Direct Co-registration of As-built and As-designed Data in Digital Fabrication

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Abstract: Additive Manufacturing in Construction (AMC) provides the possibility to print objects in unprecedented and novel ways, pushing the boundaries of what was previously possible in construction. Nonetheless, this requires an adequate and accurate co-registration of the digital representation of the printed object (as-built) with its digital model (as-designed) in order to achieve a robust quality control (QC). Most common automatic approaches are based on ICP-like distance minimization algorithm and target-based direct transformation. ICP suffers from the local minima problem and might take relatively large time to converge. Accordingly, we describe an experimental test specifically designed to underscore problems posed by objects with ambiguous surface structure which renders ICP unsuccessful. In order to overcome these shortcomings, we established a reference surveying network and transformed it to the robot (model) coordinate system. In this way, all future measurements could be transformed to the same coordinate as our as-designed model which is a pre-requisite for further inspections. The overall registration quality resulted in an RMSE of 3 mm.

1 Introduction

Digital fabrication is a design and manufacturing workflow where digital data directly drives manufacturing equipment to print parts and components of varying geometrical complexity on demand (BUCHLI et al. 2018). Compared to other current industries, however, construction is still the least digitized (AGARWAL et al. 2016; PLACZEK et al. 2021). Additive Manufacturing in Construction (AMC), however, streamlines traditional construction processes while allowing even more complex objects to be created more quickly. The use of digital construction workflow planning that relies on bi-directional workflow data, based on the so-called digital twin (EL-SAYEGH et al. 2020), is also far more efficient than analog planning processes. Construction components manufactured through AMC have nearly no limitations in terms of their complexity or shape, and require no special tools for their manufacture except for the printer itself. In doing so it decouples the cost of specialized or complex building components from their previous costs- originally such components would have to be specially ordered or manufactured offsite. Finally, by employing 3D printing, which has consistently proven to be more efficient in its direct use of materials and resources, digital fabrication, reduces waste (EL-SAYEGH et al. 2020).

Digital fabrication cannot be understood separately from the digital workflow process that drives it, which includes how a constructed space is digitally visualized. In order to better understand how digital fabrication in construction works, it is necessary to understand the concept of a digital twin. A Digital Model is a representation of the physical space and does not have any interaction

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with the digital space. A Digital Twin employs a bi-directional data flow between physical objects and digital spaces that allows the physical objects to be modified (EL JAZZAR et al. 2020).

AMC necessarily relies on smooth bi-directional data flow between physical construction spaces and components on site and the virtual environment that models and drives their production. This bi-directional data flow is the heart of digital twin, and is required throughout the entire length of the construction process. In order to accurately print construction components, continuous scanning and quality control is needed in at every step of the multi-step manufacturing process. Before the next step of a sequential workflow can proceed, active and layered scanning data must be instantly available to ensure quality control. The object being manufactured must be scanned after pre-defined production steps and compared with its digital twin to ensure that it conforms accurately with predefined tolerances of the production standards (PLACZEK et al. 2021).

Quality control (QC) can be broken down into two categories: QC without a previously alignment with the as-designed model, and QC based alignment with the as-designed model. The first category of quality control is concerned with inspection of the geometric features of a physical object, such as its edges or relative dimensions. The second, however, is concerned with finding deviations between the printed model and the designed model. This step requires that both models be co-registered accurately, as that the digital model holds the ground truth of the object (GUO et al. 2020). In other words, one approach is required to continuously scan the physical object and determine its size and shape, while another is required to compare the manufactured object with its as designed model. To fully capture the object through a data capturing technique, such as Terrestrial laser scanning (TLS) in our case, however, demands that different scanning stations be aligned into one coordinate system as well. To this end, scanning data from various scanning stations on site must be co-registered together and then accurately co-registered to the as-designed digital model for further inspections.

There are a variety of approaches for co-registration of a point cloud to a model or another point cloud (CHENG et al. 2018). The most common algorithms are distance minimization approaches, such as ICP-like algorithms (ICP: iterative closest point (BESL & MCKAY 1992). Direct co-registration, in contrary, is of advantage since it is independent of the actual object geometry and problems imposed by an iterative approach are not expected. When direct co-registration uses artificial targets on the object, it is required that those are seen in both, the captured data and the model. This requirement is often not practical since during object production the placing of markers is not possible. ICP-based algorithms can only work in principle if the shape and size of objects to be co-registered are similar. If objects have different size or vary in geometric details, for instance in the problem at hand, the model has another size than the actual realization the algorithm will tend to average and distribute the error between the two objects as shown in Fig. 1. Fig. 1 shows an as-designed model (wax material) registered with the as-printed model created from the captured point cloud using TLS. Fig. 1 (left) indicates that deviations are averaged out, due to the ICP registration between the two models. This is obvious on the top surface, ICP method indicates that the we need more material, while Fig. 1 (right), where a direct co-registration is used, a subtraction of the material is needed where we didn't average out the error. The used direct co-registration approach will be explained in Section Experiment Setup & Results3. Also, ICP is known to be susceptible to local minima if surfaces are ambiguous or the initial solution is not close enough to the optimum. Fig. 2 shows the registration result of the two identical point clouds. However, the ICP-based registration algorithm ended where still a bias between the models in the z-direction exists.

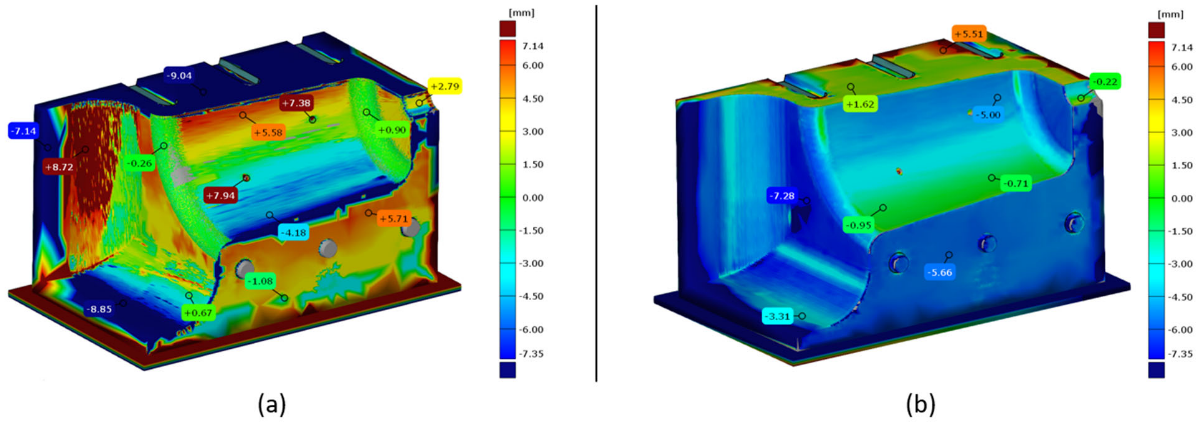

Fig. 1: As-printed model vs. As-designed model. (a) registered with ICP algorithm, (b) Target-based registration

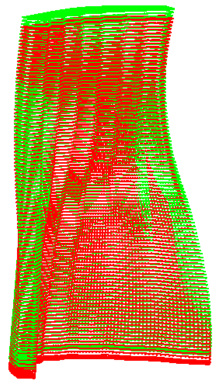

Fig. 2: ICP-based registration of two synthetic data from a wall model

Furthermore, ICP relies on rough co-registration of models, a process that can be time-consuming especially where time is an important production factor. In general, in order to enable proper co-registration and convergence to the correct optimum, the surface geometry in the overlapping area needs to resemble at least three major normal directions which are not parallel.

This paper will introduce a direct registration method between the TLS-captured point-cloud of printed object with the as-designed model. In the next section we will discuss related work surrounding registration. Our own experimental, direct co-registration setup and results will be presented in Section 3. Lastly, our conclusions and future ideas will be discussed in Section 4.

2 Related Work

Co-registration is a fundamental task that brings two or more data sets into one common coordinate system. Due to availability of various sensors which could capture different data from the objects of interest, the need to coherently combine these data sets is crucial. One of the most common approach in surveying for registration is artificial target-based registration. Targets must be placed in suitable locations in the capture area for co-registration. In the usual case of a three-dimensional object-space at least three non-colinear targets must be placed between adjacent scanning stations. The other common method for registration is ICP, in typical registration pipelines proposed by (RUSINKIEWICZ & LEVOY 2001), the registration of two-point clouds can be split into the following steps: i) Selection: The sampling of the input point clouds. ii) Matching: Estimating the correspondences between the points in the subsampled point clouds. iii) Rejection: Filtering the correspondences to reduce the number of outliers. iv) Alignment: Assigning an error metric, and minimizing it to find the optimal transformation.

Firstly, in the selection method of (BESL & MCKAY 1992) all the available points are used, which is time consuming. On the other hand, the normal-space sampling strategy is good for incised mesh surfaces that guaranties enough samples on the groove to bring the surfaces into alignment (RUSINKIEWICZ & LEVOY 2001). Secondly, there are a variety of matching strategies such as the shortest Euclidian distance (Closest point) from aligned entity to the reference entity data (BESL & MCKAY 1992). On the other hand, other researchers computed the distance between the two aligned entities in the direction of the source point's normal (CHEN & MEDIONI 1991). Nonetheless, filtering strategies are important since they are used to reduce the noise in the data for registration to exclude their effect. One method is to reject pairs with distances more than 2.5 times the standard deviation (MASUDA et al. 1999). Another method is based on rejecting the points on the boundaries (TURK & LEVOY 1994). Excluding pairs, that include points on mesh boundaries, is especially useful for avoiding erroneous pairings, that cause a systematic bias in the estimated transformation in scenarios where the overlap between scans is not completed. Lastly, error metrics are used to measure the error between the two entities as point-to-point that utilized the squared of sum distances (BESL & MCKAY 1992). However, other methods such as point-to-plane are used to find the optimal transformation. This method minimizes the sum of the squared distances between a point and the tangent plane at its correspondence point (CHEN & MEDIONI 1991). Each iteration generally is slower than the point-to-point version, however, often at significantly better convergence rates.

The output from TLS is a discrete point cloud which is a sampling point of the captured object and does not reflect all of its details, in particular the boundaries. In addition, the point cloud usually contains noise resulting from uncertain sensor measurements, environmental influences or surface material properties. If ICP should be used to co-register two TLS-based point clouds or a TLS-based point cloud and other data, it requires an initial registration of the datasets. Thus, many researchers provided an improvement to the algorithm (YANG et al. 2016; ZHOU et al. 2016). A global optimal solution for registration (Go-ICP) using the scheme based on a branch-and-bound (BnB) that searches the entire 3D motion space proposed by (YANG et al. 2016). Go-ICP, does not require an initial alignment between the two data sets, however, the algorithm is considered to be time consuming. While, Fast Global Registration (FGR) proposed by ZHOU et al. (2016), considered to be efficient. Nonetheless, FGR does not guarantee an optimal solution and might fail if the noise is too high.

Numerous researchers utilized TLS for QC of construction elements (NGUYEN & CHOI 2018; WANG et al. 2018; BUSWELL et al. 2020; MABOUDI et al. 2020; TANG et al. 2022). However, different scans are still required to be registered to further proceed QC. WANG et al. (2018) extracted the geometric features like edges from the point cloud in order to compare them with their corresponding features in the CAD model. Hence, no co-registration needed between the as-printed object with its as-designed model. Nevertheless, the authors used ICP algorithm to register the different scan stations. On the other hand, other researchers performed a distance-based deviation analysis between the printed object and its digital model (MABOUDI et al. 2020; NGUYEN & CHOI 2018). Point-to-plane ICP-based registration was employed for fine registration between CAD model and the point cloud (NGUYEN & CHOI 2018).
In our case, during the production process, after each deposition layer of the material, the printed object has to be scanned and finally checked with its digital model as a means of quality control. To insure an automatic, streamlined and fast quality inspection procedure, our aim is to register the scanned data directly to the as-designed model.

3 Experiment Setup & Results

Our experiments are performed in the Digital Building Fabrication Laboratory (DBFL) at the Technical University of Braunschweig. The fabrication room contains two robots (Fig. 3): one for shotcrete 3D printing (SC3DP) (a printing robot) and one for subtracting the material from the printed object (a milling robot). Each robot has its own coordinate system and they are already coregistered together. In addition, this fabrication coordinate system is co-registered to the model space, that is, the coordinate system where models are designed.

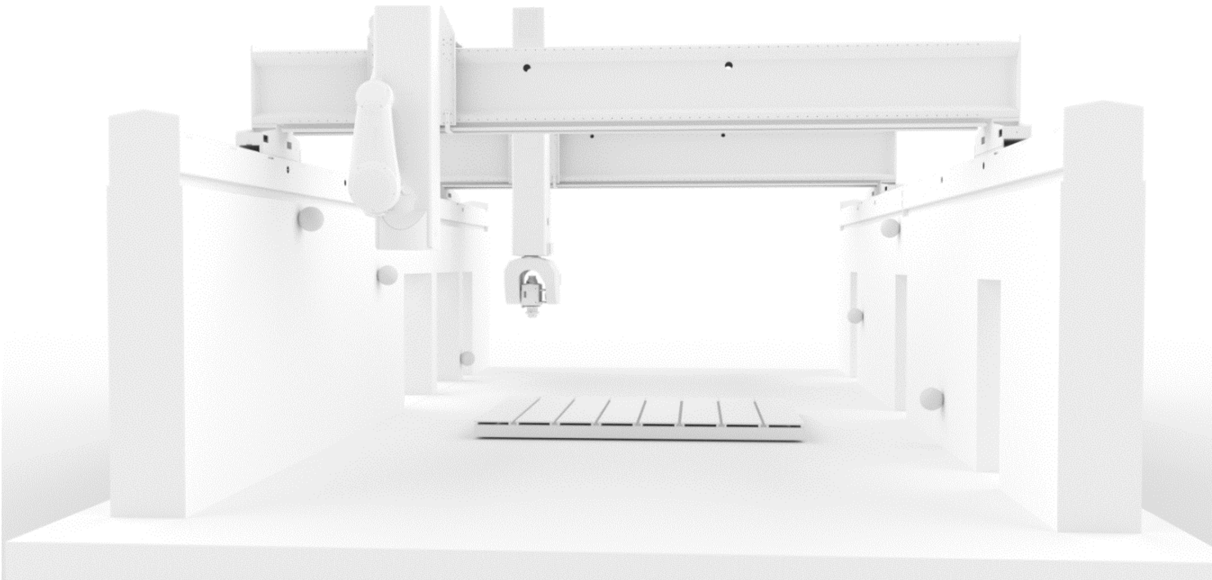

Fig. 3: Digital Building Fabrication Laboratory

Co-registration is thus required between different scan stations, and is also needed for comparison of the manufactured object and the as-designed model. Accordingly, our co-registration workflow

is divided into two main steps: i) Co-registration of scanning stations, and ii) co-registration with the as-designed model as conducted by the milling robot in our fabrication coordinate system.
A terrestrial 3D laser scanner Z+F IMAGER 5010X is utilized for scanning the printed object. For scanning, a closed loop of five scanning stations were placed in the fabrication room. To solve our registration task, the network planning in the fabrication lab for the points' measurement was done, as shown in Fig. 4.

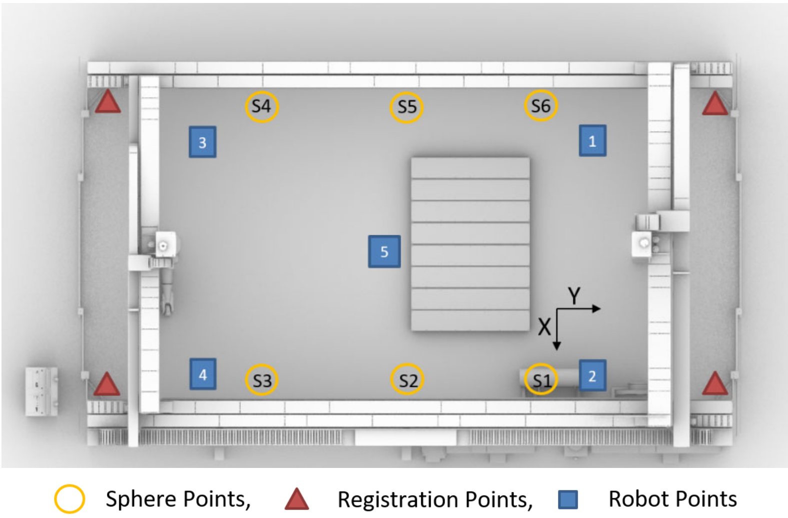

Fig. 4: Surveying network planning in the Fabrication room

In our experiment, we customized and combined a classical surveying network measurement and TLS measurement in order to bringing the as-built data to the as-designed model coordiante system.
We have three coordinate systems:

1- Surveying coordinate system: established using a Leica MS50 multistation.
2- Milling robot coordinate system (fabrication coordinate system)
3- TLS coordinate system.

The idea is that using surveying measurements, we establish a high quality framework which is connected to the fabrication coordinate system and could be used for any further data capturing in this fabrication room. To this end, first the surveying coordinate system was established. The measured points are the four registration points as well as the six sphere points using MS50, accurately. Best practices for surveying measurements (such as reading on the both faces of MS50 and considering the enviromental parameters) are employed to achieve a high quality network. The measurements of the spheres by MS50 were realized by measuring a prism that has the same height of the sphere radius. After the network adjustment, we achieved 1 mm for the maximum standard deviation of the points coordinates. Furthermore, we moved the robot to 5 points in the fabrication room (robot points in Fig. 4) and measured the position of the endpoint of the robot's using MS50 in our reference system. The maximum and minimum standard deviation of the adjusted network are 1.4 mm and 1mm, accordingly. A calibrated prism is attached to the robot to obtain its position on each of these five points as is illustrated in Fig. 5.

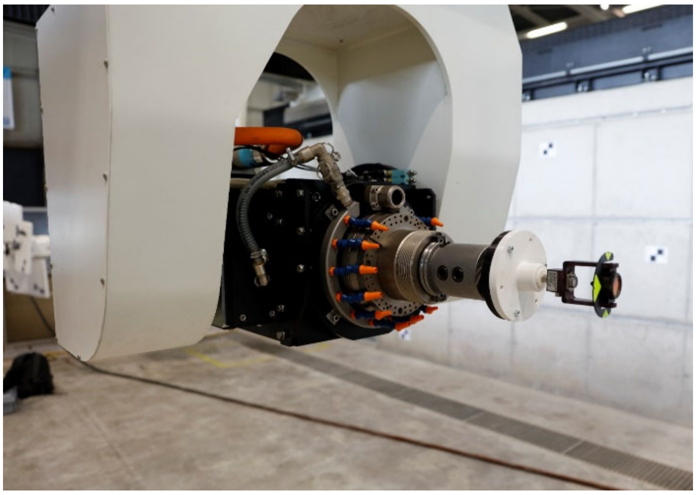

Fig. 5: Prism installed on the robot end effector

To summarize, we measured three sets of the points (Fig. 4) in our reference surveying coordinate system:

1- Registration points: Our surveying network's points to establish a reference coordinate system. There is no need to measure these points in the future experiments.
2- Robot points: To solve the transformation parameters between robot coordinate system and surveying coordinate system. Here also, there is no need to measure these points in the future experiments.
3- Sphere points: To localize TLS in all current and future experiments.

Therefore, in all TLS data capturing sessions in this fabrication room, we can localize our TLS using sphere points and transform the point cloud to the fabrication system directly and hence also a transformation into model space is possible. The positioning precision of the robots themselves has been determined to be better than a millimeter. The quality of our transformation, in fact, is in 0.5 mm range as it is shown in Tab. 1. The coordinates of five common points (milling robot points) are used to compute the parameters of a 3D Helmert transformation between the surveying reference system and robot system. The residuals of these points are listed in Tab. 1.

Tab. 1: MS50 (Surveying Coord. Sys.) to milling robot transformation coordinate system

	Residuals [mm]			
Robot point	3D	X	Y	Z
1	0.41	0.33	-0.24	-0.04
2	0.52	-0.25	0.45	0.06
3	0.57	0.17	-0.49	0.23
4	0.74	-0.61	0.00	-0.42
5	0.49	0.36	0.28	0.17
RMSE	0.56	0.38	0.34	0.23

The coordinates of the six spheres are calculated in the fabrication coordinate system by MS50 as well. These coordinates were used to transform the different scans to the room system. The overall registration of the point cloud with the surveying network resulted in a maximum deviation of 2.7 mm. The results of the registration are given in Tab. 2.

Tab. 2: Distances of spheres in coregistered point cloud to MS50 measurements

Sphere point	mm
S1	2.7
S2	1.6
S3	2.6
S4	2.1
S5	1.5
S6	2.2
Average Deviation	2.1
Standard Deviation	0.5

As it is shown in Tab. 2, the average 3D distance of the six sphere points (Fig. 4) to the corresponding points in our surveying coordinate system is 2.1 mm which is acceptable for most of the inspection processes in AMC.

We believe that the main source of these residuals is the remaining error in our surveying network (1.4 mm) accumulated by the co-registration error of our TLS stations (0.5-1.2 mm). However, the proposed strategy makes the inspection of AMC products in the fabrication room more straightforward and reliable against limitations of ICP-based approaches. The registration between the as-printed point cloud captured with TLS & the wax as-designed model is more reliable using the direct registration (Fig. 1).

4 Conclusion

This paper introduced co-registration of the printed object (as-built) and its as-designed model in context of additive manufacturing in construction. The most common methods for co-registering different entities are ICP-based methods. ICP, however, is time-consuming and often fails to achieve registration without coarse registration and is also susceptible to get stuck in local minima. In addition it assumes that the shape and size of reference and target objects are similar.

This paper expressed our experiments for employing and customizing the classic surveying and TLS measurement to coregister the as-built and as-designed model in additive manufacturing. After establishing an accurate surveying network, we used a 3D transformation to connect the fabrication (model) coordinate system to our TLS measurements. Therefore, for each of future measurements, we can transform the point clouds to the model coordinate system for quality inspection and deviation monitoring of the printed objects.

The analyses of the transformation between the fabrication coordinate system and the robot coordinate system demonstrated 0.5 mm RMSE. However, the transformation quality between scanned data and the fabrication room was in range of 3 mm. This is mainly due to remaining error in our surveying network, and also coregistration errors of TLS stations.
The obtained results are a step forward in increasing the reliability and automation of co-registration between the as-design model and its printed counterpart.
Further experiments are required to improve the accuracy and efficiency of the quality control process. One possible direction could be to employ scan planning before data capturing. This is especially very effective in our problem while the as-designed model of each object is already provided for printing process.
In order to increase the automation and skip the error prone steps of our coregistration process, we also conceptualized an idea to directly mount the TLS on the robot (Fig. 6). This provides the possibility to freely move the TLS in the printing environment, but also to directly transform the derived point clouds to the model space.

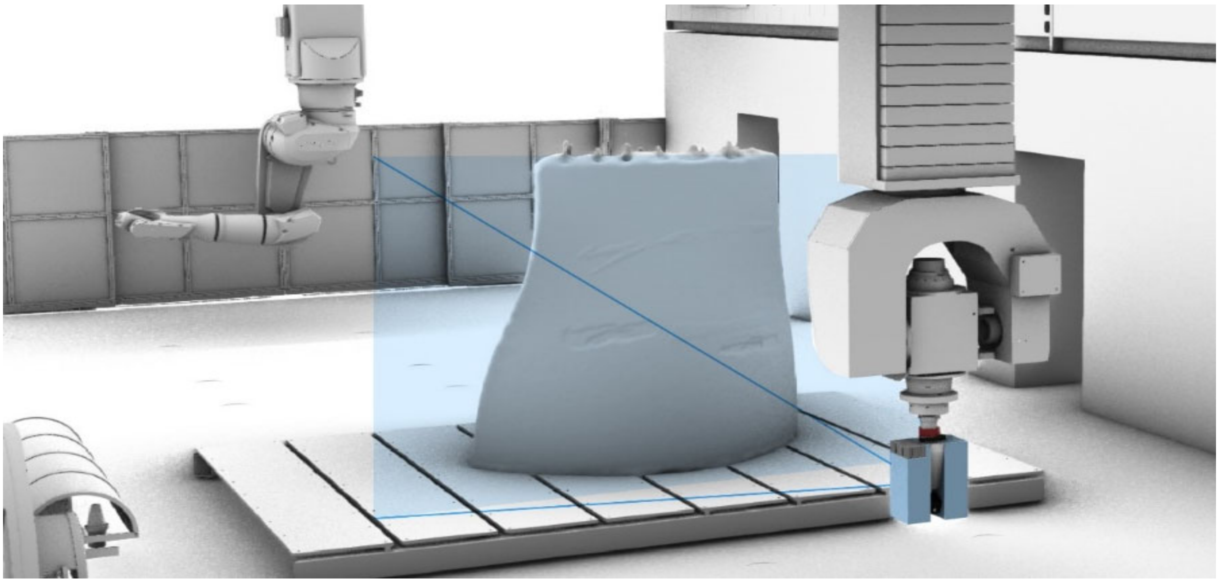

Fig. 6: Conceptual representation of mounting the TLS on the robot

Moving the TLS freely in the printing room, provides the possibility to scan those parts of the objects which cannot be captured through classical TLS setup (tripod on the ground). Moreover, 3D scan planning would be more applicable to increase the efficiency of data capturing.

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