The Research Cluster Integrative Computational Design and Construction (IntCDC) – Current Engineering Geodetic Contributions

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Key words: Engineering Geodesy, Co-Design, Digitalization, Robot Control, Robotic Total Station, Quality Model, Quality Assessment, Gradient Concrete, Fibre Composites

SUMMARY

The German Research Foundation (DFG) cluster "Integrative Computational Design and Construction for Architecture" (IntCDC) is hosted by the University of Stuttgart and the Max-Planck Institute for Intelligent Systems. The cluster aims to lay the methodological foundations to profoundly modernize the design and building process and related building systems by adopting a systematic, holistic and integrative computational approach. The non-linear co-design of methods, processes and systems is a key methodology cluster to reach this target. Interdisciplinary is given by the participation of researchers from architecture, structural engineering, building physics, engineering geodesy, manufacturing and systems engineering, computer science and robotics, humanities and social sciences.

Engineering geodesy covers the challenges related to geometry. Within this overview article the authors will focus on the research activities of the Institute of Engineering Geodesy (Institut für Ingenieurgeodäsie - IIGS). The investigations are within two Research Projects (RPs) "Robotic Platform for Cyber-Physical Assembly Process" and "Holistic Quality Model". Besides the general outline of the projects, intermediate and exemplary results will be presented.

For the first RP the interdisciplinary work is realized together with our colleagues from the Institute for System Dynamics as well as from the Haptic Intelligence Department from the Max Planck Institute. The IIGS has a 4-tachymeter-realtime-network that provides position and attitude angles to control a spider crane. Two solutions will be compared, a one prism solution supplemented by an IMU measuring the three attitude angles and a two-prism solution, where the IMU has to provide one attitude angle only.

The second RP aims at developing a Holistic Quality Model that includes social, environmental and technical quality aspects. The IIGS is working together with colleagues from Institute for Social Science as well as form the Institute for Acoustics and Building Physics. On the one hand, a general framework considering quality characteristics, parameters and criteria as well as control and decision points was created. On the other hand, very specific quality control and assessment was carried through by e.g. determining the cross sections of fibre composites that are the base for lightweight building components.

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1. INTRODUCTION

Currently, the construction industry shows the lowest digitalization index and the lowest productivity growth compared to all other industries (Barbosa et al. 2017). The first step towards digitalization is the development and use of Building Information Models (BIM). The level of BIM implementation is quite different in the countries around the world.
In the same moment, the building sector is responsible for 40% of the global resource consumption, 40% of the energy use and 50% of the global waste production. Additionally, the population is still growing. It is expected to reach approximately 10 billion people in 2050; generating 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).
Summing up these facts, efficiency gains through automation, robotics and digitalization will be the base for fulfilling the requirements of the future. Due to the extended demand for buildings the use of less materials and energy and the production of less waste is essential for a sustainable construction. The way towards sustainable construction may be paved by reducing the weight of the structural elements (by graded concrete or fibre composites) or the use of bio-materials. In the same time, the whole life-cycle of the building and not only the construction phase has to be considered.

These socially challenges demand for a research focus within this domain. In 2019 the German Research Foundation (DFG) recognized this pressure and granted well-known experts at University of Stuttgart and the Max-Planck Institute for Intelligent Systems with the cluster "Integrative Computational Design and Construction for Architecture" (IntCDC) for an initial 7 years period. The cluster aims to lay the methodological foundations to profoundly modernize the design and building process and related building systems by adopting a systematic, holistic and integrative computational approach. The non-linear co-design of methods, processes and systems is a key methodology cluster to reach this target. Interdisciplinary is given by the participation of researchers from architecture, structural engineering, building physics, engineering geodesy, manufacturing and systems engineering, computer science and robotics, humanities and social sciences Knippers et al. 2021). Within this article the authors focus on the engineering geodetic contribution to the cluster, that were already conceptualized in Schwieger et al. (2019), by summarizing the first 3 years of research work.

2. INTCDC – INTEGRATIVE COMPUTATIONAL DESIGN AND CONSTRUCTION FOR ARCJTUECTURE

2.1 Objectives and Goals

According to Knippers at al. (2021) digitalization within the construction sector is blocked by a domain specific foci; e.g. digitalization in the area computer-aided design and construction methods or within manufacturing and construction processes or within material and building systems. The research results are limited to one area and, therefore, mostly incremental and are not working as a sort of game changer. IntCDC aims to establish an overarching methodology of co-design of design and analysis methods, manufacturing processes as well as material and building systems as indicated in Figure 1.

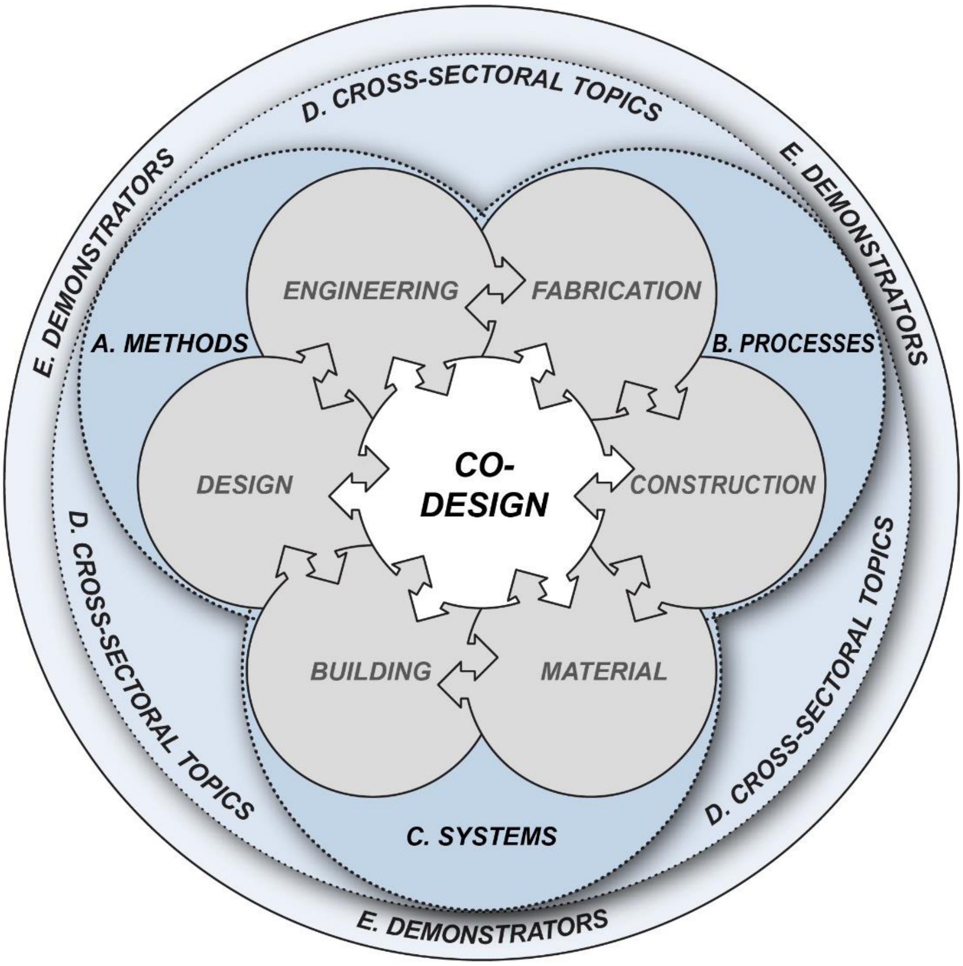

Figure 1: Co-design of methods, processes and systems (Source: IntCDC, University of Stuttgart)

Co-design is based on the simultaneous and feedback driven development of generative design methods for exploration, analytical methods for optimization, monitoring methods to capture actual behavior, cyber-physical processes of digital prefabrication and robotic construction on the building site, and also considers multifaceted stakeholder perspective. As a result, new building systems are being created for the most important architectural applications, that is, multi-story and long-span buildings, building envelopes and the densification of the existing building stock, considering social needs and expectations, environmental impacts, regulatory requirements and historical experience. IntCDC explores co-design as a methodology for the simultaneous and feedback integration of geometric, structural, mechanical, hydrothermal, acoustic properties, environmental, economic and social factors, esthetic and spatial qualities, and possibilities of cyber-physical manufacturing and construction processes (Knippers ate al. 2021). A holistic quality model is being developed to ensure the technical, ecological and social quality of co-design processes and products (Zhang et al. (2020).

The long-term goal of IntCDC is to develop a co-design methodology that operates on successive levels (Knippers et al. 2021):

(a) a predictive layer that is located in the digital domain prior to any physical construction; (b) a combined predictive and empirical layer enabled by cyber-physical fabrication and design approaches;

(c) a self-learning layer that uses artificial intelligence capacities to develop semi-autonomous or autonomous computer-aided design and robotic construction without the need for a comprehensive blueprint, corresponding global knowledge or centralized control.

2.2 General Structure

Disciplinary IntCDC ist strctured into the Research Units: RU I Archutecture, RU II Structural Engineering, Building Physics and Geodesy, RU II Manufacturing and Systems Engineering, RU IV Computer Scienece and Robotics and RU V Humanities and Social Science. But even within this RUs quite different disciplnes are considered. For examppple RU V covers so dfferent disciplines such as History of Architecture as well as Social Science, within RU II the momination of the RU made already clear that different disciplines are summarized. The importance of interdisciplinary work is highlighted by the fact that researchers of minimum two RUs work together in one Reserach Project (RP) that is established for one phase (three year period). These RPs may be prologed if they are successfull and further research is necessary. Currently (phase one, 2019 – 2022), 20 RPs are granted. Additionally, so-called asociated projects are listed that provide essential iunput to the cluster, but are nor grated by the cluster directly. An overview about all projects is given on IntCDC (2022).

The RPs work together within Research Networks (RN) to reach the respective goals. Currently, two RNs are established that are desciibed following IntCDC (2022). RN 1 addresses the Co-Design-based development of methods, processes and systems for multi-storey buildings, such as residential and office buildings, and poses the challenge of a high level of integration required in this context. Thus, the methods' development of explorative design, optimisation and analyses, visualisation and data integration through the particular challenges associated with this field of architectural application will be farmed. These include divergent design drivers, multidimensional optimisation parameters and related multifaceted stakeholders. Additionally, the interrelation between spatial and constructional ordering systems, structural and buildings physics performance, and environmental and economic demands in this field are considered.

RN 2 focuses on long-span buildings, such as large public, cultural, sports and infrastructural buildings. It serves as a challenge for a high level of performance, as structural and material efficiency plays a decisive role for economic feasibility, environmental impact and architectural articulation of long-span building systems. Therefore, the aim is to directly interlink explorative computational design methods with computational optimisation, of both highperformance building systems and their efficient construction through transient 4D (spatial dimensions combined with time) modelling, and artificial intelligence approaches, which embed the specific capability of advanced fabrication and material technology for multi-scale adaptation to forces.

2.3 Engineering Geodesy within INTCDC

Engineering geodesy plays a crucial role as an interface between structural engineering, building physics, control engineering, computer science and robotics. The aim is a permanent kinematic and autonomous geometry survey and monitoring of construction sites (outdoor and indoor) through 4D data acquisition (also in terms of semantic) based on precise seamless positioning of large-scale robots and UAVs. New stochastic sensor fusion models for imaging orm scanning sensors will help to guide the moving objects on predefined and adaptive paths. Within IntCDC the Institute for Photogrammetry (IfP) and the Institute of Engineering Geodesy (IIGS) work on these topics. This article focusses on the IIGS part of the research. In principle the IIGS deals with the integration of geodetic measurement techniques into machine and UAV guidance and control, area-wise-monitoring and multi-sensor data acquisition and quality modelling. The development of permanent monitoring methods including stochastic models and co-optimisation of survey configurations, seamless positioning methods as well as process and quality modelling are also belonging to the research interests.

More concrete, the IIGS is currently involved in two RPs. One dealing with an automation issue by providing seamless positioning for a spider crane (robotic plattform) within a cyber-physical assembly process. This RP is realized with colleagues from RU IV within RN II. The other project covers technical quality and sutainability objectives by considering technical, societal and environmental aspects in one holistic quality model. This project is formally assigned to RN II but covers in principle both, RN I and RN II. Here the IIGS researchers work together with colleagues from RU II and RU V.

3. ROBOTIC PLATFORM FOR CYBER-PHYSICAL ASSEMBLY PROCESS

3.1 Cyber physical assembly process and crawler / spider crane

The integration of large scale robots into assembly and construction processes is the main goal of the presented RP. Robots may contribute to optimize processes related to construction and bring beneficial effects like increase of productivity, achievment of quality requirements by prevention of human errors, elimination of re-works and thus minimization of construction time as well as cost reductions by staff savings (Wakisaka et al. 2000). Another aspect is the afore-mentioned issue related to geometry, which is defined as the central aspect for digitalization in construction (Schwieger et al. 2019). Cai et al. (2018) conclude, that construction robots and robotic machines have taken over many tasks and duties from human workers. Their utilization for construction processes is well suitable for automation of repetative tasks, as e.g. picking, transporting and placing of construction elements (Lauer et al. 2022), which is done by the used robotic platform within this project, a Jekko SPX532 tracked spider crane (Fig. 1, left). For such tasks, the position and the orientation of the tool center point (TCP), located at the front tip of the jib (Fig 1, right), have to be determined. In turn, the TCP can be equipped with different tools as e.g. crane hooks, grippers, screwing devices or even haptic feedback sensors.

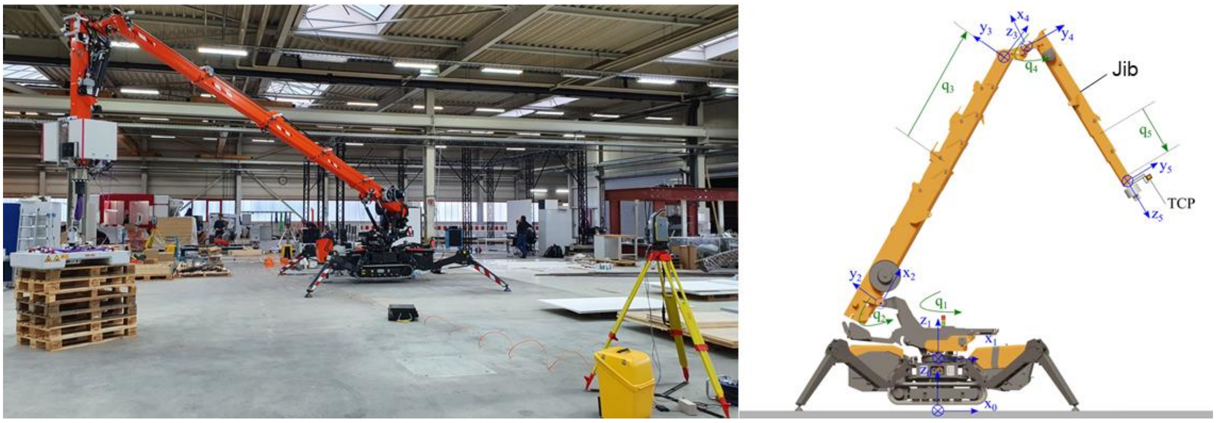

Figure 2: left – tracked spider crane Jekko SPX532; right – schematic robot layout and its components

For the automated assembly process, the position and the orientation, designated as pose in the following, are used for the control-loop feedback of the spider crane.

3.2 Real time total station network for pose determination of the crane

For handling flexible and seamless operating environments, for indoor and outdoor applications, GNSS can obviously not be considered as sensor. The decision was made in favour of Robotic Total Station (RTS) as a valuable measurement system for position determination, which provides mm-accuracy and real-time capability. In order to provide the pose, the RTS is supplemented by an Inertial Measurement Unit (IMU). However, in dynamic construction environment, obstacles may disturb the line of sight (LoS) between the RTS and the targets (attached to tracked spider crane and signalized by prisms) at any time. Therefore, it is proposed to set up an RTS-network, consisting of four RTSs, evenly distributed among the construction site. The RTS-network has the ability to bridge LoS losses of individual RTSs within the network. Moreover, the RTS network enables the tracking and measuring of two targets simultaneously, enabling the calculation of two machine's orientation angles from prisms positions, thus, replacing two of the IMU angles.

Beside the bridging of LoS losses, the RTS network (RTS-N) has further advantageous properties, which can be used to optimize quality characteristics of geodetic networks like accuracy and reliability (Niemeier 1985). The characteristics are concretized by quality parameters like standard deviations, redundancy numbers or minimal detectable errors (Schwieger and Zhang 2019). Moreover, the RTS-N enables different measurement setups. For the pose determination of the spider crane two different configurations have been implemented. In configuration A, four RTSs measure to one prism which is attached at the TCP and thus determine its position. An IMU measures the three orientation angles and complementing the pose information. In the second configuration B two prisms are attached to the robot, whereat the prism 1 is still located at the TCP and prism 2 is mounted at the rear tip of the jib. This configuration additionally allows the computation of two orientation angles from prisms' positions (Lerke and Schwieger 2021). The IMU provides the remaining third orientation angle. Fig. 2 displays the two setups A and B.

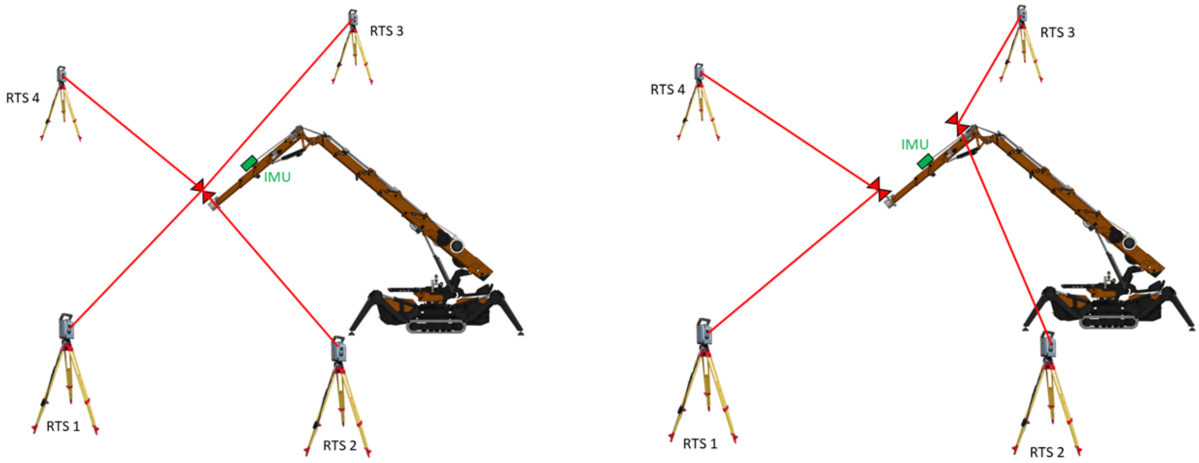

Figure 3: left – measurement configuration A; right - measurement configuration B

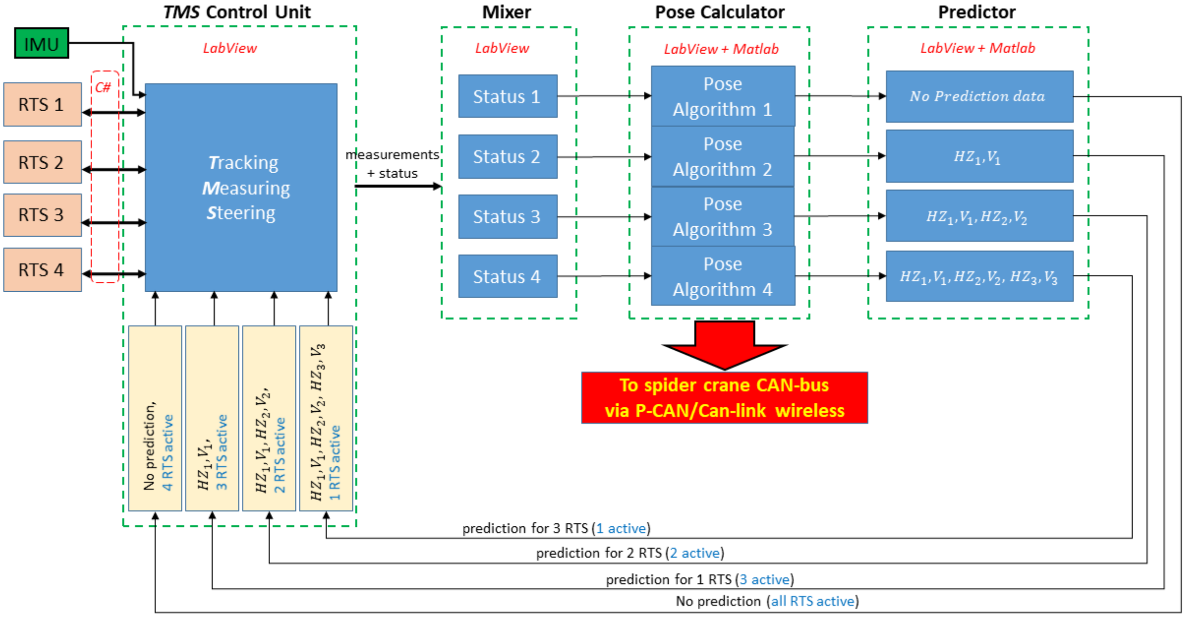

Figure 4: RTS Network control architecture

To ensure seamless operations of the RTS-N according to the depicted configurations in Fig. 2, an overarching RTS-N control scheme is crucial. The development and implementation of the appropriate concept has been one of the main challanges to be solved during the project. The developed control architecture is presented in Fig. 3. The architecture consists of four main items, TMS control unit, mixer, pose calculator and predictor. The TMS control unit is responsible for passing tracking, measurement and steering commands to and the receipt of measurement data from individual RTSs. The mixer checks the status of the RTS-N, particulary whether one or multiple RTSs have no LoS and thus not providing data. Based on the information of the mixer, the appropriate pose determination algorithm from the pose calculator unit is selected, the pose is subsequently calculated and immediately passed to the Controller Area Network (CAN) bus of the spider crane via wireless transmission. The predictor unit calculates the horizontal and vertical angles for all RTSs, where LoS is lost. These angles are sent back to the TMS control unit, allowing each affected RTS to follow-up the obscured prism without direct visual connection to it.

The following section generally describes the applied pose determination procedure. Among different possible pose determination methods, the Gauss-Markov-Model (GMM) of least squre adjustment according to Niemeier (1985) has been chosen. The underlying deterministic model based on the GMM is following the contribution of Lerke and Schwieger (2021) and thus will not be exhibited in detail. The vector of observations comprises the measurement elements of the four RTSs which are the horizontal angles h_i, the vertical angles v_i and the slope distances s_i, whereby i corresponds to the number of active RTSs. Additionally the four known RTS coordinates X_i, Y_i and Z_i are introduced as pseudo-observations. The IMU provides further measurement elements which are the Euler angles roll ϕ^{IMU}, pitch θ^{IMU} and yaw ψ^{IMU}. Thus the vector of observations is shaped as follows:

$$\underset{27,1}{\boldsymbol{l^A}} = [s_1\; h_1\; v_1 \ldots\; s_4\; h_4\; v_4\; X_1\; Y_1\; Z_1 \ldots X_4\; Y_4\; Z_4\; \phi^{IMU}\; \theta^{IMU}\; \psi^{IMU}]^T \quad . \qquad (1)$$

For configuration A, the parameter vector to be determined is:

$$\underset{6,1}{\boldsymbol{x^A}} = [X^{P1}\; Y^{P1}\; Z^{P1}\; \phi\; \theta\; \psi]^T. \qquad (2)$$

Introducing the design matrix $\underset{27,6}{\boldsymbol{A^A}} = \frac{\partial \Phi_k}{\partial x_j}$ with $k = 1 \ldots 27,\; j = 1..6$, which gives the interrelation between $\boldsymbol{l^A}$ and $\boldsymbol{x^A}$ as well as the covariance matrix of observations $\underset{27,27}{\boldsymbol{\Sigma_{ll}}}$, as stochastic model, provides the solution for the pose of configuration A by the application of the standard least square adjustment algorithm. For configuration B, the vector of observation $\boldsymbol{l}^B$ is equal to $\boldsymbol{l^A}$**.** The parameter vector $\boldsymbol{x}^B$ is extended by the coordinates of the second prism and has the form: $\underset{9,1}{\boldsymbol{x^B}} = [X^{P1}\; Y^{P1}\; Z^{P1}\; X^{P2}\; Y^{P2}\; Z^{P2}\; \phi\; \theta\; \psi]^T$. However, a closed-form solution for configuration B is not existent with the GMM. Therefore, a two-step solution has been applied, where at first the coordinates of the two prisms are determined by a first adjustment and secondly, these coordinates, combined with IMU measurements, have been used for the determination of attitude angles by a second adjustment (Lerke and Schwieger 2021).

As mentioned before, the RTS-N allows the determination and evaluation of quality characteristics such as accuracy and reliability. The accuracies can be extracted from the diagonal elements of the cofactor matrix $\boldsymbol{Q}_{\hat{x}\hat{x}}$ of the adjusted parameter vector. For the reliability, the redundancy numbers, as controllability parameters, are used to calculate the minimal detectable error ∇_{l_i} of observation l_i and subsequently the impact of ∇_{l_i} on coordinates according to Niemeier (1985) as well as on orientations in configuration B according to Lerke and Schwieger (2021).

3.3 First Results of the pose determination

To evaluate the performance of the pose determination, simulations as well as real-world tests have been conducted. For the simulation, the area of the real-world construction site (Fig. 5) has been discretised in a grid-like structure. For each resulting grid point, numerical values for accuracy and reliability parameters have been simulated. The results are depicted in so called "zonal accuracy maps", where the 3D point accuracies, the angular accuracies of the orientation angles from RTS-N as well as the 3D impacts values of ∇_{l_i} on coordinates are coded in different colour patterns and representing the quality level. These patterns superimpose the map/top view of the real-world construction area. Additionally, error ellipses complement the representation of zonal accuracy distribution.

Figure 5: Isometric view of the real-world construction area (based on data from Google Earth 2022)

Fig. 6 and 7 exemplary depict the zonal accuracy distribution for configurations A and B

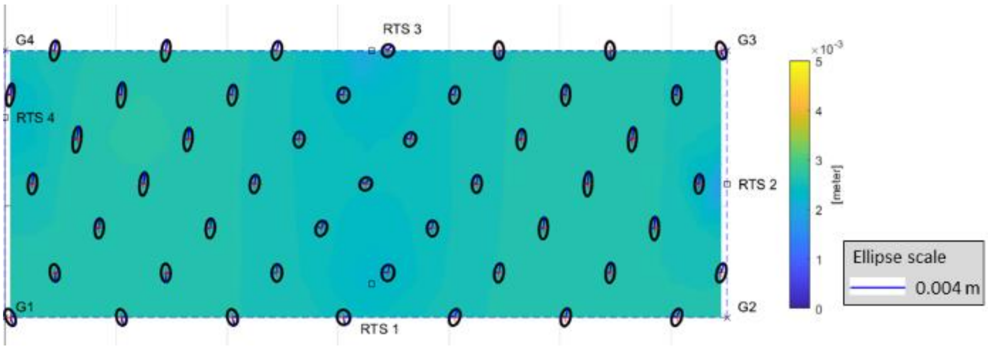

Figure 6: Confguration A – confdence ellipses and zonal positional accuracy representation (Lerke and Schwieger 2021)

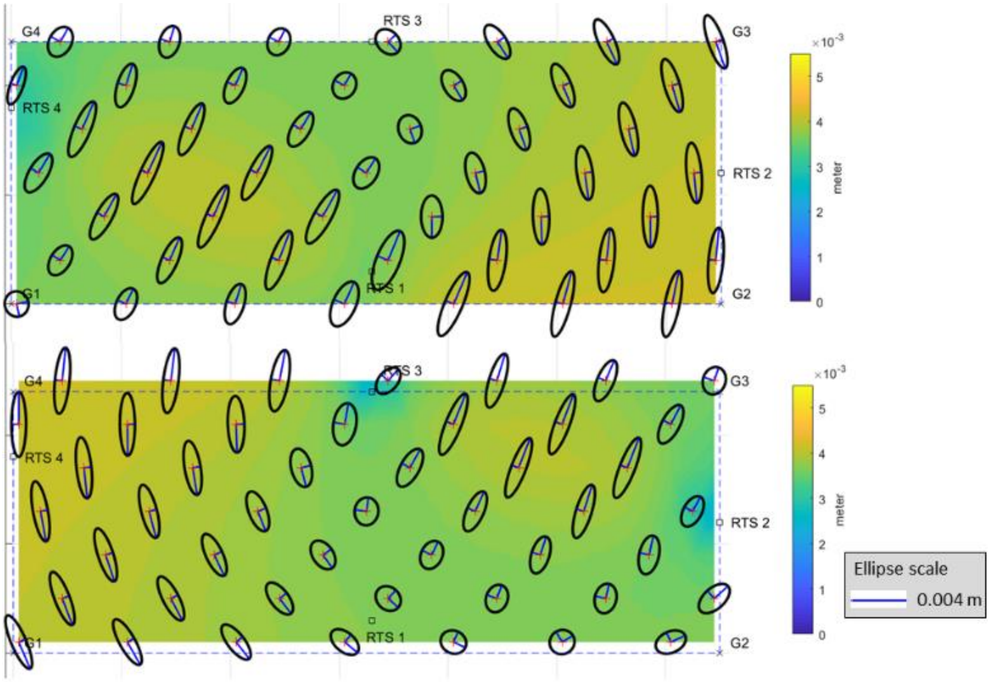

Figure 7: Confguration B, zonal positional accuracy representation and confdence ellipses; top – RTS combination 1/4 (prism 1); bottom – RTS combination 2/3 (prism 2). (Lerke and Schwieger 2021)

The following tables summarise the simulated and measured pose accuracies.

Table 2: *Summary of position accuracy results*

	Config. A	**Config B**
Simulated [mm]	2.5	3.8
Measured [mm]t	2.1	2.2

Table 3: *Summary of orientation accuracy results (configuration B only) (*depending on configuration)*

	Pitch θ	**Yaw ψ**
Simulated [°]	0.102	0.095
Measured [°]t	0.05 - 0.1*	0.05 - 0.1*

The standard deviation reach values within the 2 to 3 mm and the 0.05 and 0.1 ° region respectively. It is visible, that the simulated results match the measured results. For the overall view on the RTS-N reliability (not depicted here), the impacts of ∇_{l_i} on positions and orientations have been calculated and evaluated for each l_i. The evaluation reveals average impacts between 0.42 mm and 1.36 mm on positions and up to 0.054° on the two orientation angles of configuration B.

4. HOLISTIC QUALITY MODEL

4.1 Structure and definitions of the holistic quality model

Different quality models have been developed for different fields in recent years. These are used, for example, in software development (e.g. Ortega et al 2003). In geodesy, quality models have been defined for a long time 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. Zhang & Schwieger 2011). Theses quality models focusses on the technical aspect, in an interdisciplinary field such as IntCDC, the development of holistic quality model (HQM) is possible and essential important.

Fig. 8 illustrates the quality assurance concept for IntCDC, which was developed by three institutes within IntCDC for this RP: 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). It contradiction to section 3, where a concrete automation problem was solved with the help of engineering geodesy, this RPs has a very basic and broad topic that is concretized by the applications discussed in sub-section 4.3.

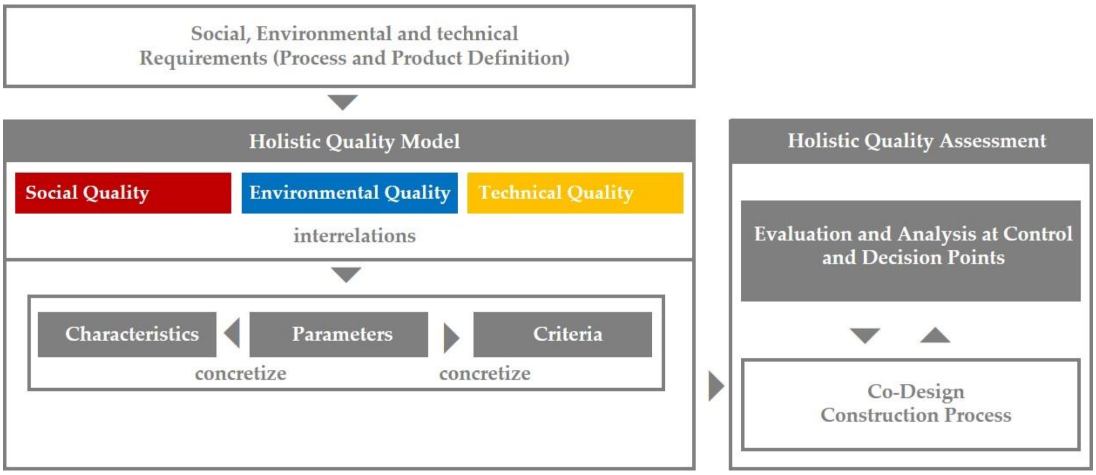

Figure 8: Quality assurance concept for construction process (Zhang et al 2020)

The quality assurance concept consists of two parts: a holistic quality model and holistic quality assessment. HQM (left part of Fig. 8) describes holistically the quality of processes and products and it is derived from the technical, environmental and social requirements of construction processes and products. The quality model consists of quality characteristics, which concretize the quality model. The product- and process-related quality characteristics are defined for the fulfilment of requirements of construction products (e.g., building components) and processes (e.g., the production processes for building components). For example, correctness and accuracy, completeness, conversion, recycling as product-related quality characteristics and time, cost, work intensity, transparency, emissions and resource consumptions of process process-related quality characteristics.

The quality characteristics define the structure of the quality model qualitatively. For concretization of the quality characteristics, several quality parameters (quantitative measures) can be defined. For example, accuracy is defined as quality characteristic; the corresponding quality parameters could be the standard deviation, the maximal deviation etc. Furthermore, quality criteria are defined based on the quality parameters for quality assurance purposes. A quality criterion defines a target or a sub-target of a quality assessment, which means that optimization of one quality parameter is needed, (e.g., the standard deviation should be minimized, or the emission and resource should be as low as possible and the production process should be as transparent as possible) or a critical value for a quality parameter that should not be exceeded (e.g. tolerance of the component size defined by standards should be met). In some cases, instead of optimizing an individual parameter, some quality characteristics need to be optimized or should be simply available, e.g., “conversion should be possible”.

Futuremore, the interrelations between the quality characteristics and quality parameters of these three quality aspects form the key elements within the HQM. Simple examples of interrelations are: if the component is not produced correctly (tolerance is not met), the component will be discarded, then emmision and resource consumption will be higher; gernelly, for higher load-bearing resistence more material will be used and the resource consumption will be higher, with higher loading-bearing resistence the adapbility of the building in the future will be better.

The holistic quality assessment (right part of Fig. 8) is based on the HQM and takes place at control and decision points integrated into the construction process. Control points specify situations in the construction process where certain quality characteristics and parameters of processes or products can be defined, measured and assessed with regard to quality requirements. The decision points are situations in the construction process where a decision with relevant influence on process or product quality is made either by humans or by algorithms. To provide feedback on potential quality-related implications of a decision, the potential future quality characteristics and parameters resulting from the decision are predicted through simulation (e.g. Monte-Carlo-Simulation).

The geodesists are close to control points of the products. However, sometimes it is already too late to take any actions if e.g. die tolerance of a component is not met. Therefore, process-integrated control points are essentially important. In section 4.3 examples of control points for the production process will be introduced.

4.2 Technical quality model

As the different quality requirements of the disciplines within IntCDC differ widely, at the beginning of the first network phase a survey was conducted to collect the various quality characteristics, parameters and criteria and receive a better understanding of the meaning of quality for the involved project partners. The results of the survey show that the technical quality is of great importance for all disciplines. Additionally, the survey shows that the technical requirements are mostly oriented on national norm and standards with the exception of newly developed building systems where there is currently no common standard that can be used (Balangé et al. 2021).

The technical quality can be divided in two main parts. The product related and the process related quality. For the product related technical quality are the building physical requirements with for example the load-bearing capacity or the exposure class and the geometric quality with characteristics like correctness or accuracy. Additional characteristics like fire protection or sound insulation have to be considered. For the process related quality the timeliness of the production process or the availability of all necessary elements are important characteristics. Some exemplary quality characteristics and parameters for concrete and timber building components are shown in Table 4.

Table 4 Exemplary quality characteristics and parameters for the technical quality concept for IntCDC for concrete and timber building components (Balangé et al. 2021).

Quality characteristic	**Exemplary parameters**
Accuracy	Standard deviation
Correctness	Tolerance correctness
Completeness	Number of missing elements, Number of odd elements
Load-bearing capacity	Load application time, Pressure, tension
Water permeability	Stress class

From the geodetic point of view, the focus within technical quality is on geometric quality. For the characteristic of correctness, the tolerances, which are in this case the quality parameter, of the building components needs to be checked. Here it should also be taken into account how the different tolerances of components are propagated through the construction process. According to different disciplines they are on the one hand either summed up (linear propagation e.g. in mechanical engineering), or on the other hand the overall tolerance is calculated using tolerance propagation as it is also common in the field of geodesy (quadratic propagation e.g. in civil engineering). This need for tolerance propagation shows also the general importance of methods for the propagation of quality through the process. This can be done at defined decision points to support the architect or civil engineer within the construction process to possibly adapt some parts of the design or the construction process itself.

4.3 Exemplary geometric quality assessment

In the following the technical quality assessment will be exemplary shown for two construction systems developed within the cluster. The prototypical production processes for gradient concrete and for fibre composite systems serve as application examples. For the quality assessment, the control points within the manufacturing process as well as the final component are considered. In addition to these control points, there are also decision points in these processes. However, technical quality is mostly assessed at control points, so that only these will be considered in more detail below.

The ***first example*** deals with gradient concrete. The aim of gradient concrete is to reduce the mass of the components and save material through this. Research on this is being carried out by the Institute for Lightweight Design and Construction (ILEK) at the University of Stuttgart as part of the Cluster of Excellence (Blandini and Sobek 2020). For this purpose, hollow bodies, in this case hollow spheres, are inserted into the component. Depending on the application, the size of the individual spheres as well as the number and distribution of the spheres in the component varies. Hollow spheres of different sizes can also be used within a component in order to achieve an optimum utilization. For the building physical characteristics, such as the load-bearing capacity, the position of the spheres is of great importance (Kovaleva et al. 2019). As part of the cooperation, a measurement and evaluation concept was developed which monitors both the sphere positions during production and the concrete height and distribution after each production step. A major problem with gradient concrete is that it can float the spheres during the casting process. This happens mainly when the concrete is not evenly distributed in the mould. For the quality assurance concept developed here, Terrestrial Laser Scanning (TLS) measurements were done. These were first carried out after the hollow spheres were placed in the formwork and later repeated after each concreting step. The interval between two concreting steps is about 10 min, so that an evaluation should be carried out within this time.

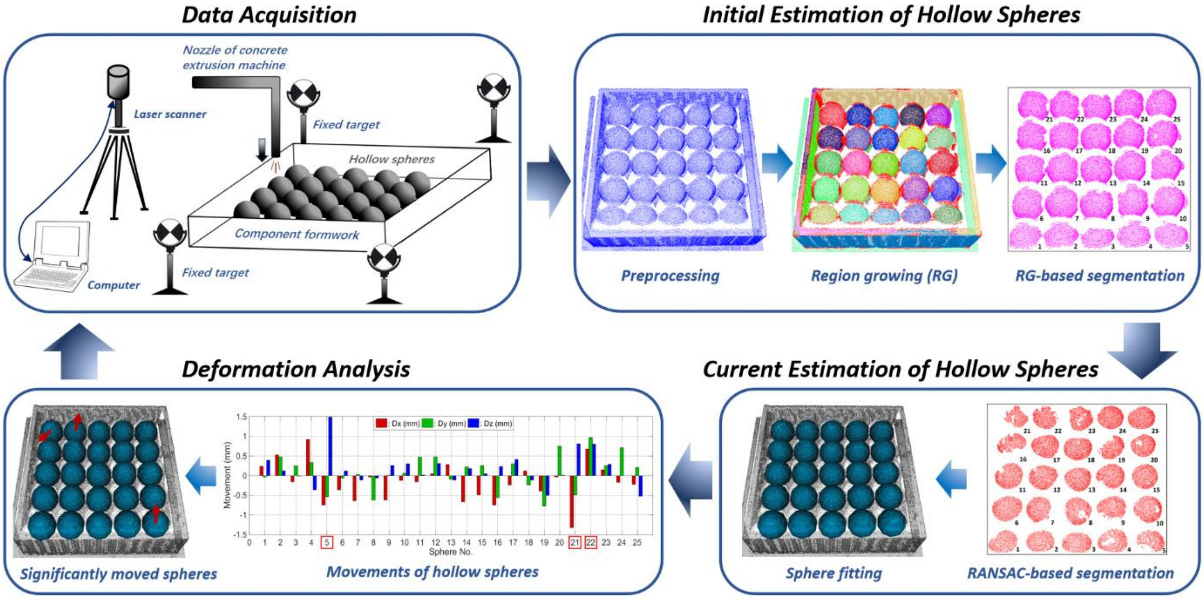

Figure 9 Measurement and evaluation procedure for technical quality control for graded concrete components (Yang et al. 2021).

Each concreting step thus corresponds to a control point of the quality assurance concept. At this point, the characteristic of correctness is checked by the parameters tolerance of the radius of the sphere or the position of the sphere. In this case, the associated criteria would be compliance with the tolerance. Furthermore, the accuracy of the sphere detection is evaluated, in this case the measurable parameter is the standard deviation of the estimated centre of the sphere and the criterion is the minimization of this. Lastly, the completeness of the sphere detection is evaluated, that is, the correspondence of the detected spheres with the total number of spheres. The last checkpoint is then located after the completion. Here, the verification of correctness, i.e. compliance with the tolerances of the component dimensions, is the central quality characteristic (Balangé et al. 2022).

The evaluation algorithm now performs an initial estimate of the sphere positions after the first measurement epoch. For this purpose, the point cloud is first pre-processed and filtered. Subsequently, the individual hollow spheres are segmented by means of region growing and then the sphere parameters are determined via a RANSAC-based estimation. Here, in addition to the coordinates of the sphere centre, the radius of the spheres is also estimated. To determine the movement or deformation, the coordinate differences of the sphere centres in X, Y and Z are considered separately to obtain information about the possible sphere movements and, in consequence, to be able to detect a possible floating up of the spheres (Yang et al. 2021). The sequence of measurements and the evaluation process is shown in Fig. 9.

The ***second example*** for the technical quality control within IntCDC is the production of coreless filament winding components. The use of fibre composite systems is common in aviation or also in the automotive industry for a long time. Positive material properties such as low thermal expansion, corrosion resistance and the strength-to-weight ratio of carbon fibre composites are some of the reasons for this (Fitzer 1985). At the University of Stuttgart, the manufacturing technology of the coreless fibre winding process has been further developed in recent years and the possibilities of these materials in construction have been demonstrated in several demonstrator projects (Menges and Knippers 2015).
A special challenge for the technical quality assessment is that there is no CAD model or an explicit geometry of the building components available up to now. The reference model for this elements is a line model without given thickness of the individual lines. Nevertheless, the real cross-section and the position of the lines is of great importance also with regard to the structural analysis of the components.
In the experiments used in the following, carbon fibre bundles pre-impregnated with epoxy resin were used. The fibre/resin ratio was 50:50. After production, the impregnated carbon fibre bundles were wound onto spools and stored frozen until use. When production started, they were taken out of the freezer to thaw 40 minutes before starting production. The production itself was carried out by a KUKA robot with a 6-axis robotic arm. The elements themselves were mounted on a manufacturing table, which could be moved around 2-axes. For quality assurance TLS measurements were carried out during production, whenever a new intersection was created, and after the completion of the element. The production set-up is shown in Figure 10.

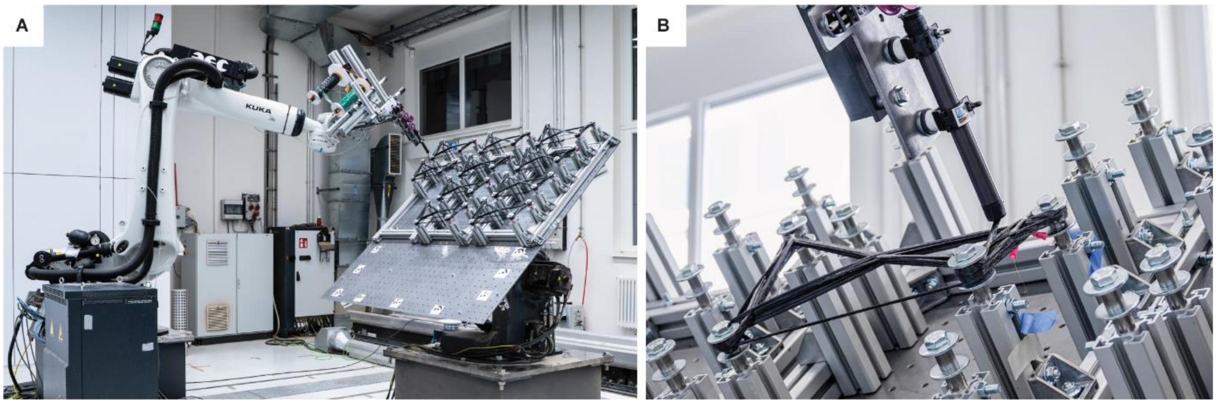

Figure 10: Fabrication set-up with KUKA robot (A) Exemplary element (B) (Gil Pérez et al. 2022).

For the evaluation of the measurement data, both for the measurements during production and for those of the final product, line segmentation and mesh generation are of great importance in order to enable comparability with the planning data. The segmentation can be done manually, as well as automated with methods such as the Hough transformation (Dalitz et al. 2017). In both evaluation methods, the line parameters have to be estimated after the segmentation. Ten, intersections can be calculated based on the segmented lines and the network topology of the real object can be generated. In addition, the individual lines were divided into 1cm segments, at which the cross section area was calculated. For this purpose, all points of the point cloud, which are located within the segment, were extracted and then projected onto a plane with the direction vector of the associated line serves as the normal vector. The convex hull was then calculated for these points and the area of the cross-sections was calculated using the points that define the convex hull.

In the context of the quality model the characteristics correctness, with the parameter of the line parameters as well as the real cross sections, the accuracy with the standard deviations of the line estimation and intersection calculation, as well as the completeness of the measured point cloud are important. The definition of the criteria is in this use application still difficult, since the production process itself is still under development and target values cannot be defined yet.

5. CONCLUSION AND OUTLOOK

This contribution highlighted the importance of geometry and therefore engineerng geodesy within the design and constrction process. Especially, it focusses on exemplary research projects within the Research Cluster IntCDC. Essentiual compoenets aof engineering geodtic rsearch as e.g. digitalization, automation and quality modelling and quality control are highlighted. One RP deals with te concrete issue of providing seamless positioning for the control of a so-called spider crane for assembly processes. The other RP has developped a holistic quality model for the whole excellence cluster and, for the engineering geodetic part, focusses on quality control of completely new production processes with partly even new materials. As the consequenec, for the first RP already promising results are presented, whereas for the sencond RP the devlopments are ongoing and intemediate results are shown.

For the second phase of IntCDC the authors hope that the RPs will be continued or even extended. It is planned that seamless positioning methods will be supplemented by image processing techniques implemented on image-assisted total stations as well as by SLAM approaches. Additionally, the application of the holistic quality model sand quality control shall be intensified with a focus on fibre composites.

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