# Geometric Quality Assurance within the Research Cluster IntCDC

**Li ZHANG, Laura BALANGÉ, Volker SCHWIEGER, Germany**

**Key words**: quality model, quality control, quality assurance, construction process

## SUMMARY

Since 2019, the Institute of Engineering Geodesy (IIGS) is involved in the German Research Foundation (DFG) cluster "Integrative Computational Design and Construction for Architecture" (IntCDC) in several fields. The researchers are from architecture, structural engineering, building physics, engineering geodesy, manufacturing and systems engineering, computer science and robotics as well as humanities and social sciences. Highly interdisciplinary research is demanded. This paper will focus on the research activities of IIGS in the field of geometric quality assurance for the construction process.

After a short introduction of the cluster IntCDC, the general quality assurance concept will be introduced. Based on this, the holistic quality assurance concept (incl. holistic quality model and assessment) which was developed within IntCDC will be introduced. The way how a holistic quality model can be integrated for quality assurance of co-design construction process will be explained, and the challenges of development of holistic quality model will be explained as well.

However, the focus of this paper is on the geometry quality assurance. The geometric quality assurance concept for fiber composite components will be shown as an example. Terrestrial laser scanning (TLS) is used to control the geometry of fiber composite components during and after the fabrication process. That means not only the quality of the product but also the quality of the process will be evaluated. Furthermore, how the process and product related quality characteristics and parameters can defined will be shown exemplary for the study case. At the end, the challenges and the future work will discussed.

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## 1. INTRODUCTION

The population is growing, it is expected to reach approximately 10 billion people in 2050; which means that there is an extensive demand for buildings to live and work. Even in North America and Europe an increase of more than 50% is expected (UNE 2017). The building sector is responsible for 40% of the global resource consumption, 40% of the energy use and 50% of the global waste production (UNE 2017). Currently, the construction industry shows the lowest digitalization index and the lowest productivity growth compared to all other industries (Barbosa et al. 2017). Therefore, improving the efficiency of the construction process through digitalization and automation is one of the solutions in the future. Besides, using less materials and energy and producing less waste is also essential for sustainable construction.

Since 2019, the Cluster of Excellence Integrative Computational Design and Construction for Architecture (IntCDC) (hosted by University of Stuttgart and the Max-Planck Institute for Intelligent Systems) is funded by the German Research Foundation (DFG) for an initial 7 years. IntCDC aims to use the full potential of digitalization by integration of the different disciplines in the building sector. The researchers from architecture, structural engineering, building physics, engineering geodesy, manufacturing and systems engineering, computer science and robotics, humanities and social sciences are working together to develop the co-design methods, processes and systems for non-linear construction process (Knippers et al. 2021). The non-linear co-design of methods, processes and systems is a key methodology cluster to reach this target. Co-design is based on the simultaneous and feedback driven development of generative design methods for optimization, monitoring methods to capture actual behavior, cyber-physical processes of digital prefabrication and robotic construction on the building site, therefore co-design considers multifaceted stakeholder perspective (Schwieger et al. 2022).

Institute of Engineering Geodesy (IIGS) is involved IntCDC in several fields, e.g. providing precise positioning for a spider crane within cyber-physical assembly process using the Robotic Total Station Network, and quality modelling and geometric quality assurance for the construction process (cf. Schwieger et al. 2022). The focus of this paper is the latter one.

## 2. QUALITY ASSURANCE CONCEPT AND QUALITY MODELS FOR CONSTRUCTION PROCESS

### 2.1 Quality Assurance Concept

In the construction industry is well aware that quality assurance gets more and more important, because lack of quality assurance leads to needless time and cost.

Since acquisition of as-built geometry and quality assurance are main tasks of engineering geodesy, IIGS has worked on quality assurance and quality models for construction process since many years. The developed quality assurance concept in Schweitzer et al. (2012) is shown in Fig. 1. In general, quality assurance includes measures to meet the quality requirements. In the quality assurance concept, the requirements are modelled in a quality model, which is a conceptual framework in which the abstract term of quality is structurally defined. A quality model consists of quality characteristics and parameters. A quality characteristic is an inherent feature of a product or process, related to requirement (Schweitzer et al. 2012). Each quality characteristic may be consists of a number of parameters. The parameters substantiate the characteristics.

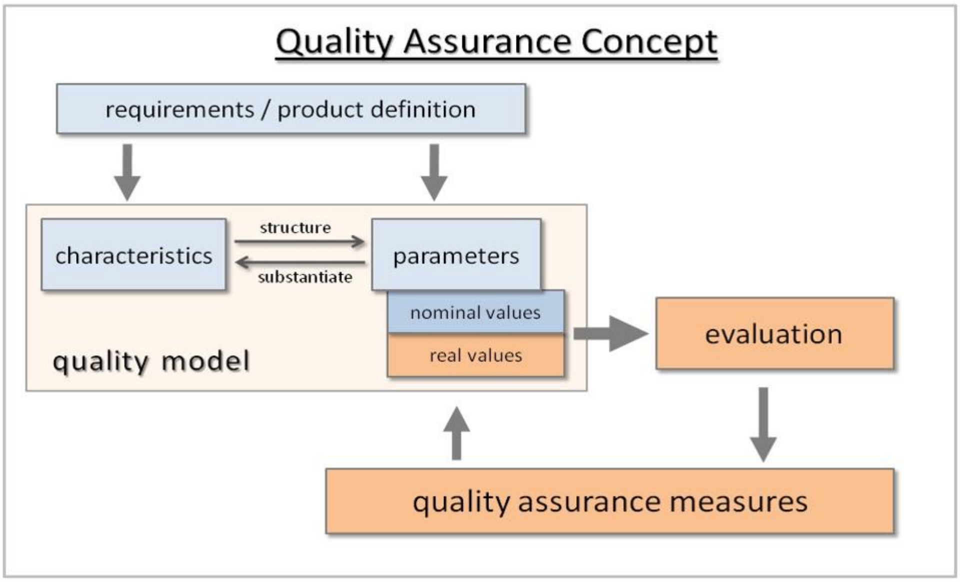


Fig. 1. Quality Assurance Concept (Schweitzer et al. 2012)

As shown in Fig. 1, the parameter can be quantified with value, which is usually measurable, e.g. by measurement methods of engineering geodesy. By comparing the real values derived from the measurements and the nominal value from the requirement, a quality evaluation can be proceed. Then appropriate quality assurance measures can be taken to adjust the quality, if the requirements are not met.

### 2.2 Quality Model for Construction Process

Quality models are application oriented, in engineering geodesy, quality models have been defined for engineering geodetic networks (e.g. Niemeier 1985) and in the field of transport telematics (e.g. Wiltschko 2004) and in the construction sector (e.g. Schweitzer & Schwieger 2011, Zhang & Schwieger 2011).

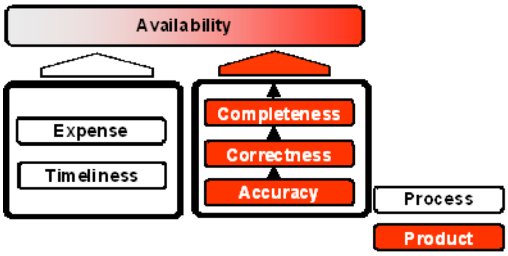


Fig. 2. Quality model for construction process (Zhang & Schwieger 2011)

Fig. 2 shows the quality model developed within an EU-project for construction processes. Because the goal is not only to improve the final product but also the quality of the work (processes), this quality model contains not only and product related but also process related quality characteristics. For example, the expense and time are process related quality characteristics and the completeness, correctness and accuracy of the products are product related quality characteristics. Because the aim in the project war to have real time quality assurance indexes as overall quality index, the availability is defined as overall quality characteristic which is not only product but also process related.

## 3. QUALITY ASSURANCE CONCEPT AND HOLISTIC QUALITY MODELS FOR INTCDC

The aforementioned quality models focus on the technical aspect. In an interdisciplinary field such as IntCDC, the development of an holistic quality model (HQM) is possible and also essentially important. Furthermore, the aforementioned quality models can be applied after the start of execution of the construction process (cf. the definition of the phases in Zhang et al. 2020). However, to integrate the idea of co-design, the researchers are working together to realize the quality assurance concept also already in the planning and design phase.

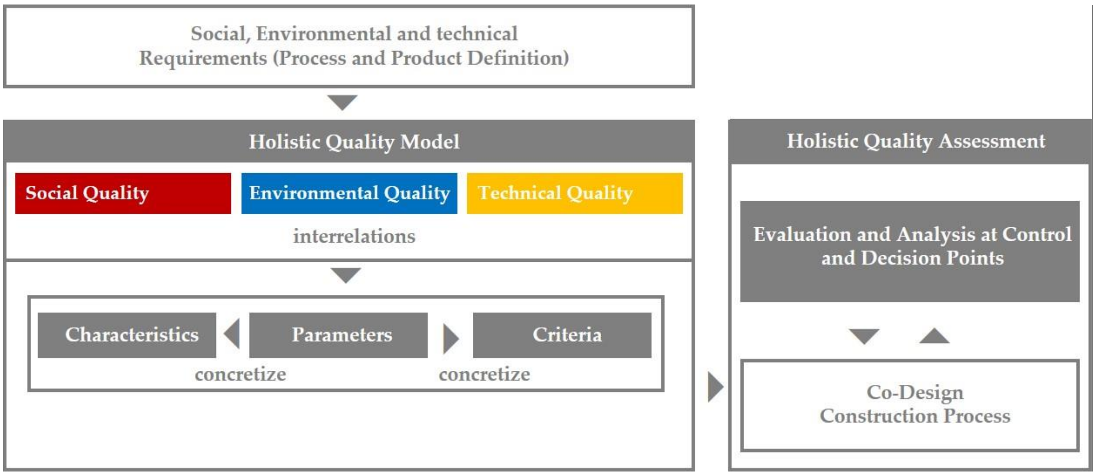


Fig. 3. Quality assurance concept for the IntCDC (Zhang et al. 2020)

Fig. 3 illustrates the quality assurance concept for IntCDC, which was developed by three institutes within IntCDC: Institute for Social Sciences (SOWI) and Institute for Acoustics and

Building Physics (IABP) and IIGS at University of Stuttgart. The concept was published in Zhang et al. (2020).

The main update of the quality assurance concept compared to that introduced in section 2.1 are as follows:

- the requirements and therefore the quality characteristics and parameters are explicitly defined from technical, environmental and social aspects;
- the criteria are explicitly defined, the criteria are the target of the quality assessment;
- by considering more quality aspects, the so-called interrelations arise, between the quality characteristics of different quality aspects as well as within the one quality aspect;
- the control point and decision point are defined for quality evaluation and decision making.

A particular challenge at beginning was to have a common understanding and same abstraction levels of the three aspects for the quality model setup (Zhang et al. 2020). The criteria are defined explicitly here, because they can be defined in various ways. For example, the criteria of a lot of parameters are some critical value for a quality parameter should not be exceeded (e.g. tolerance of the component size defined by standards should be met). For some parameters the criteria are that they should be as low/high as possible (e.g. the emission and resource should be as low as possible). These criteria could be used as optimization criteria. In some cases, the criteria are simply that they should be available, e.g., “conversion of the building should be possible”. Tab. 1 shows some examples of the quality characteristics, parameters and criteria of the three aspects.

Tab. 1. Examples of quality characteristics, parameters and criteria (Zhang et al. 2020)

| | **Quality Characteristic** | **Quality Parameter** | **Quality Criteria** |
|---|---|---|---|
| Technical | accuracy | standard deviation | should be minimized |
| | correctness | tolerance | should be met |
| | load-bearing capacity | load application time, pressure, tension | should be met |
| environmental | global warming Potential | kg CO2 eq. emitted | should be minimized |
| | total material | mass | should be minimized |
| social | control capacity | access to all relevant information, transparency of algorithmic decision making, | should be maximized |
| | adaptability | conversion potential of buildings: percentage of support-free floor plants | should be maximized |

As there are many quality characteristics, parameters, there are also interrelations between them. For example, transparent human-machine interaction/control capacity (social) influences the reliability (technical) of the process. Another example would be the adaptability of a building (social), the resulting conversion possibilities influence the life cycle of a building and thus the ecological quality. And, the amount of material used can have a positive influence on the load-bearing capacity of a building component (technical), but a higher material consumption is less good in terms of sustainability (environmental). The difficulty, however, is to model these interrelations in a numerical model.

The holistic quality assessment (right part of Fig. 3) is based on the HQM and takes place at control and decision points integrated into the construction process. Since co-design is the center of the IntCDC and the linear construction process should be transferred to a circular /non-linear process, it is of enormous importance to be able to make a statement about the quality of the process and product as early as possible, including a predictive statement.

A control point is a point in the construction process at which a specific process or product can be evaluated by means of defined characteristics and measurable parameters. In Yang et al. (2020), the TLS (terrestrial laser scanning) was applied for quality control of the graded concrete component at the defined control points, more control points are during the production (control points for process) and the other one is after the production (control point for product). During the production process, after each layer of casting, the height of the concrete level and the positions of the hollows spheres were measured by TLS and estimated, and after finalizing the production process the size of the concrete component can be controlled and compared to the planning data.

A decision point is a situation in the construction process where decisions are made that significantly influence the quality of the final product. At these, the expected quality of the final product can now be predicted (e.g. through simulation using Monte-Carlo-Simulation), thus enabling the choice of different production and fabrication methods. However, the interrelations between the quality characteristic make the decision more challenging. In Frost et al. (2022), the interrelations of the quality characteristics at one decision point in the design phase of concrete components was analyzed comprehensively. Frost et al. (2022) show the possibility and the challenge how the holistic quality concept supports the decision-making for sustainable construction in the future.

As described, IIGS is responsible for the technical aspect in the holistic quality assurance concept and the focus of research is on the geometry quality assurance. IIGS is working with different groups of the researchers who are developing construction systems with different materials (graded concrete, timber and fiber composite). In the following, only the geometric quality assurance concept for the fiber composite components will be shown as an example, because this construction system is very innovative and very challenging from the view of data acquisition and analyze. It will show how the quality assurance concept could be applied on this case study and the only examples of control points will be shown here.

## 4. GEOMETRIC QUALITY ASSURANCE FOR FIBER COMPOSITE COMPONENT WITHIN INTCDC

Fiber-reinforced polymers (FRP) have been used in many industry fields such as automotive, aeronautics, and shipbuilding for many years due to their impressive properties. For example, the carbon-fiber composites show low thermal expansion, high corrosion resistance and their high strength to weight ratio (Fitzer 1985). The robotic fabrication processes, such as coreless filament winding (CFW) has been developed, among others, at the University of Stuttgart and this technique has been applied in several building demonstrators (cf. Menges & Knippers 2015, Bodea et al. 2021). Also within IntCDC CFW is further developed for construction of fiber composite building structures. The fiber composite building structures could be applied e.g. in long-span building systems and for densification of existing building stock (Knippers et al. 2021). For example, Fig. 4 shows the fabrication set-up of fiber composite structure and exemplary element by KUKA robot with 6-axis robotic arm within IntCDC. The elements were fixed on manufacturing table rotating around 2-axes.

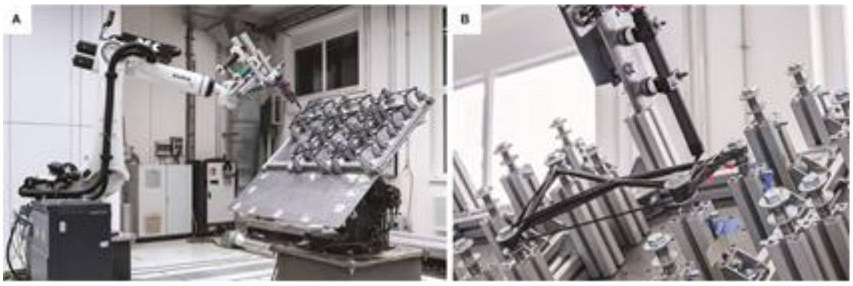


Fig. 4. a) Fabrication set-up with KUKA robot b) exemplary element (Gil Pérez et al. 2022).

The typical geodetic task of quality assurance is acquisition of as-built geometry and the comparison with planning geometry. One special challenge here is that direct geometry comparison is not possible. The available reference model of this element is only a line model without information of thickness of the individual lines. However, the real cross-section and the position and orientation of the lines is of great importance for the structural analysis of the components. Their structural performance is directly dependent on the fiber-fiber interaction. If fibers are pressed well against each other, it ensures a stabile structural performance. During fabrication, every new fiber segment will deform the previously ones (Waimer et al., 2013), so that the positions of intersection points, the positions and orientation of the lines will change during the fabrication process. The prediction of interaction between fibers is one of the biggest challenges during the design phase of such structures, with the measured geometry can help to known more about what happens during the winding process. Understanding how different parameters can affect the consecutive deformations and final geometry is helpful for fine-tuning the simulation of CFW and for making future design decisions (Balangé et al. 2022).

The geodetic task here is to determine the fiber geometry in each epoch. Here means that the position and orientation of the fibers as well as the shape, namely the cross-section of the lines need to be measured and estimated. For this purpose, TLS measurements were conducted after creation of each new intersection (e.g. cf. Fig. 5 b) and after the completion of each element.

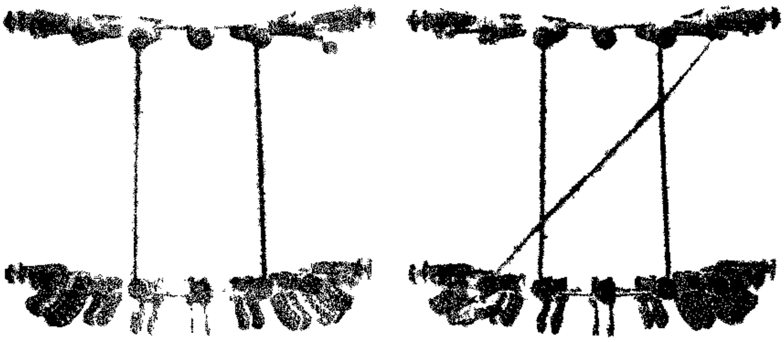
The geodetic challenge is the detection of small deformation between every epoch and the estimation of very small cross-section of lines. In the following, both process and product quality will be evaluated for quality assurance. They could be regarded as control points for process and for product respectively.

### 4.1 Process Quality

The carbon fire bundles pre-impregnated with epoxy resin were used and the fiber/resin ratio was 50:50. After the production, the impregnated carbon fiber bundles were wound onto spools and stored frozen until they are ready to be used. For fabrication, they were taken out of the freezer to thaw 40 minutes before starting the fabrication process (Balangé et al. 2022).

Each fiber composite element has a height of about 40 cm and a width of 20 cm. The diameter of the fibers is about 1 cm. The Trimble X7 laser scanner was used with a measurement resolution of 5 mm at a distance of 10 m and 3D point accuracy is 2.4 mm at 10 m, so the measurement accuracy is the about several millimeters.

In total, 30 fiber composite elements were measured in two up to seven epochs. In the following text, only two measurement epochs were taken as example for the explanation. The TLS measurements of these two epochs are visualized in Fig. 5.



a) b)

Fig. 5. Measured Epochs. a): first epoch with two separated fibers. b): second epoch with one additionally crossed fiber (Balangé et al. 2022)

After the data pre-processing (target based registration and outlier detection), the line segments are segmented manually and orientation of the lines can be estimated using the principle component analysis, besides, the start and end point of each segment are estimated. Then, the intersection points of the fibers are calculated for each epoch.

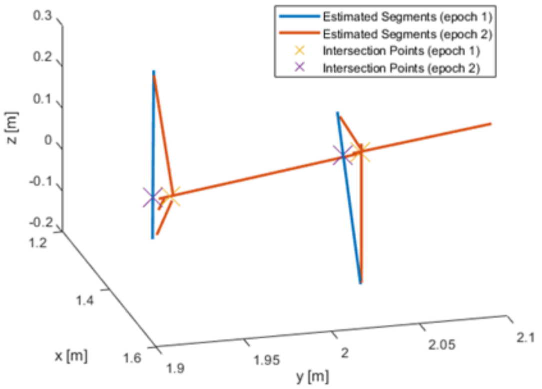


Fig. 6. Line estimation and calculation of line intersection points of two epochs (Balangé et al. 2022)

As explained aforementioned, the position of the intersection points are variating between the epochs and they need to be assigned from one epoch to the other epochs (c.f. typical example S3 in Fig. 7). The assignment the intersection points is estimated based on method in Kuhn (1955), a cost matrix is first created and then the optimal assignment is determined.

One special case is the assignment of the newly created intersection points. In this case, the perpendicular foot point of the intersection point will be estimated on the line of previous epoch. Fig. 6 shows this case, the deformation of the intersection points are 1.2 cm and 1.0 cm.

The quality evaluation shows that the final fiber geometry is dependent on a constant tension of the filament during the fabrication process. Furthermore, the total duration of the fabrication process plays a major role, because the moist fibers are drying during the whole fabrication process, with a longer fabrication duration, the fibers begin to split. The dry fibers stick less strongly to the pre-existing fiber composite structure and resulting high deformations.

One of the major geodetic challenge here is also that the elements are very thin and measurement noise are high. In addition, due to the spatial restriction in the fabrication hall, the object is obscured, for example by the robot, very often, so that the data are incomplete. The line and point geometry must be estimated using incomplete data, and thus it leads to greater uncertainty in the places with few measurement data.

Regarding the quality model for process quality, the process related quality characteristics and parameters can be defined as follows:

- the line parameters are defined as quality parameters for quality characteristic correctness;
- the standard deviations of the line and the intersection points estimation can be defined quality parameters for the quality characteristic accuracy;
- the completeness of the measured point cloud and the measured intersection points and lines can be defined as quality parameter for quality characteristic completeness.

The definition of criteria in this case study is still difficult, because the fabrication process is still under development and target values cannot be defined yet.

### 4.2 Product Quality

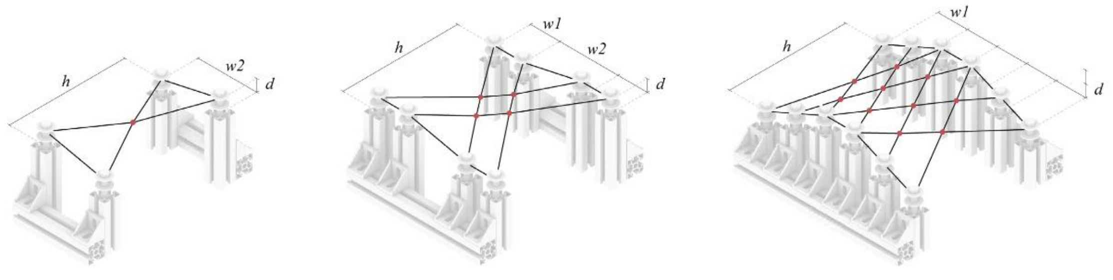
In addition to quality assurance in the process, the acquisition of the final geometry is also of high importance. Besides the positions and orientation of the individual fibers, their shapes are also very important information, because, the cross-section of fibers along the line segment is the base for calculating the load-bearing capacity of the components.

Due to irregular distribution of resin the cross-section change a lot along the fiber. As there are currently no established standards for the construction of fiber composite buildings, prototype buildings are always permitted on a case-by-case basis (Gil Pérez et al. 2020). Therefore, the requirement for the safety is much higher than it is actually necessary. The goal here is to acquire precise real geometry of the component, so that the realistic simulation can be obtained and material and thus resources may be saved in the future.

The main difference of the components used here from those in the process is that the fibers are now dried. Furthermore, the elements here consists of six windings, which leads to a larger fiber cross-section than that of the elements measured in the process.

Comprehensive interdisciplinary investigation was conducted to analysis the different influences on the overall component (Gil Pérez et al. 2022). For this investigation, all relevant and available data, such as the exact robot positions, the tension of the fibers and as well as the temperature during the fabrication were recorded.

As shown in Fig. 7, three different elements were fabricated and they become larger and more complex during the fabrication. Not only the number of intersection points and thus the fiber interaction changes, but also the size of the components changes.



**S1**
Cross

**S2**
Double Cross

**S3**
Lattice

Fig. 7. The three specimen types in their winding frames with desired fiber interaction points (n): S1 – cross (n = 1), S2 – double cross (n = 4), and S3 – lattice (n =10). Dimensions: h = 315 mm, w1 = 80 mm, w2 = 160 mm, and d = 32.5 mm (Gil Pérez et al. 2022).

To investigate the repeatability of the fabrication process and the influence of the robot position on the fabrication accuracy, ten elements with same planning geometry and fabrication process were fabricated.

The tasks of the IIGS were the definition of a common coordinate system and providing the transformation parameters and quality control of final product. For this purpose, the frames of the elements were measured before the start of fabrication and a frame coordinate system was defined. Then positions of the frames were measured to the fabrication platform.

In addition, the overall geometry of the elements need be determined. For this purpose, the individual elements were measured after fabrication using TLS. The geometry of the ten elements of the same type was then compared with each other. The focus was on calculating the fiber cross-sectional areas. The individual line segments were divided into 1 cm long sections. A plane was then placed through this segment, the line orientation is defined as the normal vector of the plane. Then a cylinder was defined around the line segment, all the laser scanner points, which should lie within the cylinder, can be used for the calculation of the cross-sectional area. These laser scanner points were then projected onto the plane. For the calculation, a convex hull is now placed around the projected points (see example shown in Fig. 8). The QuickHull algorithm (Green & Silvermann 1979) is used for this calculation. With the cross-sectional areas, the surface moments of the individual segments are determined. In addition, in Balangé et al. (2022), the B-spline approach was also used for cross-sectional area estimation. It was shown that both approaches have a comparable results, and that it depends on the available data which approach provides a more realistic result (Balangé et al. 2022).

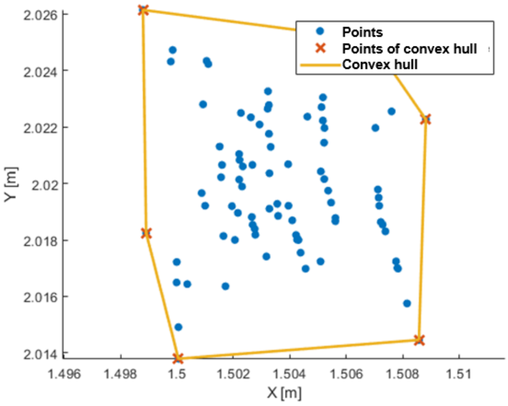


Fig. 8. Example of cross-sectional areas calculation (Balangé et al. 2022)

Analysis of the results shows that the calculated areas tend to smaller than they are. The reason is that the laser beam penetrates the material. For this reason, one of the future research is to investigate the influence of the material on the TLS measurements.
Regarding the quality model for product quality, the product related quality characteristics and parameters can be defined as follows:

- the line parameters (besides the position and orientation, also the cross-sectional areas) are defined as quality parameters for quality characteristic correctness;
- the standard deviations of the line and intersection points and the cross-sectional areas estimation are defined as quality parameters for the quality characteristic accuracy;
- the completeness of the measured point cloud can be defined as quality parameter for the quality characteristic completeness.

Most of them are similar to these for process quality, also the definition of criteria in this case study is still difficult, because the prototype is still under development.

## 5. CONCLUSION AND OUTLOOK

The research within IntCDC shows again that the quality assurance is of enormous importance, especially for interdisciplinary research and development. In order to ensure smooth cooperation between all disciplines, a holistic quality model and assessment is crucial. In order to realize the holistic quality assurance concept, the requirements of all parties are involved for the creation of the quality model and they are the basis for the quality evaluation.

Furthermore, for the development of new construction processes, quality control is especially important, not only for the final product but also during the process at defined control points.

In addition, to the technical challenges in construction, there are also new challenges for the geodetic measurement that need to be solved (e.g. influence of the material on the TLS measurements). Moreover, the definition of quality criteria for many applications is still an open question, which will be investigated in the context of further cooperation within the cluster.

## ACKNOWLEDGEMENTS

The research published in this article is supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2120/1 – 390831618. The authors cordially thank the DFG.

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## BIOGRAPHICAL NOTES

Dr.-Ing. **Li Zhang**

| | |
|---|---|
| 2002 – 2003 | Studies of Geodesy in China (University of Wuhan) |
| 2004 – 2009 | Studies of Geodesy and Geoinformation in Germany (University of Stuttgart) |
| 2009 | Research Associate at Institute of Engineering Geodesy, University of Stuttgart |
| 2015 – 2018 | Vice Chair Administration of FIG Commission 5 "Positioning and Measurement" |
| 2019 – 2022 | Chair of Working Group „quality assurance of measurment data “ within Commission 3 “Measurement Methods and Systems“ of DVW (Deutscher Verein für Vermessungswesen, engl. German Association of Surveying) |
| 2016 | Dr.-Ing. Geodesy (University of Stuttgart) |
| 2019 | Co-Chair of FIG Commission 5- WG5.6 "Cost Effective Positioning" |

M.Sc. **Laura Balangé**

| | |
|---|---|
| 2013 – 2018 | Studies of Geodesy and Geoinformation in Germany (University of Stuttgart) |
| 2018 | Research Associate at Institute of Engineering Geodesy, University of Stuttgart |

Prof. Dr.-Ing. habil. **Volker Schwieger**

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|---|---|
| 1983 – 1989 | Studies of Geodesy in Hannover |
| 1989 | Dipl.-Ing. Geodesy (University of Hannover) |
| 1998 | Dr.-Ing. Geodesy (University of Hannover) |
| 2004 | Habilitation (University of Stuttgart) |
| 2010 | Professor and Head of Institute of Engineering Geodesy, University of Stuttgart |
| 2015 – 2018 | Chair of FIG Commission 5 "Positioning and Measurement" |

## CONTACTS

Dr.-Ing. Li Zhang/ M.sc. Laura Balangé / Prof. Dr.-Ing. habil. Volker Schwieger
University of Stuttgart
Institute of Engineering Geodesy
Geschwister-Scholl-Str. 24 D
D-70174 Stuttgart
GERMANY
Tel. + 49/711-685-84049 | -84054 | -84040
Fax + 49/711-685-84044
Email: li.zhang@iigs.uni-stuttgart.de | laura.balange@iigs.uni-stuttgart.de |
volker.schwieger@iigs.uni-stuttgart.de
Web site: https://www.iigs.uni-stuttgart.de/