Seamfully connected

Real working models as tangible interfaces for architectural design

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Abstract. This paper describes work conducted as part of an interdisciplinary research project into new approaches to using computer technology in the early phases of the architectural design process. The aim is to reduce the existing discrepancy between familiar, analogue ways of working in the early design stages and the increasingly widespread use of digital tools in office practice. Taking this as its starting point, a prototype for a design platform was developed. The core of the project is a direct, real-time connection between real volumetric models, an interactive 3D sketching-tool and interactive digital content that supports the design process. The conceptual and technical core of this connection is an integrated object recognition system. In this paper we describe the need for an integrated solution, the underlying conceptual idea and the recognition methods implemented including their respective strengths and limitations.

Keywords: Design Tool, Urban Design, Early Design Stages, HCI.

1 Introduction

Despite the widespread use of computers in architectural practice, they are still only rarely used in the early design phases of architectural projects. A primary reason for this is the poor human machine interaction of currently available systems. The starting point for the interdisciplinary teaching and research project "CDP" (Collaborative Design Platform) is to examine how digital tools can be used to support architects in the early design stages. The design scenario for our investigations was urban design at a scale of 1:500. The aim of the project is to reduce the existing discrepancy between established design tools (such as working models) and digital tools to eliminate discontinuities in the design process caused by having to switch between media. This desire to link the handling of existing design tools with the potential of digital tools formed the basis for the development of an interactive working environment that fits directly into the design process, and has been implemented as a hardware and software prototype. The digital systems are 'seamfully'[1] integrated in the established design-tools, closing the gap between

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[1] The term "seamful" can be attributed, according to Chalmers and MacColl, to Mark Weiser [1]. For Weiser seamless connections reduce components, tools and systems to their 'lowest common denominator' sacrificing the richness of each component. Instead, Weiser advocates what he calls "seamful systems (with

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analogue ways of working and digital design support tools. This is achieved not by replacing established design tools with digital tools but rather by combining the strengths of both so that they complement one another. Based on this concept, a hardware and software specification was developed. The key problem was to devise a way in which real objects can be digitised as a whole in real time so that they can be incorporated into the digital context and tracked without requiring additional handling or work steps that could interrupt the flow of the design process. The solution we developed is an integral object-recognition system that allows one to use familiar working methods with real, three-dimensional working models in direct combination with digital content. The requirements that the system needs to fulfil can be defined as follows:

- An integral solution is required to avoid interrupting the flow of the design process.
- Real-time digitisation of the model, using the volumetric blocks as “input devices”.
- The characteristics / degree of abstraction of the real blocks must be maintained.

With these requirements in mind, in this paper we discuss the conceptual considerations and technical implementation of the integrated object recognition system. A comprehensive overview of the collaborative design platform and prototypical implementation, as well as information on the hardware concept, is presented in an earlier paper describing our preliminary work [2]. Further publications describe the implemented plugin-framework, the 3D sketching tool and connection to an immersive visualisation environment [3–5].

2 Design tools

Design tools have always been essential to the architectural design process. But why are design tools so important for the creative process? Sketches and models are much more than purely a means of presentation. They can be regarded as thinking tools and pools of ideas. Through their visual and tactile feedback they contribute to an internal dialogue, also called “visual thinking”, that takes place while using design tools and makes it possible to grasp complex design problems and to work on them [6, 7]. They provide feedback and act as a kind of ‘conversational partner’, setting up a creative cycle between the designer and the tool. The more senses involved in this creative cycle, the more complete our perception of the feedback. In addition to our sense of sight, which can process “about 75% of the total available information”, our sense of touch plays an important role, especially in combination with a model [8]. What makes this particular sense special is that, alongside our perception through the five different sensory modalities, “the sense of touch is our primal and only non-distal sense – touching results in being touched.” [9, 10] This sense of touching and being touched, unlike other senses, establishes a “real” sense of dialogue in which the designer and the object of design are on one and the same level of perception. Its importance becomes clearer when one considers that “there are two processing streams in the brain – one involved with perceiving objects, and the other involved with locating and taking action toward these objects.” [11] In contrast to a hand sketch, trying out an idea or playing through a train of thought is anchored very much in the practical and direct manipulation of objects. The shifting, turning, distorting and cutting of physical objects supports the process of visual thinking in a much stronger way. This is what represents the essential quality of working with models as a design tool. Whether sketching or using models, what characterizes these established working methods is their simplicity, directness and lack of need for precision. These are not qualities computers are known for, and the rea-

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‘beautiful seams’)”.This makes it possible to retain the individual components and their respective strengths and still be able to achieve a consistent interaction experience.

son why indirect input devices such as a mouse and pointer are often more of a hinderness to creative processes than a help.

3 The design platform

If one examines in this context the typical working methods used today in the design process, one can observe the parallel and sequential use of “established” tools on the one hand and digital tools on the other. The individual tools are usually used independently of one another so that one has to constantly switch between the analogue and digital tools, consequently interrupting the thought process. The aim of the project is to resolve this discrepancy and provide architects with a working tool that, through an integrated workflow, supports the design process by providing objective assistance but without interrupting the thought process. To begin with, we defined the following objectives for an interactive design platform:

- Suitable for use as tool for thinking
- Integration into the design workflow. Intuitive HCI
- Direct connection of different design tools
- Provides direct feedback in the form, for example, of analyses and simulations.

Based on these requirements, the aim of using digital tools to facilitate the creative process cannot therefore be to replace established tools with digital counterparts. This would lead to a loss of tactile feedback and of the intimate connection between the designer and the object of design. Rather, established tools should be retained and made more useful by coupling them with digital content to bring together and reinforce the strengths of both realms. In the context of our research project this is achieved by creating a direct connection between real working models, an interactive 3D-sketching tool and digital design supporting information.

A prototypical design platform was implemented based on this concept. The prototype enables the architect to work as usual using models and sketches. The direct coupling of established design tools with one another and their enrichment with digital tools that support the design process make it possible for architects to work without interrupting the creative flow. Supporting information such as simulations, analyses and calculations are computed in real time and displayed in the analogue model (Fig. 1, left). The real model is augmented with additional digital layers of design-relevant information. Examples of this include the real-time simulation of shadow patterns or the real-time analysis of path distances or flow patterns. This additional real-time interaction allows the designer to immediately assess the impact of design decisions and provides objective information to assist the designer in assessing variants and justifying his or her decisions. The interactive coupling of model and hand sketch also makes it possible to sketch directly in the model and annotate the building volumes in a virtual perspective view of the design scenario (see Fig 1, right). The interactive sketching environment based on a real volumetric model, combines established design tools in a new and intuitive way and opens up totally new ways of approaching architectural design problems. The tool overcomes many of the interruptions caused by switching from model to sketch to computer visualisation, creating the conditions for a continuous design workflow. In addition, the ability to sketch over other sketches or to sketch inside other sketches provides immediate distortion-free feedback and facilitates the process of visual thinking in a completely new way.

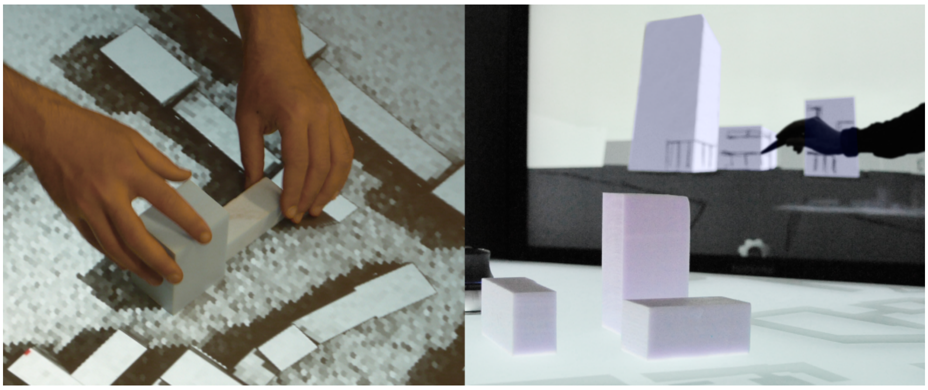

Fig. 1. The collaborative design platform in action.
Left: the real model is coupled with interactive content, here a shadow analysis. Right: Interactive sketching tool – real model in the foreground with perspective view on the vertical screen. The digital sketch and the real model are interconnected.

Using the working model en bloc as a direct input device introduces a series of entirely new interaction possibilities. In contrast to typical Tangible User Interfaces, the objects are not solely used as an adaptation of the control system. Through the markerless, direct connection between the physical and digital worlds, the analogue objects are connected to the interactive content not just in two dimensions but also as whole volumes, and as such become direct participants in the digital design scenario. The architect can work as normal using familiar design tools. Through the direct connection, all existing real information (shape, position…) is also available in real time as digital data, which is then made available for use by the aforementioned design support tools. Changes to the volume (cutting, shaping, etc.) are transferred in real time to the digital world and directly influence the tools and the decision-making process of the architect.

4 Prototypical implementation

To be able to use real working models as tangible interfaces, the core aspect of the project is consequently an integrated object recognition system. The focus here lies on the one hand on achieving a hardware and software solution that fits seamlessly into established ways of designing without introducing hurdles or fracturing the process into separate steps. On the other hand, the digital image must resemble the forms of the real building volumes as closely as possible. This doesn't necessarily mean that the model needs to be reconstructed in exact detail. The difficulty lies instead in replicating and maintaining the degree of abstraction present in the real model (which is in most cases vague and imprecise) in the virtual model. If the digital reconstruction is too precise, it can detract from the elementary nature of the real model.

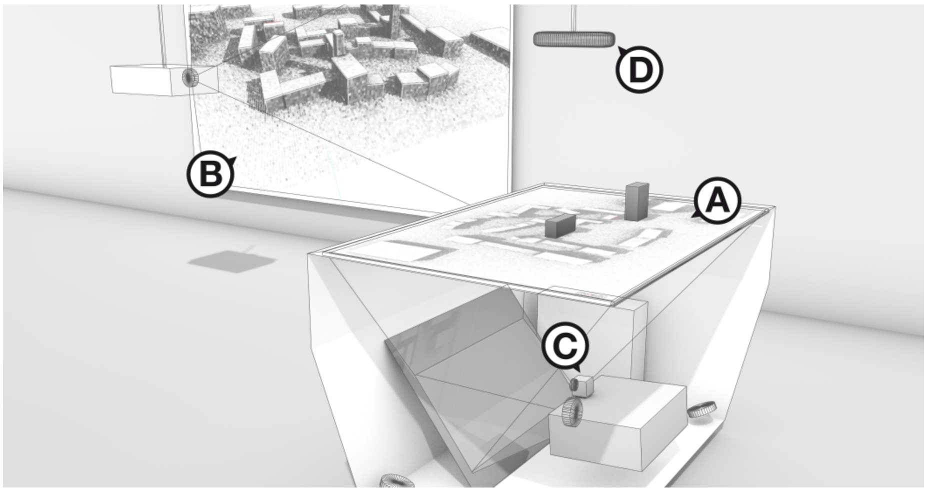

Fig. 2. Hardware setup

The above considerations have fundamental implications for the design of the hardware and software concept of the prototype. The hardware setup (Fig. 2) is based on a custom-made, large-format multi-touch table (158 cm × 96 cm). This is the work surface and design platform for the architect (A). The underlying plan information is derived from GIS data in CityGML format, which is displayed as a grain plan on the surface of the multi-touch table. A perspective view (B) of the entire scene is displayed on a separate, vertically mounted touch screen that accepts pen input. By using the "diffuse illumination principle" it is possible to recognize every item that touches or has been placed on the table. The camera (C) captures an impression of the "footprint" of the placed objects (position, size, angle, shape), anchors these in the coordinate system und makes it possible to track the movement of objects as well as of fingers. An additional IR depth camera (D) mounted above the multi-touch table captures the real 3D massing model on the fly. Each distinct element of the footprint is registered and allocated an ID, which can then be linked directly with the digitised 3D form obtained from the IR camera. This combination makes it possible for the user to shift or turn registered objects without its 3D form having to be recognised and computed anew. Every change to the real model – whether a block is recut, shifted, removed or a new object is placed on the table's surface – has a direct real-time impact on the digital image, and with it on the calculations, the perspective view and the virtual sketch.

The configuration of the prototype described here illustrates just how important integrated object recognition is to the operation of the system. Only by integrating such functionality directly into the system can a design platform be created that allows architects to work as usual using their established tools while simultaneously exploiting the potential of computer technology. The use of two different cameras (a top infrared camera and bottom black and white camera) extends what is possible to achieve with the software implementation and is fundamental for the reconstruction algorithms used to digitise the real working model in real time, as described in the next section.

5 Related work

With respect to the above, two different areas of related work have emerged as being particularly relevant. The first of these is work undertaken in the field of physical computing – especially in the context of architecture. The second is the aspect of object reconstruction in coupling the real world with the digital world which is of particular relevance from a software viewpoint.

5.1 Tangible user interfaces / Physical computing

The use of real objects as interfaces in the architectural context is not a new topic. The first projects in this field date back to John Frazer's machine-readable models in 1980 [12]. Frazer's prototypes made it possible to digitise real objects using a system of building blocks made up of "intelligent" cubes. This concept meant, however, that the hardware setup was restricted to using predefined building blocks. Another approach can be seen in the Urp project [13]. Urp made it possible to use analogue models to examine and control interactive simulations. Because it used marker tracking, it was first necessary to construct a 3D model which was then combined with the markers in the interactive scene. This intermediary step introduces an unnecessary interruption to the creative process and reduces the act of 'designing', unlike our approach, to the mere moving around of blocks. Another project that examines the connection between real and digital worlds is "Pictionaire": "It enables multiple designers to fluidly move imagery from the physical to the digital realm" [14]. Based on a multi-touch table with two additional top-mounted beamers as well as a high-resolution digital camera it is possible to direct interact between the aforementioned analogue approach and digital content in both directions: analogue to digital and back.

5.2 Object reconstruction

The topic of surface reconstruction is a widely studied problem dating back to the early 80s when it was applied in order to reconstruct surface models from medical images (e.g. bones reconstructed from medical CT scans) [15]. Our concern here, however, is reconstruction from (sparse and noisy) point clouds as produced by sensors such as the Kinect camera. One of the most prominent works on leveraging 3D data from cheap depth sensors like the Kinect is Kinect Fusion [16]. As the Kinect is able to output depth images (greyscale images where the pixel value corresponds to a metric distance) with a frame rate of 30 frames per second, the principle of this approach is to fuse the information from many of these frames into a single global 3D model while manually moving the Kinect within or around the scene. With this approach, however, reconstruction of the scene is performed as a whole and no segmented models of individual objects are obtained. Additionally, the hand-held based reconstruction approach used in Kinect Fusion would require the architect to divert attention from working on the model to the reconstruction process, again interrupting the creative flow. Of the multitude of general surface reconstruction algorithms available, the Poisson reconstruction [17] is of particular interest for our situation. It regards surface reconstruction as a global problem and is thus more resilient to local disturbances than local methods (such as the marching cubes algorithm). Poisson reconstruction is also known for being able to handle noisy input point clouds of varying density very well. The resulting mesh is smooth, evening out measurement noise but also rounding off object edges and creating closed surfaces.

6 Integrated object recognition

In the application scenario – urban design modelling – the 3D massing is limited to simple forms which correspond to the level of detail of a 1:500 scale model. The objects are typically rectangular blocks, simple extruded bodies and freeform surfaces like roof forms. To realise the digitisation and reconstruction of these forms in real time and on the fly, two different 3D object reconstruction methods were developed and implemented. Using a series of differently-shaped test bodies at a scale of 1:500, we tested both methods for their suitability at a level of detail of LOD1 and LOD2. The difficulty when working at this scale and design stage has less to do with the precision reconstruction of the model than finding an adequate form for capturing and presenting the vaguely defined architectonic forms. Therefore our assessment criteria was the authenticity of the reconstruction results with respect to the LOD standard and the real model.

6.1 Reconstruction Method 1

In the first method, a combined reconstruction was used. The basic form of the object is determined using the tracking camera inside the multi-touch table, which produces a two-dimensional image of the base of the object. Using this image, the 2D polygonal shape of the footprint of the object is determined and registered in the coordinate system. With this reconstruction method, this footprint serves as the base of the object. The Microsoft Kinect camera is used to estimate the average height of the object and the final 3D model is obtained by extruding the footprint to this height. The precise processing pipeline is as follows:

1. Detection phase: Obtain an approximate search region for the desired object to reconstruct via 2D tracking and capture its point cloud.
2. Refinement phase: Calculate the average height of the cluster of interest (COI) relative to the table plane by averaging over all of the COI's points in all the captured point cloud.
3. Reconstruction phase: Construct a 3D model by extruding the 2D contour to the estimated height.

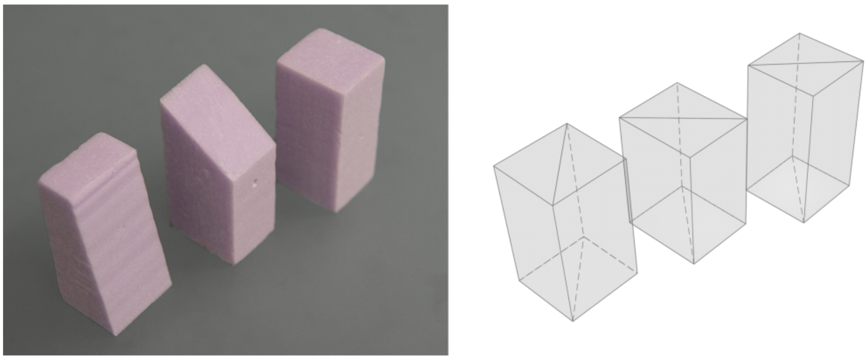

Fig. 3. Reconstruction method 1 – original and reconstructed shape: the blocks and slanted surfaces look almost identical in the digital representation

This approach makes it easy to reconstruct the volume of the element. For simple volumes such as rectangular blocks, cylinders and other 2½-dimensional bodies, this approach produces excellent results with clear contours and surfaces. Freeform shapes or shapes with slanted surfaces like roof forms are, however, simplified into 2½D bodies. Figure 3 shows the original and the resulting object after realtime-reconstruction. Using an average of more than one captured frame, the estimated height error for a 2½D object is within a range of 2-3 mm.

6.2 Reconstruction Method 2

While method 1 produces excellent results for cuboids and simple extrusions, surfaces with inclined planes or freeform bodies are straightened into blocks. To address this problem and support inclined surfaces and freeform shapes, a second approach was also examined. With this method, the implemented freeform reconstruction is a whole object 3D reconstruction performed using the point cloud data only (i.e. not the 2D footprint). The footprint is only used to determine the correct point cluster of interest (COI) and for tracking the object when it is moved. Because the full reconstruction of a 3D object viewed from one vantage point only is an under-constrained problem – some surfaces of the object (usually vertical walls) are not visible to the camera – this method therefore assumes that the non-visible surfaces are vertical extrusions from the base at the plane of the table. The processing pipeline is as follows:

1. Detection phase: Obtain view (centre position and orientation) of the desired object to be reconstructed using 2D tracking and capture its point cloud.
2. Refinement phase: The refinement phase tries to further subdivide the object into different parts (e.g. to separate a tower from an adjoining building) and estimates point normals necessary for the reconstruction.
3. Reconstruction phase: The reconstruction phase finally creates a triangulated 3D mesh of every sub-building and sets the object's coordinate frame

During the test run described, it became clear that this approach is more susceptible to errors than the first method (Fig. 4, Fig. 5). Complex shapes and freeform volumes are in general represented more accurately than when using the extrusion method. However, simple 2½D objects like rectangular blocks exhibit artefacts such as not perfectly orthogonal planes and plane subdivisions where the original shape is actually described by a single plane. This is mainly due to two reasons: we do not use the accurate 2D footprint for the extrusion in this case, and the point cloud data used is much finer giving rise to errors produced by sensor noise and individual missing depth measurements. The cause is simply the increased complexity involved. In contrast to the first method, the 3D reconstruction takes into account all points of the cloud to reconstruct the shape, and not just the height coordinates. This makes it possible to reconstruct complex shapes and freeform volumes, but simple bodies, such as rectangular blocks, are also analysed as a point cloud resulting in a triangulated form without clean edges or perfectly flat surfaces. Increasing the mesh density has shown that the finer the mesh, the more the shape is rounded off.

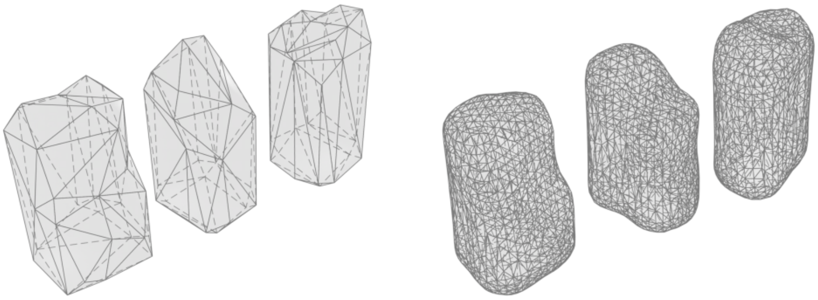

Fig. 4. Method 2. The reconstruction is based on the entire point cloud which makes it possible to reconstruct inclined surfaces, freeform shapes and complex blocks. Unfortunately the clean edges and flat surfaces of the corresponding real blocks (Fig. 3) are lost in the process.

6.3 Comparison

An analysis of each reconstruction method (figure 3-6: different building volumes at a scale of 1:500) clearly shows the strengths and limitations of both approaches:

Table 1. A comparison of the two scan methods

	Reconstruction Method 1	Reconstruction Method 2
Method	Extrusion of footprint to averaged height	Freeform top shape is converted to blocks and smoothed
Result	2 ½ D | extruded 2D form	Simplified 3D form

Disadvantages	Only simple, cuboid forms (2½D) can be realistically identified and represented. Freeform shapes are approximated as 2½D shapes.	Simple volumes are not represented as simple geometries due to measuring noise and errors. They show as complex shapes with non-orthogonal angles and unnecessary surface fragmentation, causing simple volumes to lose their clean edges and planar surfaces. Small deviations cause “dents” in the mesh. This method is more error prone.
Advantages	Clear edges and surfaces are retained. The averaging out of block heights compensates for errors.	Makes it possible capture freeform shapes and roof surfaces.
LOD	Level of Detail 1	Level of Detail 2 and above

Fig. 5 shows a selection of test bodies (A) and their representations digitised with method 1 (B) and method 2 (low (C) and high mesh density (D)).

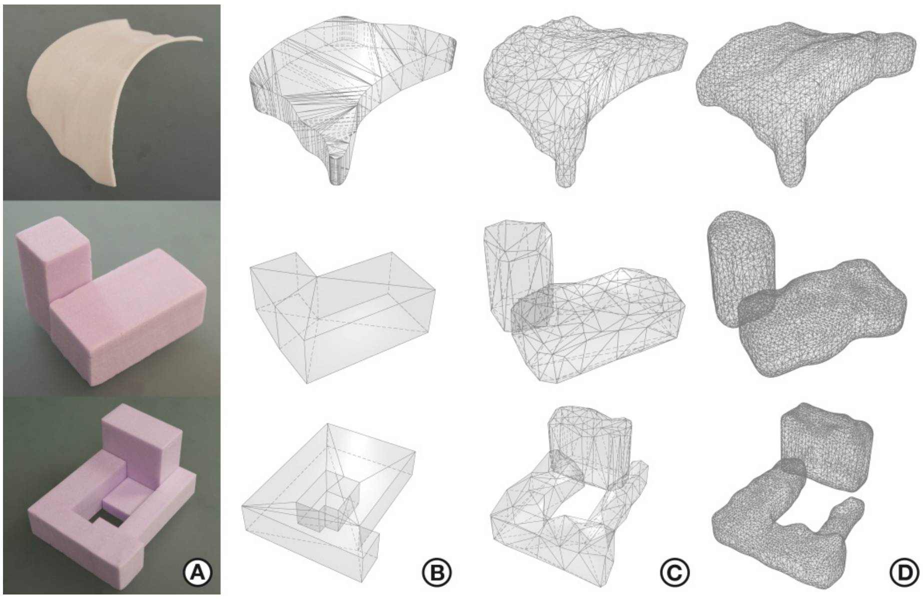

Fig. 5. A comparison of both reconstruction methods using different basic forms.

7 Future concepts

In future, we will examine potential concepts for improving the results of the reconstruction module. A particular area of focus will examine algorithmically combining the strengths of both systems. The following extensions will be investigated and compared with the existing methods:

- Moving Kinect cameras with multiple vantage points: as the Kinect Fusion [16] project suggests, reconstruction accuracy can be greatly improved by fusing data from frames captured from different vantage points.

- Combined base and top detection using the 2D object footprint to constrain the freeform reconstruction. By using an approximation algorithm, undercutting and other complex shapes reconstruction can be improved.
- Primitive based: surface reconstruction by fitting simple geometric objects such as planes, boxes, spheres, cones and so on into the point cloud. Schnabel et al., for example, further extend this primitive fitting approach by detecting architectural primitives like pitched roof forms or dormers [18].

8 Conclusion

The setup described in this paper is a design platform for the early urban design stages that closes the gap between the real and the digital world and makes it possible to achieve an uninterrupted connection between established ways of working and digital design tools. The conceptual and technological implementation is based on the integrated object recognition of physical models at a scale of 1:500. The two methods for real-time object reconstruction that are described here show clearly the potential and possibilities of the project's approach. In addition, the test runs conducted clearly show the strengths and weaknesses of the respective individual methods. With respect to the criteria that for the reconstruction of the real model, a replication of the existing degree of abstraction is more important than a precise millimetre-scale reconstruction of the object, neither of the implemented methods is universally applicable. It is conceivable, however, to use each of the different methods for different situations, depending on the level of detail (LOD) required: method 1 is best suited for work at LOD 1 (buildings are cuboid forms or simple extrusions of the floor plan) while method 2 is better suited when freeform shapes and inclined roof forms need to be reconstructed – even though the clear-cut surfaces and edges of the volumes are lost in the process. Fig. 5 shows clearly, that a fine mesh size suites best for freeform shapes while a rough mesh is best for slanted surfaces. The use of automatic mode-detection could be used to employ the respective reconstruction method depending on scale and level of detail. Future research will examine alternative extensions based on the existing implementation with a view to developing a generally usable concept and algorithm for different forms of buildings. In order to be able to support further LODs in future, approaches to reconstructing undercut forms and other similar problems will be examined.

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