Real-World Three-Dimensional Measuring of Built Environment with a Portable Wire-Based Coordinate-Measuring Machine

Samuel Forsman

Abstract

A long-term strategy within the forest products industries is to increase the products' refinement and thus their value. This strategy applies to both primary and secondary processed wood products. Further down the value stream, different kinds of knowledge are needed in order to add value and efficiency in the supplier process. In this study, the focus was on as-built three-dimensional (3-D) sensing as a means to increase the level of product prefabrication when supplying engineer-to-order joinery products to the construction industry. A 7-m ranging three-axis portable wire-based coordinate-measuring machine (PWCMM) was evaluated in terms of performing as-built site-dimensional verification in 3-D. This is a needed means for moving the fitting of joinery products into the digital domain at the design stage, thus increasing the level of prefabrication and automation possible when supplying engineer-to-order joinery products. The PWCMM has been used to replicate different construction sites to gain as-built spatial information as input into the suppliers' design, manufacturing, and on-site assembly processes. The evaluation shows that the accuracy in each coordinate position can be within a millimeter range. However, questions still remain about the capability to meet the demands on accuracy and usability for on-site dimensional verification when supplying joinery products. Issues with error leverage and low measurement resolution limit the practical possibilities in terms of level of accuracy and detail of the reproduction of the as-built environment.

The sawmill industry has a tradition of supplying vast volumes of primary-process wood products with limited refinement value to vast geographical areas. This generates significant export incomes for world-export-leading countries like Canada, the United States, Sweden, and Germany (Swedish Forest Industries 2013). However, these products face challenges with demand, and an expressed strategy within this industry is to increase the products' value refinement. The secondary wood processing industry also struggles with this strategy. This study focused on supplying engineer-to-order joinery products, henceforth referred to as ''joinery products.'' This is a secondary wood-processing industry, with the construction industry as the major customer. Worldwide, the construction industry is one of the most important elements of every economy and the major customer for most wood products. Therefore, increased interaction with this industry has the potential to reveal value-adding opportunities for wood products.

Joinery products are highly refined one-of-a-kind wood products such as entrances, glass partitions, doors, windows, interiors, cabinet fittings, special fittings, stairs, etc., designed to fit specific customer needs. These components are engineered and manufactured in factories off site, where they are packaged and transported to the construction site where they are assembled. This is a process with two main parts: (1) factory production, which is more efficient, and (2) work at the construction site, which is less efficient and/or labor intensive. The amount of labor-intensive work at the construction site is dependent on the level of product prefabrication and on how well the finished joinery products fit the intended location. Reliable as-built spatial data from the construction site are crucial to the manufacture of joinery products that can be assembled efficiently. Currently the assembly work often consumes half of the joinery-product supply budget, and manual fitting of components is a major contributor to the time consumption of the assembly work. Therefore much value refinement can be achieved through improved interaction with the customer and improved on-site assembly efficiency through decreasing

The author is a PhD Student, Dept. of Engineering Sci. and Mathematics, Div. of Wood Sci. and Engineering, Luleå Univ. of Technol., Skellefteå, Sweden (samuel.forsman@ltu.se [corresponding author]). This paper was received for publication in September 2014. Article no. 14-00086.

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spatial uncertainties regarding the environment ambient to the joinery products.

The use of building information models (BIM) is increasingly implemented in the architecture, engineering, and construction (AEC) domain. These semantically rich three-dimensional (3-D) models that store information in a single integrated source were originally developed to enhance planning, visualization, and communication during design, and to aid in the detection of mistakes during construction, process simulation, and space planning during management (Sacks et al. 2004, Akinci et al. 2006, Eastman 2008, Xiong et al. 2013). With a history of being created during design, the as-designed or as-planned,BIMs are the predominate BIMs in the AEC domain. These BIMs may vary significantly from the actual current condition, the as-built or as-is conditions of the facility. These differences arise from a variety of sources, such as undocumented design changes, inadvertent errors in the construction, and renovations during the ensuing period (Xiong et al. 2013). There is, therefore, a need for BIMs based on as-built or as-is conditions. Hereafter as-built is used to refer to both terms. Further, as-planned is used to include to both as-planned and as-designed terms.

The generation and use of as-built geometrical conditions in construction has gained momentum in the research literature, covering such areas as quality-assessment, progress and productivity monitoring, materials tracking, and automated routing for construction vehicles. (Tang et al. 2009, Huber et al. 2011, Turkan et al. 2012, Anil et al. 2013, Argüelles-Fraga et al. 2013, Kim et al. 2013, Xiong et al. 2013, Bosché and Guenet 2014, Bosché et al. 2014). Much focus is on automation of the process of acquiring the as-built geometries from different 3-D sensing technologies (Anil et al. 2013, Kim et al. 2013, Xiong et al. 2013). In the following, I focus on achieving as-built geometries from construction sites that can be used as a means for increasing automation within the process of supplying joinery products.

Uncertainties of as-built geometrical conditions with currently used methods for as-built verification have been shown to cause a number of types of waste in the supplying of joinery products: unnecessary transports, motions, waiting, overprocessing, overproduction, and defects (Forsman et al. 2012). Potentially, much of this waste can be eliminated through different automation actions based on BIMs with accurate as-built geometries and with semantics of the construction process. Here are three examples of automation actions that would eliminate waste: (1) move manual fitting from the end of the supply process to the digital environment early in the supply process in order to allow automatically performed product-to-room fitting and to allow use of numerically controlled machinery to perform the physical fitting on the product components; (2) because of size limitations of in-transport routes on site, design the size of the parcels in the digital domain to optimize on-site delivery; (3) synchronize the supply process to the construction process by ensuring that the environments adjacent to the joinery products have been prepared for the assembly of the joinery products. These examples show that increased certainty of as-built geometrical conditions has the potential to vastly improve the efficiency of supplying joinery products to the construction industry.

The purpose of the study was to evaluate whether a portable wire-based coordinate-measuring machine (PWCMM) is sufficiently accurate and usable to perform practical as-built site verification in 3-D to a level where fitting of joinery products can be performed in the digital domain during design.

The hypothesis is that the PWCMM can eliminate dimensional uncertainties of as-built construction sites to a level on par with joinery-product tolerances and meet practical usability demands. Investigations on sensor accuracy and effects on measurement uncertainty when using the PWCMM functionalities are presented together with accuracy and usability experiences from four cases. The original contribution of this article is on 3-D sensing of construction environments with a PWCMM and generating digital models of the real world that can be used for fitting of joinery products in the digital domain during design.

Theoretical Overview of As-Built 3-D Measuring

Measuring geometries in 3-D is a widely used technology in many different industrial applications. The general purpose is to achieve as-is geometrical information of the measured object (Pereira and Hocken 2007, Cuypers et al. 2009, Barini et al. 2010). The culture of ensuring the correct geometrical shape of components has been the foundation for industrialized processes. This is exemplified by Henry Ford and the use of interchangeable components. Currently three major technology categories can be identified: (1) coordinate-measuring machines; (2) laser scanners; (3) optical measuring techniques. These three methodologies are used in different industrial contexts and with a different resolution and scale depending on application. In the following, focus is on coordinate-measuring machines (CMMs).

CMMs translate the positions of the measurement probe to a 3-D coordinate system (Schwenke et al. 2008). Two types of CMMs can be identified: conventional CMMs and portable CMMs. Conventional CMMs are stationary and are widely used in control stations in the manufacturing industry. These are highly accurate (0.3 to 2.0 μm), but they normally control positions on an object with a known 3-D model rather than depicting an object and generating a 3-D model from the coordinate observations (Barini et al. 2010, Leitz Metrology 2014, Nikon Metrology 2014). Two types of portable CMMs are most common, articulated arm coordinate-measurement machines (AACMMs) and optical portable CMMs. The AACMMs are measurement arms and have five to seven rotary joints or axes and measure with ASME B89.4.22 single-point accuracy of 20 to 140 μm within a working range of a 1.5- to 4.5-m radius (American Society of Mechanical Engineers [ASME] 2004, Sładek et al. 2013, Hexagon Metrology 2014). Optical portable CMMs are optical camera-based triangulation systems with a handheld probe. The probe positions are sensed through markers on the probe, whose position is compared with a set of reference markers. The ASME B89.4.22 single-point repeatability is 37 to 95 μm, and the working range is a coordinate system up to 17 m^3 (Cuypers et al. 2009, Creaform Measurement Solutions 2014, Nikon Metrology 2014).

The majority of research about CMMs concerns conventional CMMs, and Cauchick-Miguel et al. (1996) claimed that their measurements could be influenced by a wide range of errors. This is reflected in much of the subsequent research, for example, uncertainty in coordinate measurements (Wilhelm et al. 2001), sources of geometry errors (Schwenke et al. 2005, 2008), dynamic errors of CMM (Jinwen and Yanling 2011), and separation of machine and probe errors (Nafi et al. 2011). Much of this research is about understanding measurement uncertainty and suggests that the levels of uncertainty of the conventional CMMs are small in relation to geometric accuracy in the construction industry. However, conventional CMMs are stationary and therefore not feasible for measuring as-built geometries at construction sites.

The research on portable CMMs is more limited, but still, considerable effort has been devoted to understanding the uncertainty of the measurements and calibration and error correction. Shimojima et al. (2002) suggests a calibration method with better performance than the accuracy specified by the manufacturer. This is needed because of difficulties with traceability of the measuring machine, since calibration is done by the manufacturer and by an unpublished method, a situation similar to the studied PWCMM. Other research deals with identification and modeling of the AACMM errors and proposes correction handling for improving performance (Santolaria et al. 2008, Sładek et al. 2013) or finding the optimal measurement area (Zheng et al. 2012) or suggests correction models for thermal errors that do not affect the calibration conditions (Santolaria et al. 2009). No use of portable CMMs in construction and joinery-production contexts has been identified.

In construction-related research of as-built measuring, other 3-D sensing technologies are used, most commonly laser scanning. The focus on measurement accuracy in this research is limited, but some research that quantitatively investigates the accuracy of laser-scanner data finds that mixed pixel removal can cause significant measurement errors (Tang et al. 2009). Further, it found that laser-scanner resolution, distance to object, object color, object radius, and laser-beam intensity are the five variables contributing the most to the measurement error (Shen et al. 2013). Little focus is on tolerances and on lowering the uncertainty of scanning to achieve dimensional reliability and information needed in terms of ''Productive Metrology'' (Kunzmann et al. 2005). A guide for planning 3-D imaging of built environments specifies general levels of accuracy and levels of detail (US General Services Administration 2009), but there are not any definitions of accuracy needed for different guilds of the construction work. Since the guild of supplying joinery products is even less represented in the research literature, this is also valid for that guild. Therefore, much of the needed measurement accuracy is situation dependent, and this impedes classification of suitable products for as-built measuring at construction sites.

Methods

3-D sensing of as-built construction site geometries with a portable wire-based coordinate-measuring machine, the Proliner 8 (Prodim 2014), was studied in the context of supplying joinery products. Machine accuracy and usability were analyzed from the perspective of increasing automation within the supply process by moving the product-to-room fitting to the digital environment. Machine capabilities were examined, and data from four cases were captured through interviews, direct observations, participation, and control of documentation. Documentation from notes, photographs, and documents was the basis for analysis.

In these cases, the PWCMM was used for 3-D sensing of as-built construction-site dimensions. The machine capabilities and case experiences of the PWCMM measuring have been evaluated against the potential of eliminating spatial uncertainties through the following criteria:

1. Accuracy, i.e., opportunities to eliminate spatial uncertainties of the construction site to a level on par with claimed tolerance requirements on joinery products (± 1 mm) and preferably meeting the ''golden rule of metrology,'' wherein measurement uncertainty should not exceed a tenth, or at most a fifth, of the tolerance requirements, thus ± 0.1 to 0.2 mm (Beckert et al. 2010).
2. Usability, i.e., opportunities for adapting the technology to the joinery-product supplier's process. This concerns issues such as measurement range, portability, information quality, efficiency in performing measurements and the necessary data processing, level of expertise needed to operate and to reconstruct 3-D geometries for measurement purposes, quality improvements in project information communication, and ways information quality might enhance the manufacturing and on-site assembly processes.

Accuracy testing of PWCMM sensors

The Proliner 8 PWCMM registers the position of a stylus probe as coordinates in a Cartesian coordinate system. The stylus probe is connected to the machine with a wire extracted from a measurement arm that can rotate in both horizontal and vertical directions (Janssen 2004, Prodim 2014). The machine has three sensors, one for the wire extraction, a second for the measurement arm's horizontal position, and a third for the arm's vertical position. The range of the wire is up to 7 m, and the measurement arm can be rotated 402° horizontally and 104° vertically. Coordinate registrations are performed with a stylus probe positioned on an object, and the user operates a remote control to order the machine to register that position (Fig. 1). The measurements are presented to the user on the screen of the PWCMM. The output data from the PWCMM measurements are stored as DXF files that can be transferred to most computer-aided design (CAD) software.

To test the accuracy of the PWCMM, the random error of measurement registrations when using the PWCMM was measured. This gives a PWCMM user an understanding of the possible accuracy that could be expected from the measurements without the need for special equipment. By using only supplied components, this test can be performed by any user of the PWCMM.

The experimental setup uses the PWCMM and four mobile reference targets. With these reference targets glued to the ground, fixed measurement registrations can be made owing to the support they provide to the stylus probe of the PWCMM. Each measurement position in the tests uses these to fix the measurement probe when recording the observations. The performed sensor tests use a fully randomized design with 30 replicates.

Wire-extraction sensor test setup.—The setup for testing the accuracy of the PWCMM wire-extraction sensor used four reference targets fixed on the floor along the 7-m range of the wire extraction (Fig. 2). The wire-extraction positions recorded were 100, 280, 470, and 650 cm from the machine origin. The horizontal sensor position was fixed, and the vertical sensor positions were 11°, 5°, 3°, and 2°. In the

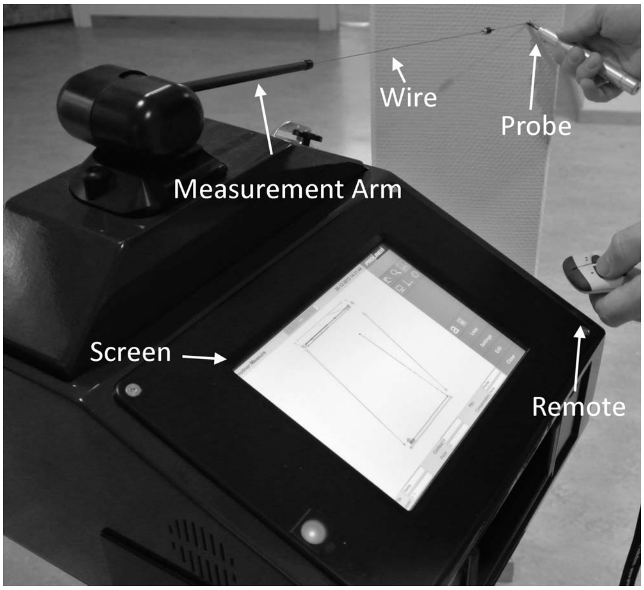

Figure 1.—The tested portable wire-based coordinate-measuring machine with its wire-connected measurement probe. The measurement arm has fixed ranges for horizontal and vertical rotation, 402° and 104°, respectively.

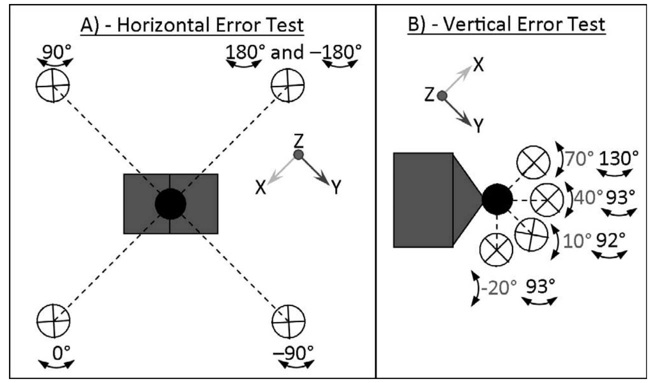

Figure 3.—Setup for testing measurement-arm position sensors. (A) Horizontal sensor was tested at five arm positions: –180°, –90°, 0°, 90°, and 180°. (B) Vertical sensor was tested at four arm positions: –20°, 10°, 40°, and 70°. The horizontal position could not be fixed, and it varied from 92° to 130°. In both figures the XYZ *data show the orientation of the coordinate system.*

Cartesian space the *X*-direction represents the wire-extraction position, the *Y*-direction represents the horizontal sensor position, and the *Z*-direction represents the vertical sensor position.

Horizontal and vertical sensor test setup.—For the horizontal sensor accuracy testing, the PWCMM was positioned horizontally on the floor with four reference targets positioned along the measurement arm's 402° horizontal range (Fig. 3A). The reference targets were positioned with 90° intervals from the beginning to the end of the horizontal range at –180°, –90°, 0°, 90°, and 180° positions. The 180° position reused the same reference target positions as the –180° recording. Each position has a wire extraction of 700 mm from the machine origin. In the Cartesian space the *X*-direction goes along with the axis between the 180° and 0° positions, the *Y*-direction goes along the axis between –90° and 90° positions, and the *Z*-direction goes out from the image plane.

For the vertical-sensor accuracy testing, the PWCMM was positioned vertically on the floor. Four reference targets were closely positioned on the floor allowing a vertical motion of the measurement arm at –20°, 10°, 40°, and 70° positions along its 104° range (Fig. 3B). Each position has a wire extraction of 300 mm from the machine origin. The horizontal motion of the measurement arm was not fixed; the horizontal positions were 93°, 92°, 93°, and 130°. In the Cartesian space the *X*-direction goes along with the axis between the –20° and 70° positions, the *Y*-direction goes perpendicular to the *X*-direction in the image plane, and the *Z*-direction goes out from the image plane.

Responses.—In the test of accuracy of the machine's three sensors, the variability of measurements from four positions was used. Owing to the recording of the PWCMM positions being made in a Cartesian coordinate system, the data are stored as three numerical values, *X, Y,* and *Z*. The coordinate values from the four positions needed to be compared between the measurement positions.

The chosen design for this comparison was to calculate the size of a response vector from the center of gravity for each of the measurement positions. The center of gravity was found by using the mean of each *X, Y,* and *Z* coordinate value among the 30 replicates. Equation 1 shows the calculation of the position of gravity, X_{PG}, for the *X*-coordinate value for one of the four test positions.

$$\overline{X_{PG}} = \sum \frac{X_n}{30} \tag{1}$$

where X_n is the *n*th *X*-coordinate value for one of the four test positions. This was also repeated for the *Y*- and *Z*-coordinate values and for each test position. In this way the center of gravity was established at each test position. Then a response vector was calculated as the distance from the

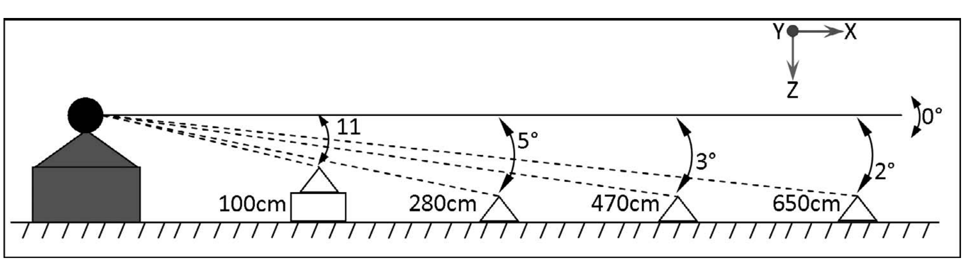

Figure 2.—Setup for testing the wire-extraction sensor. The four tested wire-extraction positions, 100, 280, 470, and 650 cm, are shown together with the four different vertical positions of the measurement arm. The horizontal position was fixed. The XYZ *data show the orientation of the coordinate system.*

center of gravity for each measurement recording by using Equation 2.

$$XYZ_{RV} = \sqrt{(X_{RP} - \overline{X_{PG}})^2 + (Y_{RP} - \overline{X_{PG}})^2 + (Z_{RP} - \overline{X_{PG}})^2} \quad (2)$$

where X_{RP}, Y_{RP}, and Z_{RP} are the coordinate values for each measurement recording, which were compared with the center of gravity for each test position. With the center of gravity treated as a reference value, the response vector represents an absolute value of the error of each measurement recording. Now the variability of the random error of the PWCMM can be represented. The response vector XYZ_{RV} is used for all of the performance evaluations of the PWCMM sensor accuracy.

An analysis of variance (ANOVA) was performed for significance testing of the measurement error contributions of the machine's three sensors. A Tukey's pairwise comparison (Tukey 1953) was performed to control whether the measurement error at the tested factor positions differed significantly between each other. It was assumed that if the random error is low, the relative accuracy is high, thus ignoring the systematic error.

Testing of PWCMM leap function

The PWCMM has a function called leap to extend the measuring range by relocating the machine while maintaining measurements before and after relocation in the same coordinate system. Four reference targets are measured before and after machine relocation, and the positions of these are used to calculate the new position of the machine after relocation (Fig. 4).

The PWCMM leap function was tested by measuring an 88-m-long corridor wall with a series of nine machine relocations (leaps). The mismatch error of each leap was tested by measuring the position of two fixed reference targets on the wall before and after each leap (Fig. 4). There was a set of two reference targets for every performed leap along the 88-m distance. The upper wall reference for each set of two wall references was aligned to a horizontal line laser projection from a Leica Lino L2 (Leica Geosystems 2014). The individual leap mismatch error, in size and direction, was measured as the difference in position for each of the two wall references before and after machine relocation. This was compared with the mismatch information displayed by the PWCMM. After each leap, the absolute mismatch error was measured as the distance from the registered position of upper wall reference target to the horizontal laser reference line. The absolute error was measured in a two-dimensional sense because of the absence of a three-dimensional reference. The horizontal accuracy of the Leica Lino L2 line laser is ±1.5 mm/5 m. Two test runs were performed.

The four cases

Four case studies have been carried out with different levels of complexity. Measurements have been performed with the tested PWCMM, a Proliner 8. A Leica Lino L2 line laser was used to create horizontal or vertical reference lines that were used to control orientation of the Cartesian coordinate system when modeling the measurement data. The measurement data were exported from the PWCMM to Solid Work CAD software, where they were refined into 3-D models.

Case 1 was a room-section contour measured for supplying prefabricated wall and glass partitions including doors to an industrial premise being rebuilt into an office environment. The measurement was performed as two contour measurements where the wall and glass partitions were to be positioned. The two contours were measured separately and aligned manually in CAD software. No leap function was used.

Case 2 involved measuring conference room wall surfaces for an indoor wooden panel system and measuring a series of office contours that will receive prefabricated wall, door, and window partitions, constituting the office rooms against the office corridor. The conference room wall

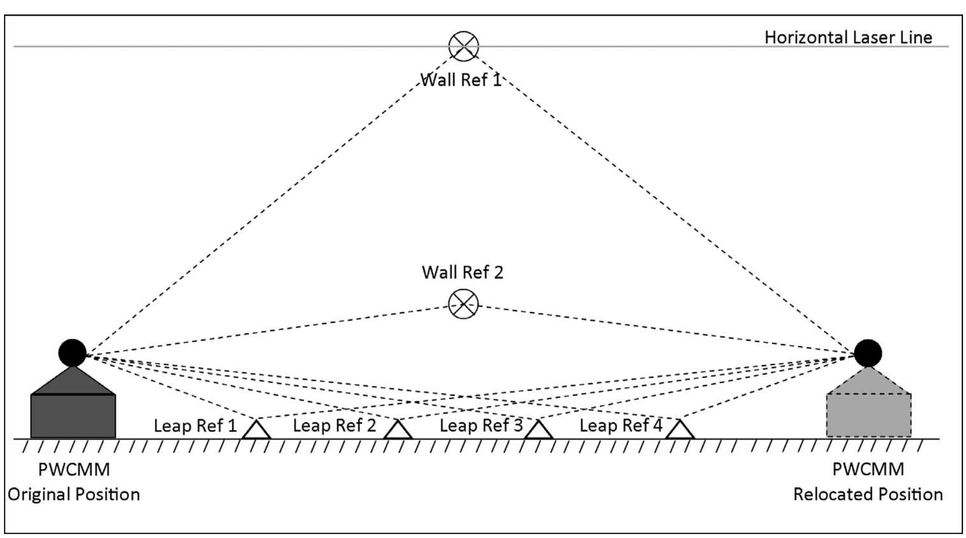

Figure 4.—Setup for leap function testing. The figure shows how leap references on the floor and the wall references are measured before and after portable wire-based coordinate-measuring machine (PWCMM) relocation. The upper wall references were aligned to a horizontal laser line projection. The PWCMM uses the leap references to calculate its new location in the coordinate system. The wall reference measurements show the size and orientation of the introduced error. The measured deviation from the laser projection gives the absolute error after the series of relocations.

surfaces were measured by defining the surface planes with three coordinates and then measuring the contours of these wall segments. For the series of offices, the PWCMM's leap function was used to extend the range in order to measure the series of office booths. Measuring the office's rectangular contours was done with two coordinate registrations for each side of the contour. Before relocating the machine, four reference targets were registered with the leap function. After relocation, the same reference target positions were registered. This allowed the leap function to calculate the new machine position so as to maintain the new measurements within the original coordinate system.

Case 3 involved measuring a complex-shaped object of large scale, a 12-story staircase, where the joinery-products supplier was to develop, manufacture, and assemble a staircase railing system in solid wood. The inside profiles of all staircase sections were measured as contours of a number of both small and large surface planes. Each of the 12 floors' staircases was measured separately with a single positioning of the PWCMM. No leap function was used here. For every floor, a horizontal reference laser line was projected against the side of the floor sections of the staircase. Before performing the full measurement, the measurement method was tested by manufacturing and assembling three prototype railing sections based on the PWCMM measurements. After refining the measurement data to a 3-D model, floor-height measurements in the model were compared with manual steel tape measurements and drawing.

Case 4 involved the measurement of a building with complex exterior and internal shapes with curved walls or other than 90° wall–wall alignments. The materials supplied involved shelf systems, clothing wardrobes, reception desks, visitor seating, wall panels, a ''hidden'' door in line with a wall panel system, postboxes, etc. (Fig. 5). The PWCMM measuring was performed twice with two different methods. The first was a plan projection method, where the floor plane was defined with three coordinates, and then the positions of the walls were measured close to the floor and projected onto the floor plane, from which the wall surfaces then were extruded vertically. In the second surface-measuring method, the machine stylus probe was swept over the wall surfaces to register many coordinates. Then the wall surface planes were defined by averaging the measured coordinates of each wall surface. By this means information on the walls' vertical alignment was captured. The corners between walls and wall-to-floor were defined as the intersections between the surface planes. In both these measurements the range of the PWCMM was insufficient, and the machine's leap function was used with one machine relocation. Differently colored models from the two different measurement methods were compared mutually in CAD software. The models were superposed on each other to illustrate the mutual differences. Complementarily, a laser scanning measurement was performed by an external contractor using a Leica Scan Station C10, to which the PWCMM measurements were compared.

Results

PWCMM sensor accuracy

A 3-D scatterplot for each of the three sensors, the wire-extraction sensor, the horizontal and vertical position sensors, shows how the measurement recordings are distributed around the measurements' center of gravity (Fig. 6). For the wire-extraction sensor positions, the error spread is ±0.8 mm in the *X*-direction, ±0.5 mm in the *Y*-direction, and ±1.9 mm in the *Z*-direction (Fig. 6A). The error spread for the horizontal sensor positions is ±0.95 mm in the *X*- and *Y*-directions and ±0.5 mm in the *Z*-direction (Fig. 6B). For the vertical sensor, the error spread is equal in all three directions, ±0.25 mm (Fig. 6C). Note that *X*-, *Y*-, and *Z*-directions cannot be compared between the tested sensors owing to different Cartesian orientations in the setup.

The size of the measurement error that can be expected at each PWCMM measurement registration depending on the sensor positions is shown by the confidence interval plots (Fig. 7). The wire-extraction sensor gives absolute errors in the range 0.27 to 0.35 mm at the 100-cm position, and 0.78 to 1.13 mm at the 650-cm range, both with a 95 percent individual confidence (Fig. 7A). The horizontal- and vertical-position sensors show a more constant contribution to the measurement error along their working range (Figs. 7B and 7C). Note that the measurements for the horizontal and vertical sensors use different amounts of wire extraction, which explains the difference in size of the mean error between them. A one-way ANOVA shows that there are significant differences in error size between the wire-extraction sensor positions. For the horizontal- and vertical-sensor positions, there are no significant differences in error size between different sensor positions. A Tukey's pairwise comparison between wire-extraction sensor positions shows that the measurement error at 100 cm is significantly lower than at other wire-extraction positions.

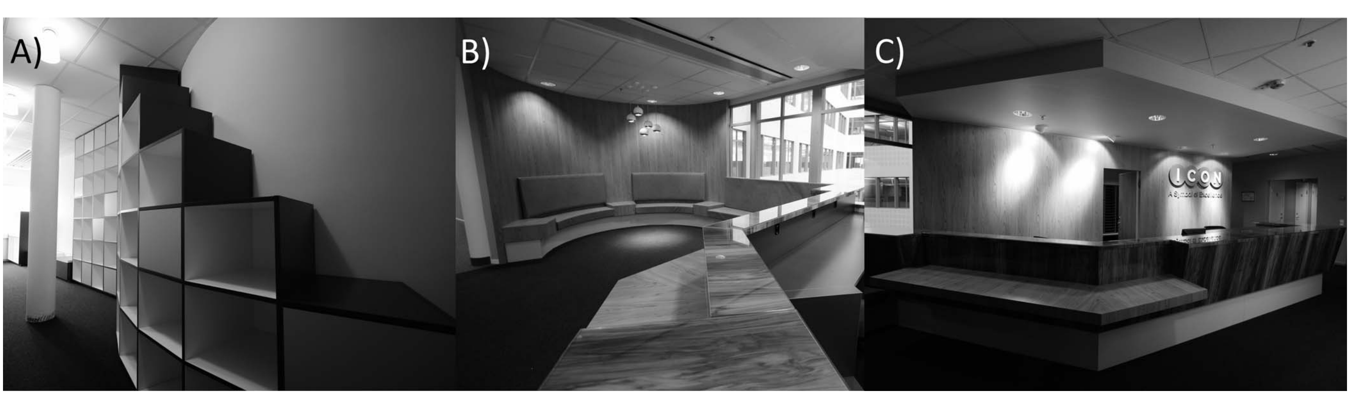

Figure 5.—Examples of supplied products from Case 4: (A) a floor to ceiling shelf system; (B) a visitors' seating area with wall-integrated seating; (C) reception desks.

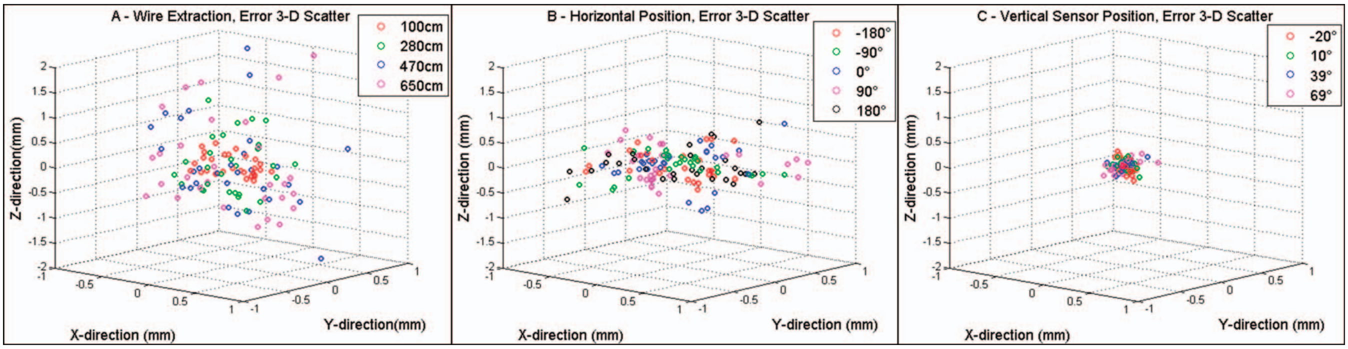

Figure 6.—Scatterplots of the three portable wire-based coordinate-measuring machine sensors show the error distribution in the three XYZ *directions. The different colors represent the different test positions. (A) Errors from the wire-extraction sensor, (B) errors from the horizontal sensor, and (C) errors from the vertical sensor.*

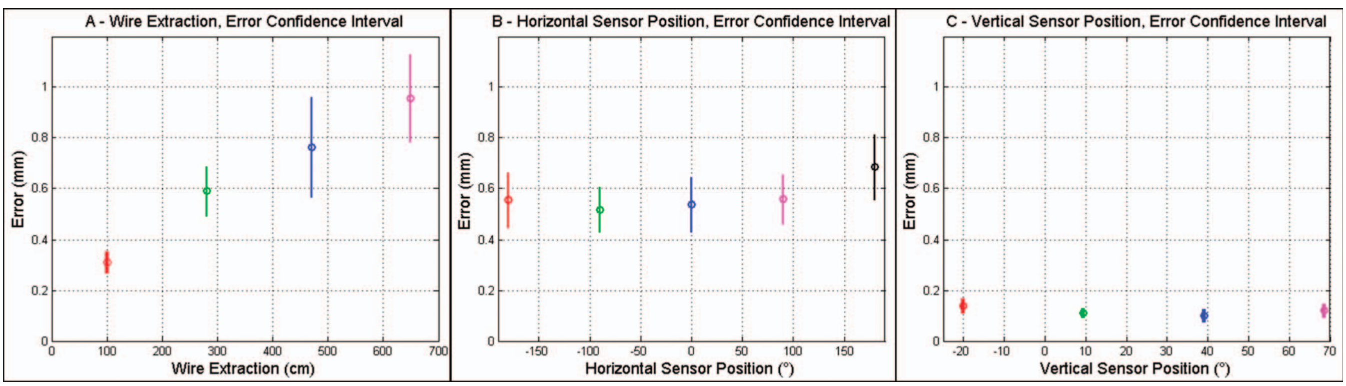

Figure 7.—Ninety-five percent individual confidence intervals along the range of the three portable wire-based coordinate-measuring machine sensors: (A) wire-extraction sensor, (B) horizontal sensor, and (C) vertical sensor.

The measurement error at 280 cm is significantly lower than at 650 cm, but not significantly lower than at the 470-cm position. The errors at 470 and 650 cm do not differ significantly.

Tested leap-function performance

Measurements of the 88-m-long corridor with a series of nine PWCMM relocations, or leaps, show that the measured individual mismatch errors for each of the leaps are larger than on the user information given from the machine (Figs. 8A and 8B). The machine's user information shows mismatch errors in the range of 0.5 to 2 mm (CMM-Info), while the measured mismatch ranges from 0.25 to 6.5 mm (Ref1 and Ref2). The mismatch error has irregular orientations. As the leap series continues, the measured absolute mismatch error is significantly larger than the accumulated individual mismatch errors (Figs. 8C and 8D). Here, the absolute error reaches values of hundreds of millimeters. The absolute error can also change directions (Fig. 8C).

Case results—Accuracy and usability

In Table 1 is an overview of accuracy and usability experiences from the four cases presented here.

Results of Case 1: Factory to office restoration.—This first case was seen as successful by the joinery-product supplier who used the processed measurement data in the design modeling of their product (Fig. 9). The joinery products were assembled on-site without measurement-related problems. However, some accuracy and usability issues were noticed (Table 1).

Results of Case 2: New supplier office.—In the second case the processed measurement model of the conference room showed uncertainties that became evident on studying the corners and the way the measured surfaces met each other. In the six measured corner points, there were mismatches of 0.43, 1.46, 2.36, 3.44, 5.54, and 8.68 mm (Fig. 10). The measurement of the series of offices for glass partitions caused trouble for the PWCMM extension of the measurement range, the leap functionality. In one of three trials with the leap function, the PWCMM responded with mismatch information of 5.2, 1.99, and 42.05 mm after each of the three machine relocations. Finally, in all three trials, the PWCMM could not calculate its new position after relocation. Ultimately, the PWCMM measurement could not contribute to the supply of the series of wall and glass partitions. The summary of case experiences shows some accuracy and usability issues but also advantages over manual measuring techniques (Table 1).

Results of Case 3: Staircase railing.—In Case 3, a 12-story staircase was measured with the PWCMM. The process was to measure on site, process the measurement data to a 3-D model, align the product model to the measured model, manufacture the product, and finally assemble it on site (Fig. 11). The first test measuring and measurement-based manufacturing and assembly of prototype railing sections was successful. However, in the following full measuring of the 12-story staircase, a number

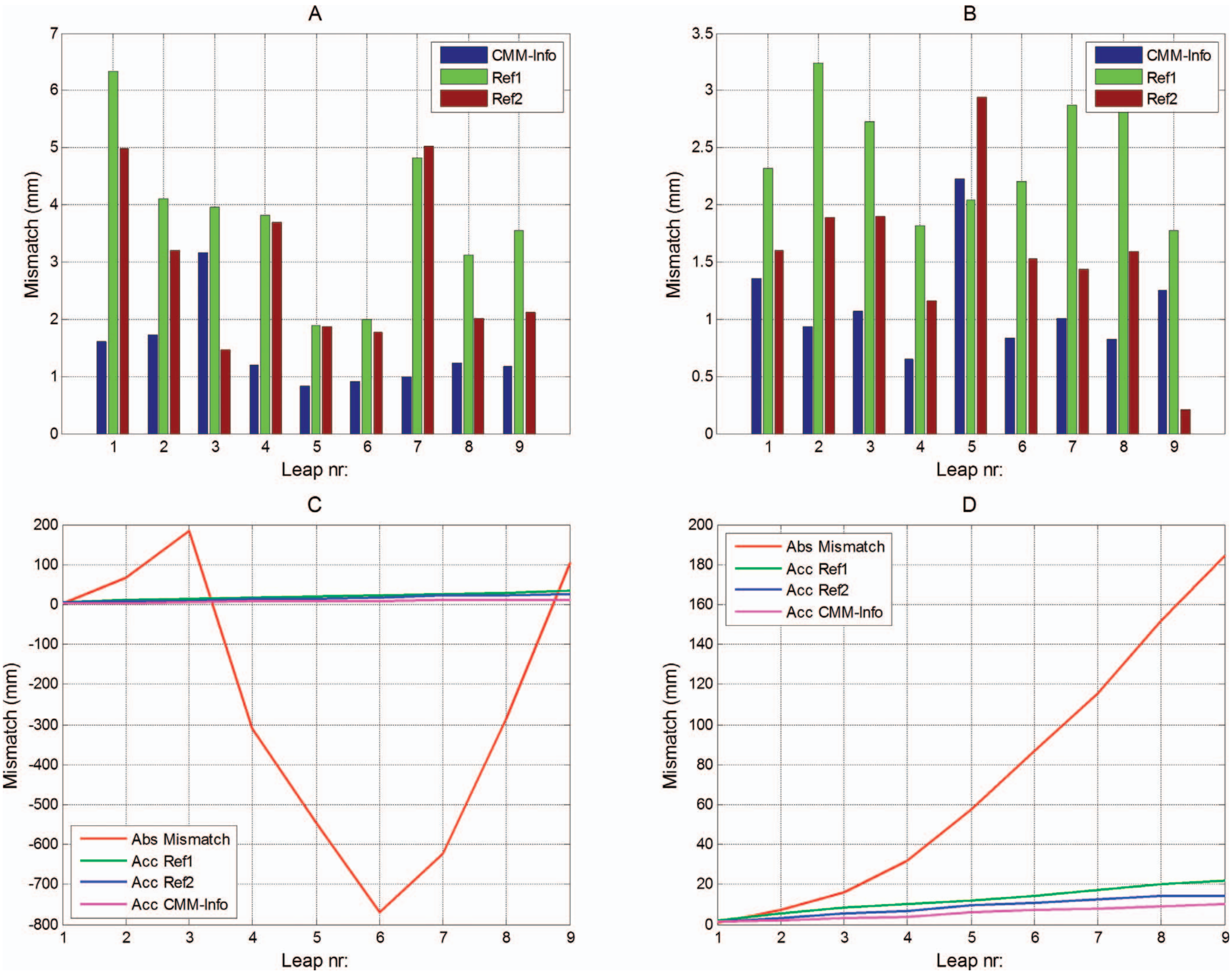

Figure 8.—Mismatch introduced using the portable wire-based coordinate-measuring machine (PWCMM) leap function. (A and B) Measured individual mismatch versus machine mismatch information for the two test runs (green and wine-red bars vs. blue bars). (C and D) Measured absolute mismatch (red line) versus accumulated measured individual mismatch (green and blue lines) and accumulated individual mismatch information given from the PWCMM (pink line). Absolute mismatch = measured deviation between wall reference and the laser projection in Figure 4.

of uncertainties of the measurements were revealed when processing the measurement data. For example, some measured surface planes were not parallel or perpendicular to each other, as they were expected to be. These deviations often resulted from one erroneous coordinate registration, or error leveraging, when defining one of the planes in the PWCMM model. Further, small angular deviations of surface planes were found that could easily be thought reliable, since measured objects likely contain small irregularities that owing to leveraging can have a large effect on accuracy. These were recurring problems affecting the measured floor heights and staircase contour size, measures defined in the architectural drawings. Owing to these uncertainties and the fact that processing the 3-D model based on measurement data was time-consuming, the supplier chose to process the full 12-story 3-D model based on architectural drawings.

Floor heights from both the PWCMM model and the steel tape measures were different from the heights specified in the architectural drawings and were also different from each other (Fig. 12). Sometimes the measured floor heights are close to each other, sometimes not, which indicates measurement uncertainties. However, these differences are still within the requirements of the Swedish building code (Hus AMA 1998). The case-experience summary shows many accuracy and usability issues (Table 1).

Results of Case 4: Office reception interiors.—In the fourth case, the two different PWCMM measurement methods—the plan-projection measuring method and the surface-measuring method—give somewhat different measurement data, while the resulting 3-D models are similar (Fig. 13).

Superposing the models from the two measuring methods confirms the similarities (Fig. 14). However, with the example measurements, displayed as A1 to A3 and M1 to M5, and the wall W1, differences between the two models can be distinguished. The wall W1 shows the most visible difference, which is explained by the facts that the

Table 1.—Case accuracy and usability experiences.

Accuracy experiences	Usability experiences
Case 1	
• 0.9-mm uncertainties discovered on replicated measurements of a contour line • Uncertainty whether the contour measurements were correctly positioned	• Easy to measure the contour line • Line laser projection would have been useful to correctly position the contour measurement • Range was insufficient • Successful delivery with good prefabricated fit
Case 2	
• Corner mismatch of meeting contours due to error leveraging when defining surface planes with three coordinates • Leap function caused significant mismatch error indications, up to 42 mm • Comparison to manually performed laser distance meter measurements of room opening gave differences in measures up to 14.58 mm • Measuring of opposite walls showed deviations from wall parallelism up to 17.40 mm	• Difficulty measuring all positions due to construction-site obstacles, thus affecting practical range • Errors easily pass undetected during modeling if the intersections of the measured objects are not carefully zoomed • Supplier engineer discarded measured data as a result of lack of confidence • Machine positioning (horizontal/vertical) affects error sensitivity • Leap function wasn't feasible for narrow corridor measurements • PWCMM measurements are relational, giving information on vertical alignment of walls • Reference line or plane from line laser useful
Case 3	
• Small surface planes limit the accuracy of plane definition • Uncertainties from manual aligning of floor-to-floor models • Erroneous measurements difficult to notice during measuring • Difficult to judge whether measurements are accurate • One floor plane was measured as tilted 0.58° because of a 45-mm height distribution between three measured coordinates • Floor-height measurement comparison shows differences in results	• Sufficient measurement data were not practically possible to acquire to process an understandable 3-D model; additional information was added during modeling • Range barely sufficient to measure one floor-to-floor stair section • Leap function wasn't practically feasible • Modeling was time consuming • Errors small in relation to measured object hardly detectable on PWCMM screen • PWCMM users often do not see the screen when performing measurements
Case 4	
• 3-mm deviations caused by PWCMM leap function observed • Double curvature on surfaces not detected • Curved wall measured as flat surface plane due to visually undetected curvature • Measuring method used affects accuracy performance	• Range was insufficient; one machine relocation was performed using the leap function • Difficult to capture double curvature of surface planes • Not practically possible to capture all construction-site details and surface curvatures • Difficult to understand captured data on the PWCMM screen

surveyor did not measure it as a curved wall with the surface measuring method and that it was a continuous wall that was not measured in total by either of the two methods.

Of the two different PWCMM measurement methods, the measures A1 to A3 and M1 to M5 from the surface-measuring method were closer to the measures from the laser-scanning 3-D model (Fig. 15). The maximum deviation between the PWCMM measuring methods was 0.07° and 7.9 mm for measures A1 to A3 and M1 to M5. These are differences that are visually difficult to detect that can have substantial effect for a joinery-product supplier.

Further, an advantage of the surface-measuring method was that it captured the presence of nonvertical walls at the construction site. It can be seen how the surfaces of the superposed models intersect each other, which is because of the presence of nonvertical walls in the model of the surface-measuring method (Fig. 16). This was not captured by the plan-projection measuring method.

Again, the case-experience summary shows many accuracy and usability issues (Table 1).

Analysis and Discussion

The desired result of testing the PWCMM is that the uncertainties of the as-built geometrical dimensions of the construction site can be reduced to a level that allows joinery-product fitting to move to the digital environment early in the supply process instead of being performed manually at the end of the supply process. This has the potential to vastly improve the efficiency of supplying joinery products to the construction industry. To achieve this, measurement errors on par with tolerances for joinery products (± 1 mm), preferably meeting the golden rule of metrology, must be achieved.

Sensor accuracy

The testing of the three PWCMM sensors shows that the amount of extracted wire is the source of the most significant effect on the size of the PWCMM random error. For the error from wire extraction, the largest error contribution is in the *Z*-direction (Fig. 6). The error in *X*- and *Y*-directions is smaller than the total error of the horizontal sensor. The test setup for testing the wire extraction also involves a vertical movement of the

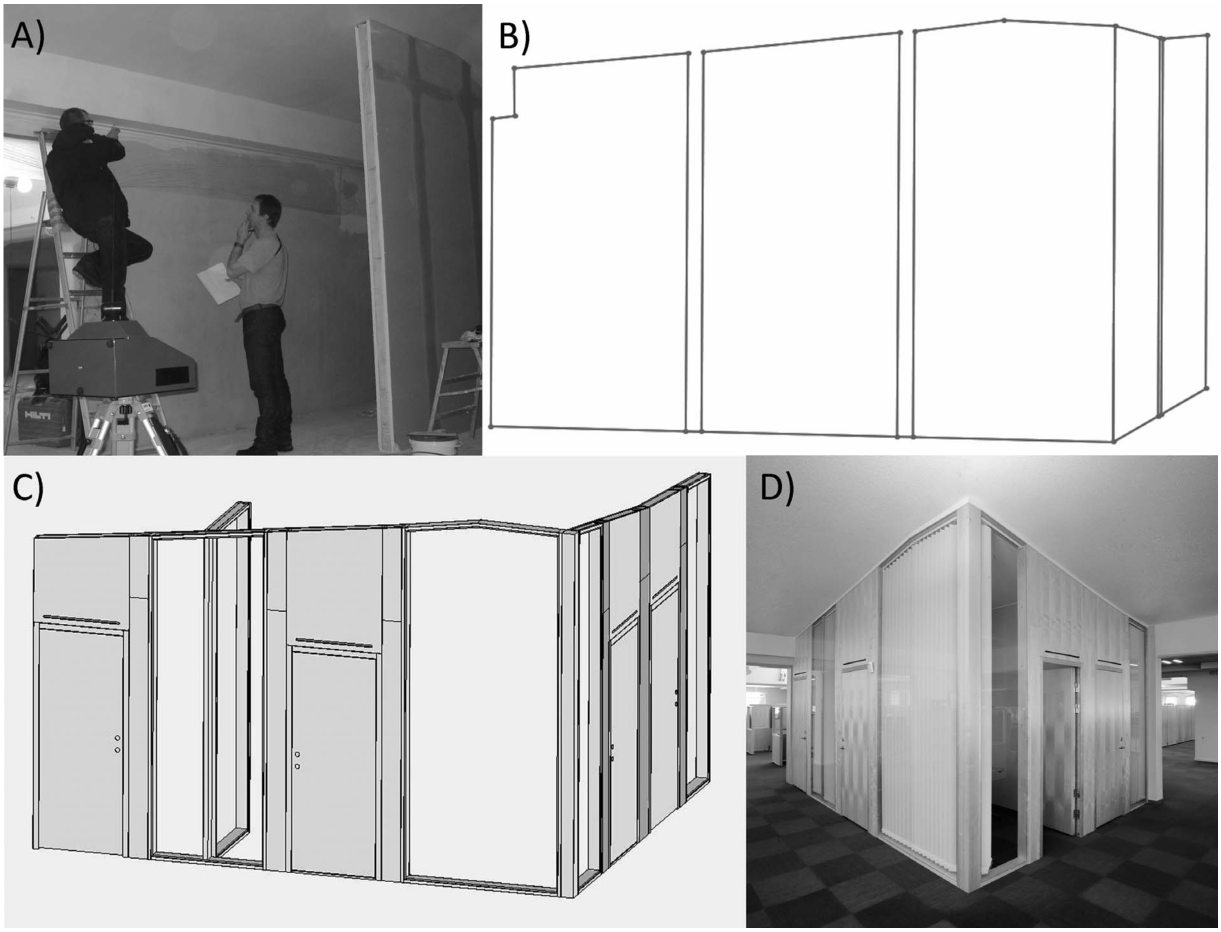

Figure 9.—On-site measuring and measurement data processed into a finished product: (A) measuring the contour, (B) the measured contour, (C) the product computer-aided design model fitted to the measured contour, and (D) the finished product at the construction site.

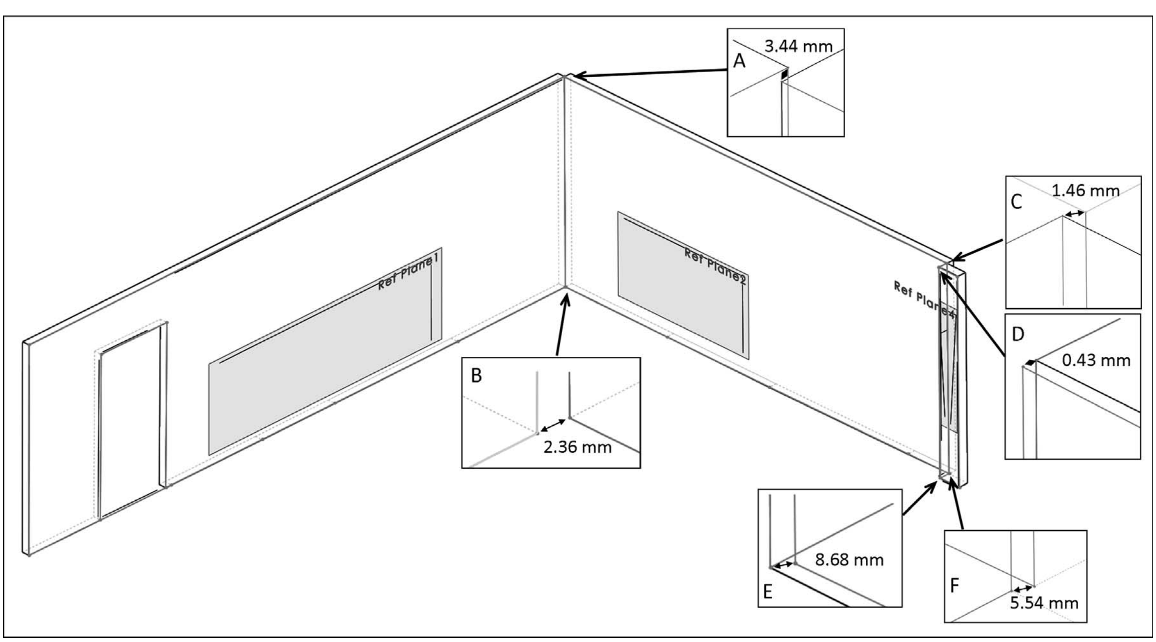

Figure 10.—Case 2 measurement model with mismatching corners. The magnified corners (A to F) show the gaps between the measured surfaces.

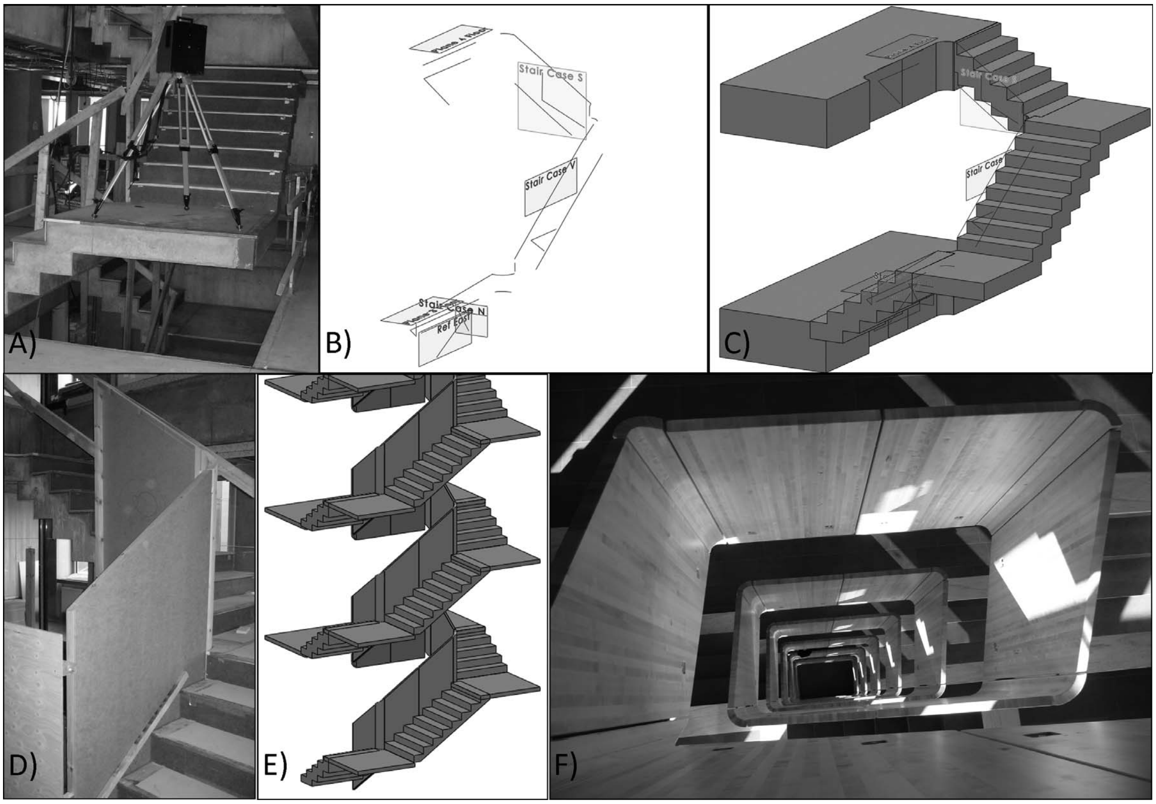

Figure 11.—Measuring, modeling, manufacturing, and assembly of a 12-story stair-railing system: (A) on-site measuring, (B) measurement data processing, (C) measurement 3-D model, (D) test-assembly of prototype, (E) aligned product model and site model, and (F) finished staircase railing on site.

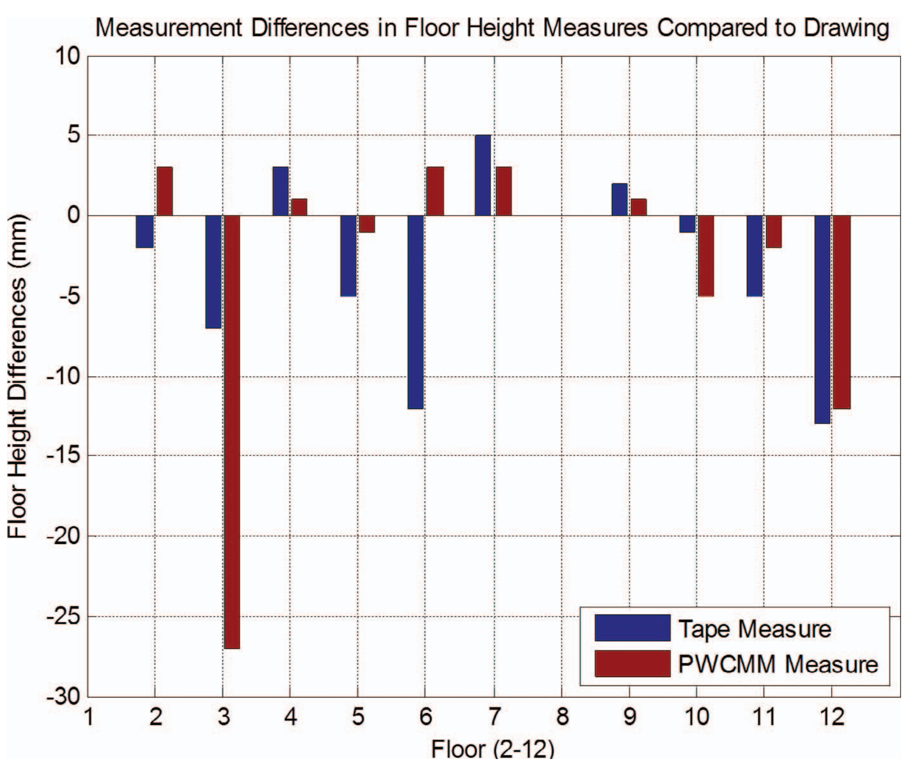

Figure 12.—Portable wire-based coordinate-measuring machine (PWCMM) and steel tape measures of floor heights compared with drawing.

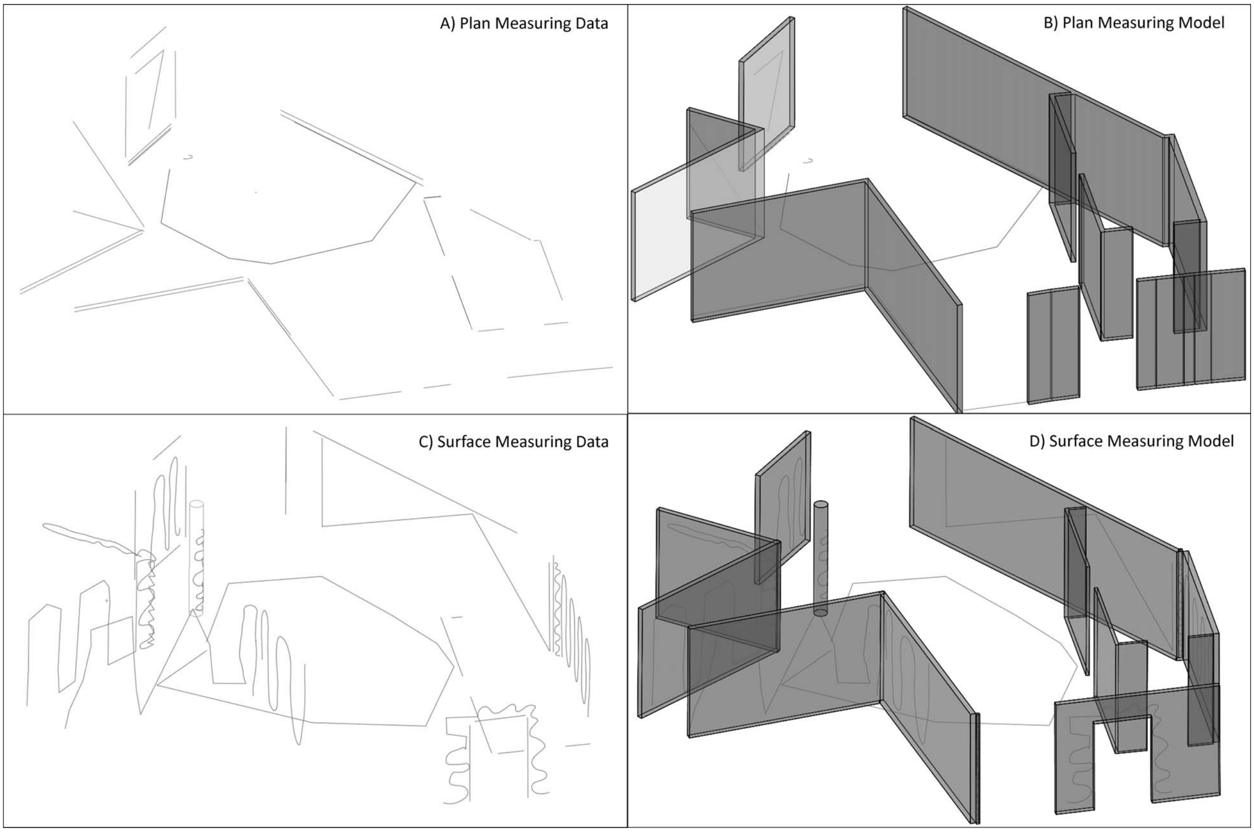

Figure 13.—Two different portable wire-based coordinate-measuring machine (PWCMM) measuring methods, plan-projection measuring versus surface-measuring method: (A) plan-projection measurement data, (B) plan-projection measurement model, (C) surface-measuring measurement data, and (D) surface-measuring measurement model.

measurement arm, which means different positions in the *Z*-direction. Therefore, despite a low effect on the measurement error from the vertical sensor, the error contribution is leveraged with the amount of extracted wire from the PWCMM. This shows that the error increases proportionally with the amount of wire extracted from the PWCMM. It is likely that also the error of the horizontal sensor is affected in a similar fashion.

At close range, within 100 cm, the level of accuracy is close to the requirements of the golden rule of metrology and highly interesting for verifying as-built site geometries when supplying joinery products. However, as experienced in the studied cases, the normal situation is that measurements need to be carried out in the outer range of the tested PWCMM. Then the random error can be expected to be 0.78 to 1.13 mm in a single coordinate registration. This would be on a par with the tolerance requirements on the products of the joinery-product supplier.

Analysis of leap function

The results show that using the PWCMM leap function adds uncertainty to the measurements. The mismatch errors displayed on the machine may seem insignificant, but the actually measured mismatches are up to three times larger (Figs. 8A and 8B). Furthermore, the test shows that the absolute mismatch error can increase for every leap, to vast proportions, significantly larger than the accumulated individual mismatch errors. Moreover, the mismatch orientation is irregular. Because of these circumstances, the PWCMM user cannot predict the effects of the mismatch errors when using the leap function for series of leaps.

The case experiences have shown that the 7-m range is often a limitation of the usability of the PWCMM. Both the size of objects and the presence of obstacles make using the leap function necessary. Therefore, the leap function is desirable, but currently the absolute mismatch error increases greatly after a few leaps, which reduces the usability of this function. It should be possible to further develop the leap function by using a method whereby repeated measurement registrations of the reference positions are averaged. If the absolute mismatch could be reduced to a few millimeters after a few leaps, the machine's usability would be considerably improved with respect to the needs of a joinery-product supplier.

Case analysis

With the purpose of creating representative as-built 3-D models that can be used for digital product-to-room fitting of joinery products, the cases reveal a number of issues with accuracy and usability of 3-D sensing of as-built construction site dimensions with the PWCMM.

Accuracy analysis.—The case experiences have shown measurement errors of considerably higher magnitude than the test of the sensor accuracy reports. Chiefly four factors have been identified that affect measurement accuracy in the studied cases:

- Accuracy of measured coordinates
- Representativeness of chosen coordinates

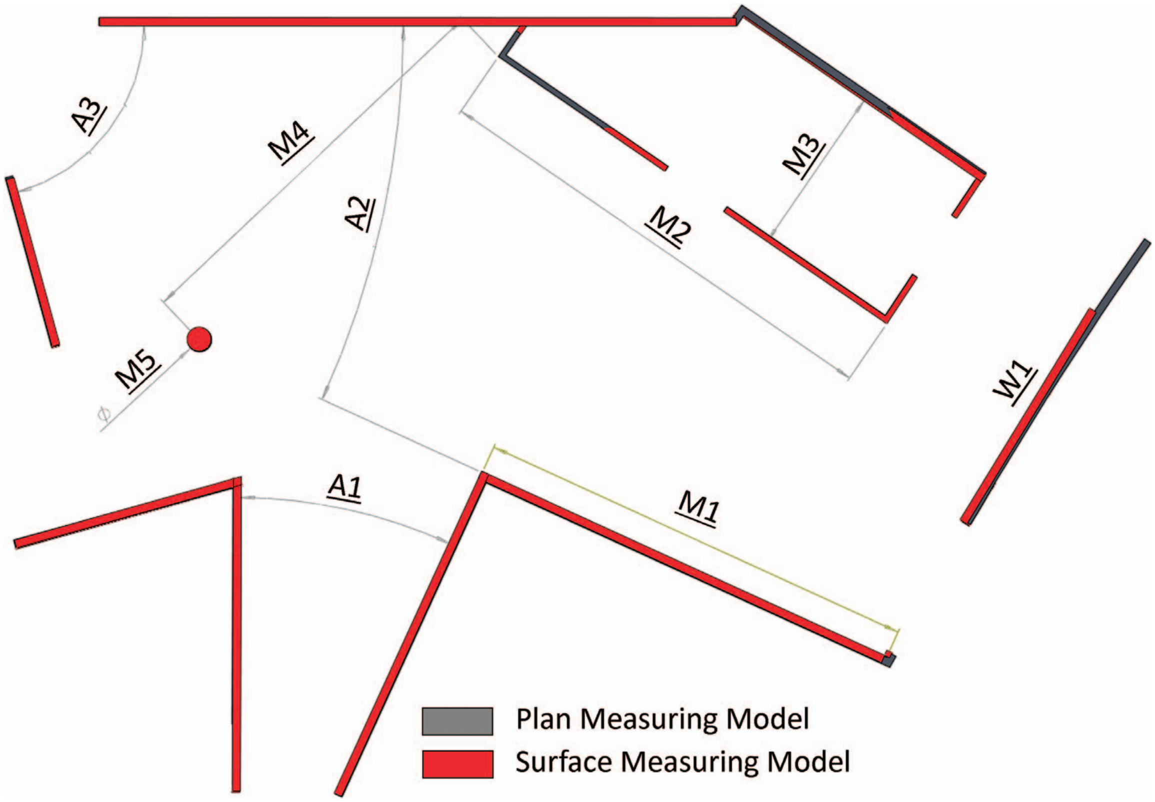

Figure 14.—Superposed models from the plan-projection measuring model (gray) and surface measuring model (red) show few visible dissimilarities. The model measures A1 to A3, and M1 to M5 are used to quantify differences between the measurement models.

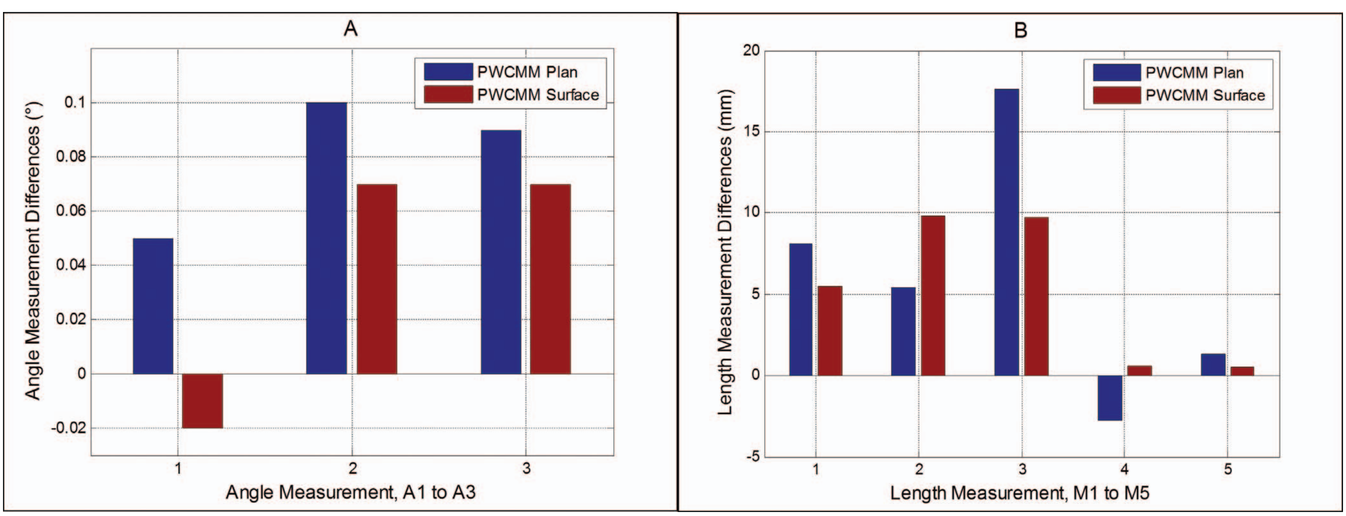

Figure 15.—Differences between the portable wire-based coordinate-measuring machine (PWCMM) measurement methods compared with laser-scanning reference: (A) wall angle differences and (B) length measurement differences.

- Error leveraging
- Leap function

First, the accuracy of measured coordinates is affected by the distance from the PWCMM to the measured object. When measuring, this distance always varies, and therefore the accuracy varies as well. The results show that errors in the outer range are up to three times larger than at short range. In the cases where the PWCMM often was operating in its outer range, accuracy was lower, but still on par with joinery-product tolerances. Despite this, uncertainties in measurement accuracy of significant magnitude have been experienced when processing measurement data in the studied cases.

Second, a measured coordinate accuracy of about ± 1 mm or less puts demands on the representativeness of the measured coordinate position. At a construction site, a contour line or a surface often has irregularities with a magnitude larger than ± 1 mm affecting the accuracy of the

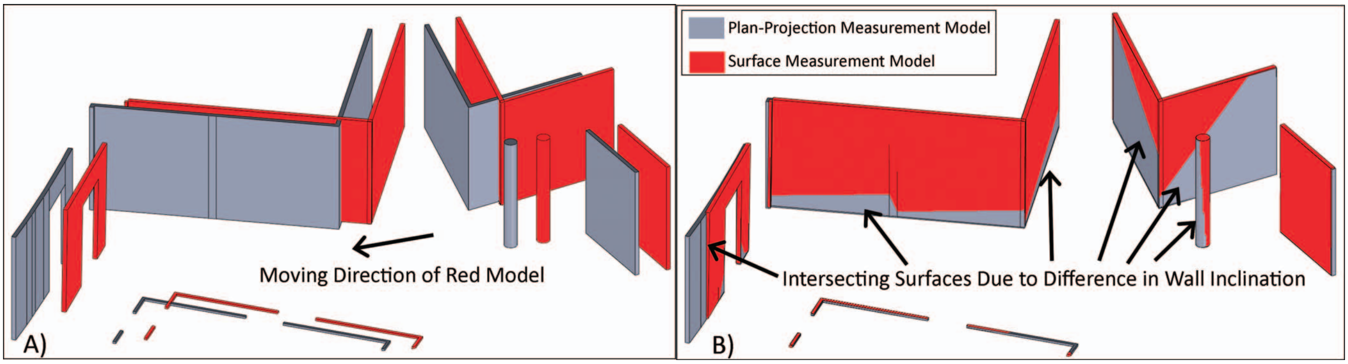

Figure 16.—Example of differences between models from plan-projection and surface-measurement methods. (A) The two measurement methods' different models before being fully superposed; (B) the surfaces of the superposed models intersect each other because of differences in the walls' vertical and horizontal alignment.

PWCMM measurements. This was experienced in all cases but can be exemplified in Case 2, where corner mismatches were caused by low representativeness and error leverage when defining the surface planes (Fig. 10). Similarly, in Case 3 the uncertainties of the floor heights were affected by this coordinate representativeness issue when defining the floor plane with three coordinates. Therefore, the measured surface planes became skewed.

Third, error leveraging is an error contributor in most PWCMM measurements. In the small scale, error leveraging occurs when measuring contours with two coordinate positions at each side and then connecting the contour lines where they intersect. This occurs in almost every PWCMM measurement. Another frequent error-leverage situation occurs when defining a surface plane with three coordinates that are not well extended in all Cartesian directions and then performing measurements far outside the area of the surface-defining coordinates. Owing to normal measurement errors, these surface planes get slightly skewed. When the outer contour of that larger surface is thereafter measured and these measurements are projected onto the defined surface plane, the errors from the first defining coordinates are leveraged. This is a source of significant error leverage that was observed in the corner mismatches in Case 2 and floor heights and contour-size uncertainties in Case 3. The uncertainties in Case 3 were smaller than tolerance requirements in the Swedish building codes for floor-plane heights but significant for the fitting of the staircase railing system supplied in this case. The studied cases show that the errors from the less representative coordinate measurements and from error leveraging interact and therefore increase the original error of the PWCMM.

Decreasing the sensitivity to error leveraging would be beneficial for PWCMM usability. To achieve this, the measuring should be planned to register as many coordinates as possible and average these values when acquiring as-built information from the construction site. The surface-measuring method in Case 4 (Fig. 14) is one example of how to use the power of averaging with the tested PWCMM. This method was found more reliable than the plan-measuring method and can therefore increase the accuracy of measuring as-built construction sites with the PWCMM. However, because the PWCMM data need to be processed in CAD software, the application of an averaging measuring strategy to measure rectangular-shaped objects is limited by the lack of line-fitting operations in CAD software. Currently most CAD software is not well suited to importing measurement data for which fitting operations are needed, and this affects the usability of the tested PWCMM.

Fourth, extending the operative range with the PWCMM leap function is a very attractive feature that unfortunately introduces significant errors. The use of the leap function was introduced in Case 2 and Case 3, but prevailing construction-site conditions prevented successful measurement using a series of leaps. In Case 4, the leap function was used successfully. Here, one leap was used, and uncertainties in the range of 3 mm were found. Aside from the size of the error introduced by leaps, the problem is that the direction of introduced error cannot be predicted by the user. By measuring parts of the objects before and after the leap, the orientation of the error can be assessed when modeling the measurement information and possibly compensated for. A more accurate leap function would require higher PWCMM sensor accuracy, or that the method for the leap function be further developed with repeated measurements of the reference targets and averaging of their measured positions were used in the calculation of the PWCMM position after the leap.

Furthermore, another factor affecting PWCMM measurements is that the as-built environments at construction sites often have undesirable horizontal and vertical surface curvatures. These are often of such magnitude they affect the fitting of joinery products. Even if the accuracy of the tested PWCMM were adequate to measure some of these undesirable surface curvatures with an averaging method, the repeating of a mesh measuring strategy would be needed. Here, repeated measurements of a full geometric identification method as presented by Skalski et al. (1998) would be needed. For large-scale objects such as construction sites, such kinds of high-density mesh measurements would be time-consuming with regard to data acquisition and would require complementary equipment showing the mesh pattern. The modeling of such data would require considerable processing time and improved software support. In terms of usability, the tested PWCMM with its manual probe positioning would not be appropriate for such high-density measurements.

Owing to the involvement of these factors in the PWCMM 3-D sensing, measurement errors significantly larger than the tolerances of joinery products have been experienced in the studied cases. With the difficulties of estimating the size and direction of errors, the reliability of the PWCMM measurement based models is not on par with joinery-product tolerances. Hence, the hypothesis of eliminating dimensional uncertainties of as-built construction sites to a level on par with joinery-product tolerances is rejected.

Usability analysis.—Three main usability issues have been experienced in the studied cases:

- Range and reach
- Limitations in ''picturing'' the construction site and its details
- Level of expertise needed to perform accurate measurements
- Processing measurement data to measurable 3-D models

First, the range and reach of the tested PWCMM is unique compared with other products on the market. However, in the studied cases, the PWCMM often needed to work in the upper end of the range, or else the range has been insufficient. Furthermore, the measurements need to be in line of sight for the machine wire. Even a small ledge on a surface can be an obstacle to positioning the measurement probe. Therefore, these range and reach limitations often restrict the possibilities of sensing many positions that can increase the level of construction-site detail that can be depicted. In the attempts to overcome these limitations with the leap function, there have been severe accuracy issues. Therefore, limitations in range and reach have been a major usability issue.

Second, limitations in ''picturing'' the construction site and its details mean that the PWCMM measurements and modeling can only supply a simplified reconstruction of a construction site. This simplification means that spatial information of importance to the joinery-product supplier can still be missing. Experiences from the cases and from the joinery-product suppliers involved are that 3-D models of construction sites are rare. Therefore, the as-built verification cannot be performed using only a few control coordinate positions; the site needs to be depicted and reconstructed into an understandable model. Practically speaking, there are limitations on the level of detail that can be achieved. In Case 3, it wasn't practically possible to capture measurement information needed to reconstruct an understandable 3-D model. Here, additional information from drawings was added to the model reconstruction. Because of this, the model has limitations in what parts can be used for fitting products to the as-built environment. Therefore, limitations in the ability to depict site details present a severe usability issue.

Third, measuring a construction site with the PWCMM requires a high level of expertise. The case experiences have shown many potential handling errors. There are many details that need to be captured when measuring a construction site. Further, the measurement probe has an offset that the user needs to consider for accurate measurements. Displaying large objects on a small screen makes measurement progress difficult for the user to follow on the PWCMM screen. Therefore, it can be difficult to judge whether enough information is captured until measurement data are processed in CAD software after measuring. The cases have shown many uncertainties that needed consideration when reconstructing a 3-D model from the measurement data. An experience of the construction site and understanding of the measurement process have been essential. Therefore, the reconstruction of measurement data also requires a high level of expertise and is difficult to perform for anyone other than the person who did the original measuring. Consequently, many errors can be introduced without high-level expertise in PWCMM measurement and the reconstruction of measurement data into a 3-D model. This is therefore a critical usability issue, and thus the hypothesis of meeting practical usability needs is rejected.

Conclusions

A portable wire-based coordinate-measuring machine (PWCMM) has been examined in the context of performing as-built dimensional site verification for supplying joinery products to the construction industry. Reliable as-built construction site dimensions in 3-D are a necessity for moving fitting of joinery products to the digital domain and by that means improving the efficiency of the supply process. To achieve this elimination of dimensional uncertainties of as-built construction sites to a level on par with product tolerances is seen as a minimum requirement. The random errors of the PWCMM are close to meeting tolerance requirements for joinery products, and when the objects measured are small, the requirements of the golden rule of metrology are also close to being met.

The studied cases show greater uncertainties in accuracy than the investigation of the random error gives the appearance of. The case analysis shows that practical accuracy is affected by limitations in coordinate representativeness due to the roughness and/or unevenness of construction site surfaces and error leveraging. These accuracy issues can potentially be reduced with an increased possibility of measuring with increased coordinate density and applying averaging of measured coordinates.

Construction site PWCMM measurement often requires the device to work in the upper end of the working range, or beyond, making it necessary to use the leap function, which further increases inaccuracy. This is a zone in which the PWCMM produces its highest level of random error. Further, the construction can only be depicted with a low resolution. Because this depiction is performed manually, the skill of the measurer is crucial to its quality. Automated processing of PWCMM data to 3-D models is hardly possible because of the need for understanding of the measurement data. Additionally, the many uncertainties in resulting models are obstacles to the usability and improved automation of the process of supplying joinery products. Therefore, the hypothesis of eliminating dimensional uncertainties of as-built construction sites with the PWCMM to a level on par with joinery-product tolerances is rejected.

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