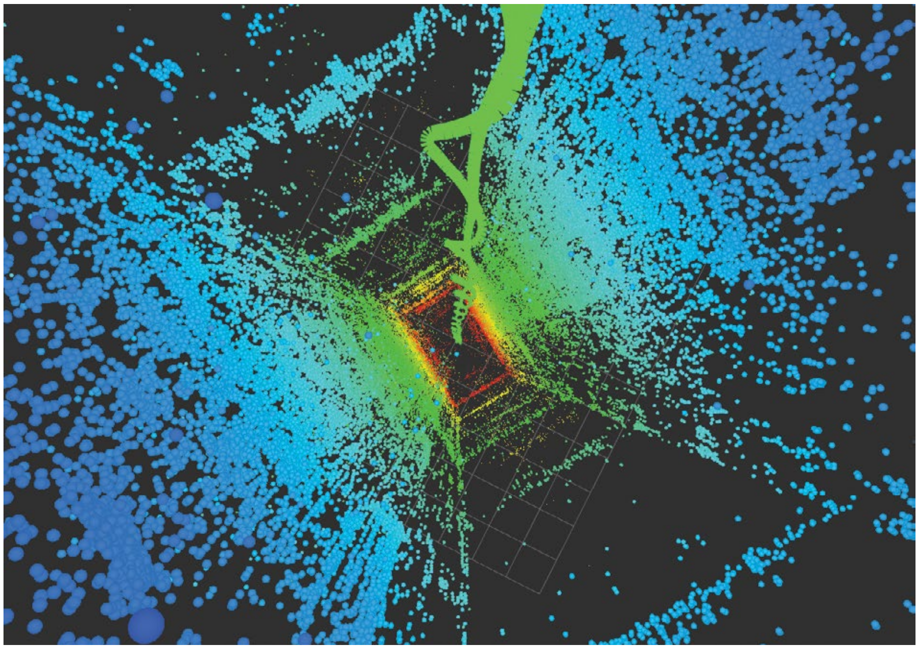

Figure 6. 3-D point cloud of the elevator shaft, including camera trajectory (green).

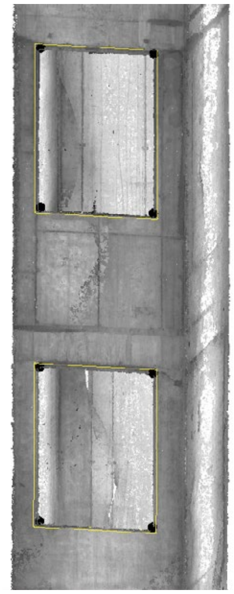

Figure 7. Two shaft door openings detected by the digital mapping system.

ideally synchronized with the camera operation. In order to increase the accuracy of SLAM, the hardware must guarantee proper synchronization between the IMU and cameras. The relative movement information from the IMU and the camera are combined, using a sophisticated optimization method that has been fine-tuned for elevator shaft mapping.

SLAM is still subject to light drift, especially in the vertical measurement direction with the measures described. However, lifting the camera from the shaft pit floor up and then back down the shaft can reduce this, i.e., the camera at the end of the measurement is at the same vertical position. Reimaging the same parts of the shaft enables the identification of the overall vertical drift of measurements up and down, supplying information for the algorithm to make a drift correction. Both the hardware sensor setup and post processing software were developed by Schindler, together with the start-up company Sevensense Robotics AG.

Step 2: 3-D Reconstruction of the Elevator Shaft Based on the Images

The images including the coordinates obtained in Step 1 can now be stitched together to make a full 3-D point cloud of the elevator shaft. Different from a 3-D CAD model based on three-dimensional planes, a 3-D point cloud is a set of millions of points, each with a 3-D coordinate, and is therefore many orders of magnitude more precise. To obtain this 3-D point cloud, existing algorithms common in drone landscape mapping can be utilized. In this specific application, the Pix4D software was used, with the referenced images input to derive a full 3-D point cloud. See Figure 6 for an example of an elevator shaft point cloud obtained using this method.

Step 3: Identification of the Elevator Doors and Placement of Virtual Reference Lines

The 3-D point cloud obtained in step 2 is now fed into an algorithm, which detects the elevator shaft door openings. The algorithm fits straight planes to the four shaft walls and detects the cut-outs, resulting in the position of the four corners of the shaft door openings (see Figure 7). Having obtained these corners, the algorithm fits two plumb lines through the corners, which serve as references for elevator installation. These plumb lines are iteratively fitted, such that all elevator doors can be mounted in the corresponding shaft

> “This process requires some minimal texture to be present on the elevator shaft walls for use as reference points, i.e., raw shafts with visible concrete structure are preferable to white-painted shafts.”

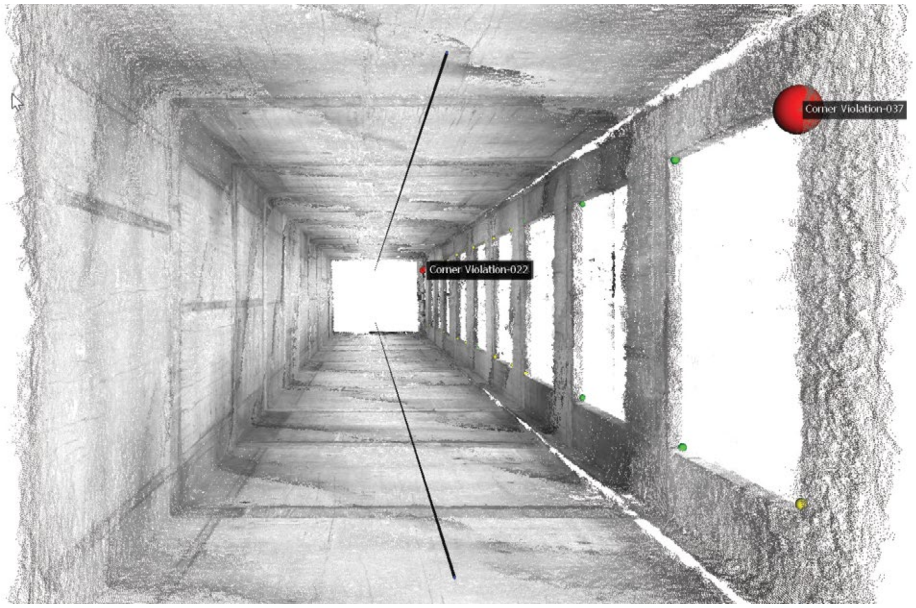

Figure 8. Top view of shaft, with virtual reference lines. Red dots indicate tolerance issues with respect to door placement.

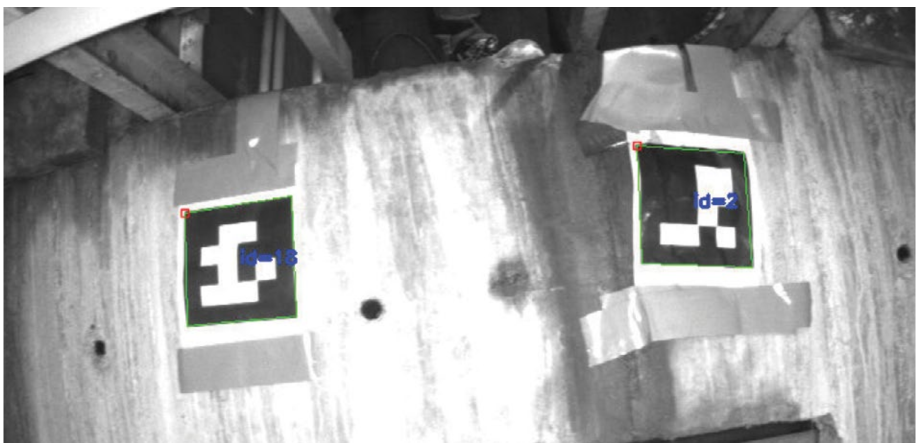

Figure 9. Two AR markers, as detected by the scanning apparatus.

door openings within the admissible adjustment range. The algorithm also indicates if fitting is not possible, and specifies at which elevator shaft door openings corrections have to be made (see Figure 8).

Step 4: Virtual Installation of Elevator

Based on the virtual reference lines obtained in Step 3, virtual elevator guide rails, as well as guide-rail mounting brackets, can be inserted into the 3-D point cloud. While the elevator guide rail placement is straightforward, with a constant shift following the virtual reference lines, the placement of the rail brackets is more complex. Part of the bracket is connected to the rail, and part of the bracket is projected as necessary to the shaft wall, to account for any differential in shaft construction, and to ensure optimal installation. The next step checks whether the admissible adjustment limits of the bracket can be met. This allows evaluation of whether each bracket fits into the elevator shaft or not, prior to elevator installation.

Augmented reality (AR) markers (see Figure 9) recognizable by the camera can be placed in the shaft pit and head, so the

Figure 10. Shaft with complete virtual elevator installation. Red brackets show a tolerance issue.

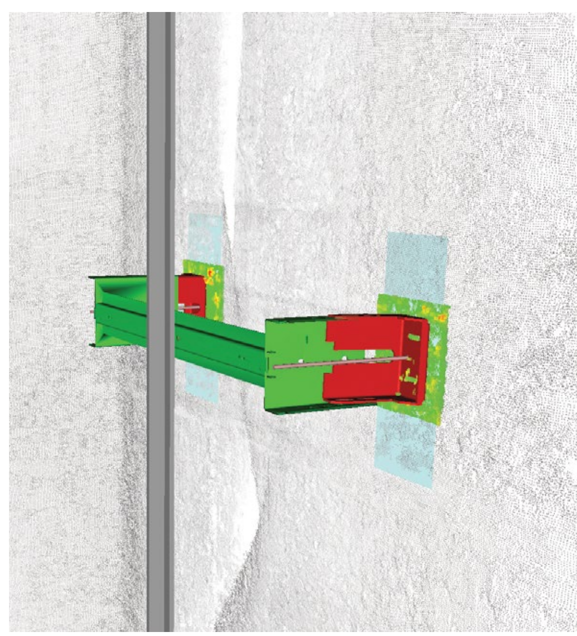

Figure 11. Detailed view of bracket. The insufficient adjustment range of the bracket is visible.

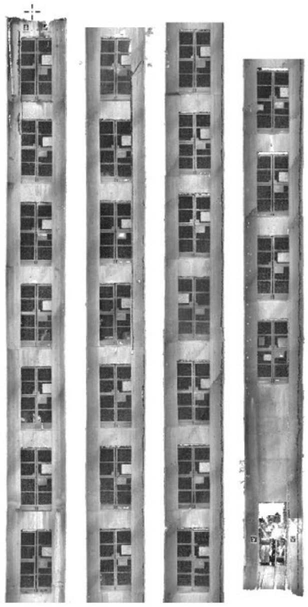

Figure 12. Point cloud of 80-meter shaft (split into four parts).

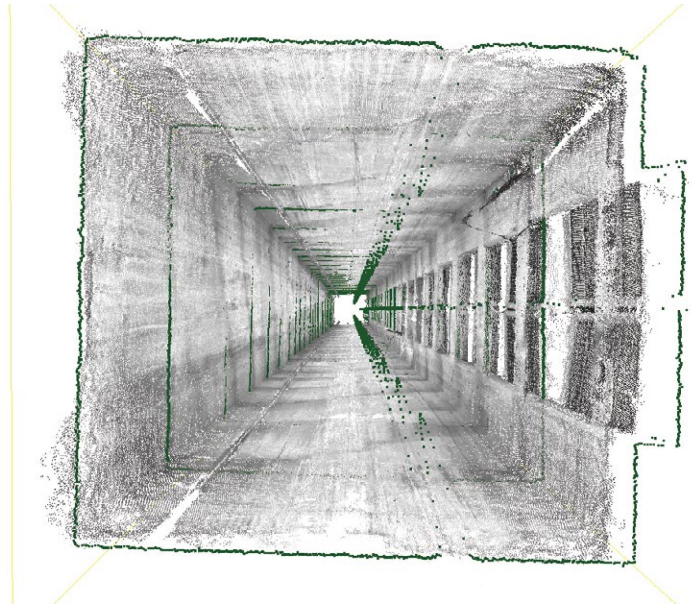

Figure 13. Scanned shaft point cloud, with 2-D laser scans overlaid.

system can indicate where the fitter should mount plumb lines for actual physical elevator installation. Figure 10 shows the elevator virtually installed in the elevator shaft. Figure 11 shows a detail of a bracket with tolerance issues.

The placement of AR markers is advantageous, not only to indicate plumb line positioning, but also for the following two use cases: First, AR markers can serve as references points for elevator placement if several elevators in a group have to be aligned to each other, or to an external reference, such as building axes. In this case, the surveyor can place markers in specific door openings of the elevator shaft, and the system can subsequently align the virtual reference system to these markers. Second, the AR markers can be used to stitch together point clouds of shafts containing multiple elevators, whereas for accuracy reasons, every shaft in the multi-shaft application is measured separately.

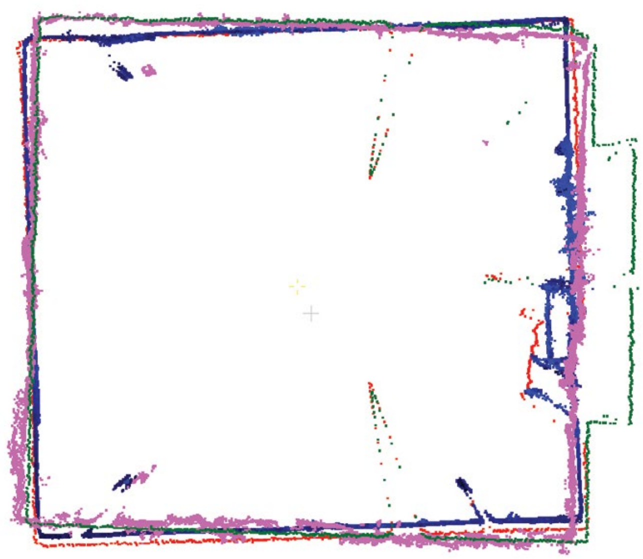

Figure 14. Comparison between point cloud and 2-D laser measurement. Blue and red lines indicate camera and 2-D laser measurements in the pit, respectively. Purple and green curves indicate measurements of camera and 2-D laser in the shaft head, respectively. A slight twist in the shaft is visible.

Case Study

The camera system prototype was tested in an elevator shaft in Hong Kong with a height of 85 meters and 26 floors. The 3-D reconstruction of the shaft can be seen in Figure 12. As a reference, manual measurements were taken in the shaft and a 2D laser scan was made at each floor, both in reference to mounted plumb lines. In addition, the position of the camera-based measurement system was verified by a high-precision position tracking system. Figures 13 and 14 show a comparison of the 2D laser measurement with the point cloud obtained by the camera. For local shaft cross-sections, accuracy in the range of 1 centimeter was achieved. The position accuracy of the sensor over the entire shaft length is shown in Table 1 and Figure 15. This measurement data was obtained by comparing the camera position derived by SLAM and the ground-truth data derived from the position tracking system. On average, the horizontal positioning errors are lower than 1 centimeter, with maximum errors of 2.5 centimeters. The effect of the speed with which the camera is moved in the shaft is clearly visible: Slower movement of the camera system yields much better results than faster movement. In conclusion, these first measurements show the potential of such a camera system. The camera system can be further verified and fine-tuned to get even more accurate measurement results.

Outlook

Digital elevator shaft mapping enables the creation of accurate 3-D models of buildings and opens up new horizons for how elevators might be installed in the future. For example, AR-enabled glasses could be used to guide the elevator installation with unparalleled precision. In the near future, robots could be used to install elevators, and digital twins of the building and all systems could allow back offices to access the actual situation on-site. This outlook goes beyond the discussed use case of shaft tolerance verification and outlines visionary use cases.

Dataset	Vertical Errors		Horizontal Errors	
	Mean (m)	Max (m)	Mean (m)	Max (m)
0844	0.07032	0.16929	0.00612	0.02547
0908	0.06523	0.14120	0.00724	0.02532
0959	0.17554	0.32746	0.01032	0.04168
1014	0.06640	0.11494	0.01017	0.03282

Table 1. Comparison between total station readings, showing horizontal and vertical scan errors.

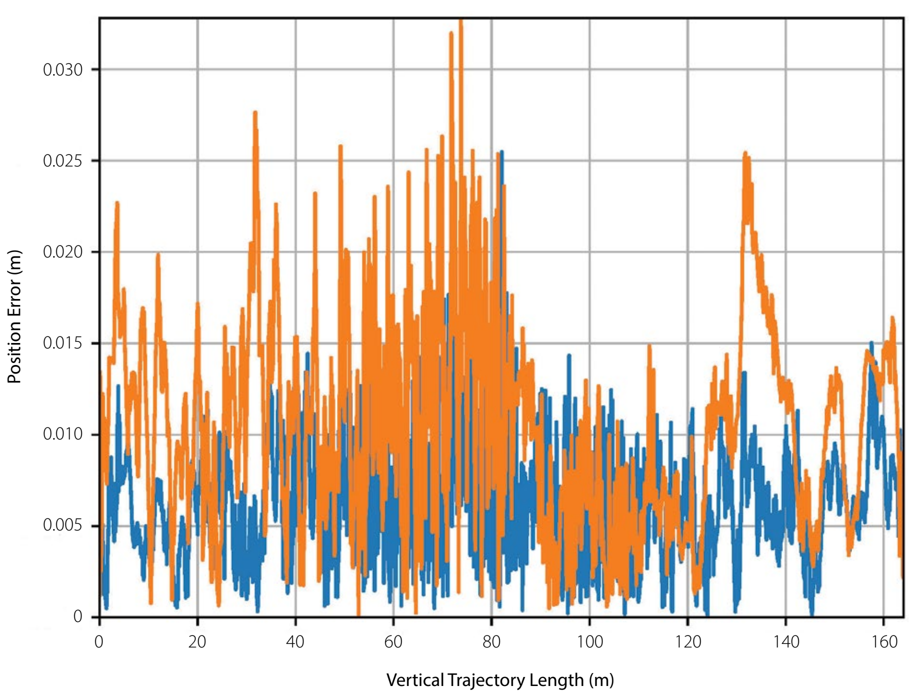

Figure 15. Comparison between all station readings. The horizontal error is plotted over the vertical trajectory length, comparing slow and fast recording sessions.

The Future of Elevator Installation

Today, completely digital planning data for elevators is the norm. But when it comes to installation, a lot of hand measurements must still be done on-site to transform digital planning into reality. The described process of shaft mapping can be used to indicate exactly where each rail bracket is placed and where each hole is drilled—and not in a theoretical computer model, but in the real environment with all associated tolerances. In addition, the camera-based measurement creates a so-called "feature map" of all the optical structure patterning on the shaft walls, alongside the 3-D reconstruction of the shaft. Using this as a reference point, the camera is always able to localize its position in the shaft. This has many implications for the future of elevator installation.

For example, consider if the camera is additionally equipped with a laser pointer. The position of the laser pointer in the shaft is known from the camera, and the exact drill location can be derived from the digital shaft model. The laser pointer can be precisely directed to indicate to the fitter where to drill. The fitter does not need to consult any plans and associated hand measurements, but can proceed straightforwardly with the installation. As a result, there are fewer errors, higher quality and higher efficiency.

Laser-guided installation is simply a first step towards AR-based installation. AR glasses could be used to guide the entire installation, showing not only where to drill, but also how brackets should be mounted, how they have to be adjusted, and where the rails need to be placed. This could guide human installers directly from data in the digital models, closing the digitization gap

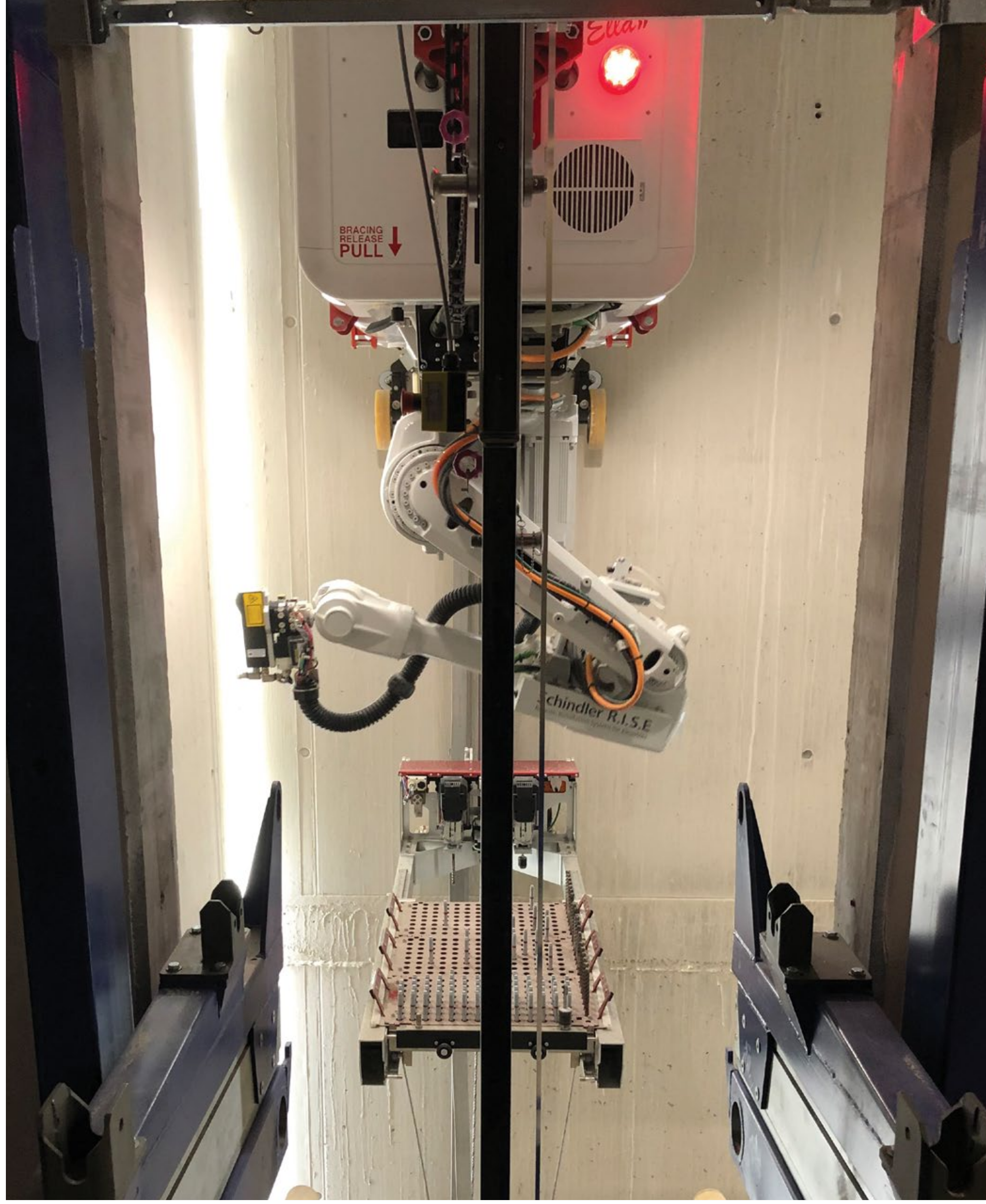

Figure 16. The self-climbing robotic installation system for elevators (Schindler R.I.S.E.) incorporates the technology of the digital mapping device to guide automated elevator system installation.

between digital planning and execution on the construction site.

Digital shaft measurement is also closely connected with an innovation initiative for robotic elevator installation. The authors' firm has pioneered a self-climbing robotic installation system for elevators (Schindler R.I.S.E.) which moves up the elevator shaft, drilling and mounting anchor bolts accurately, with benefits in safety, health, quality, efficiency, as well as a link to digital planning. Currently, the robotic system still uses reference wires, which are spanned in the shaft for orientation, and also incorporates laser scanners as positioning aids. Combined with the digital shaft-mapping system described in this paper, robotic installation can be drastically simplified by directly passing the drilling coordinates to the robot. A picture of the installation robot is shown in Figure 16.

Digital Twin As-Built

In this paper, the focus was on digital elevator shaft scanning and digital placement of elevator components; however, this approach can be applied widely in the building industry. Drone mapping of buildings is increasingly used to document construction progress, as well as to verify that buildings have been built correctly. Advanced laser scanners can measure room size and also indicate points of interest using reflectors. Companies, including Leica and Faro, are using these technologies as inputs to building information modeling (BIM) as-built solutions, and various companies and start-ups are innovating in the creation of digital twins of buildings, including the Schindler-owned startup BuildingMinds.

The use of camera-based imaging and subsequent modeling is especially applicable in modernization projects, in which existing built components must be correctly measured and mapped. Point cloud models can accurately record unprecedented levels of detail with exacting precision. Within modernization projects, architects and planners can start with the point cloud and associated 3-D model of an existing building, and subsequently transform it into the new building within the digital space. As the process of mapping and modeling presented in this paper evolves, there is clear potential for the digital pre-installation of building parts and components into point-cloud models of the real environment, far beyond elevators. This approach is also suited for applications that require a range of levels of precision in installation, including for example, façade or window mounting, suspended ceilings or flooring. Perhaps most similar to elevator installations are mechanical, electrical and plumbing (MEP) installations, where, for example, the described approach could be used to pre-check proper piping in buildings under construction.

Further applications could include prefabricated building components, especially if they come in connection with built in-situ parts of the building, such as floors, staircases or wall elements. With the rising popularity of timber buildings, this kind of application might become especially relevant in the interplay between normative massive construction and prefabricated timber elements. Last but not least, laser scanning and mapping is also gaining popularity in the real estate industry to obtain accurate models of buildings, allowing, for example, the tenants to virtually furnish their rooms before they move in, to get a first impression of the actual layout, and to facilitate planning. ■

Unless otherwise noted, all image credits in this paper belong to Schindler.