



Integrative Mixed Reality Sketching

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Abstract

In Architecture, Engineering and Construction (AEC), early design decisions have great impact. Sketching is a fast and immediate early design tool and means of communication. Communication with other professionals is challenging, because of varying professional languages.

We propose a novel integrative sketching application to improve communication. Our application uses mixed reality interaction to allow sketching directly into 3D space, capture the process as temporal data, utilise animation in form-finding. We describe an exemplary workflow that integrates parametric geometry generation and digital manufacturing domain expert feedback into the early design phase of sketching via real-time data exchange.

The workflow is evaluated by architectural design experts. Our findings indicate that the immediate domain expert feedback coupled with the novel 4D freehand sketching approach is a highly proficient way of aiding design decisions and streamlining AEC processes, improving communication between designers and mathematicians.

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1. Introduction

AEC is a collaborative workflow. It is the combined effort of numerous experts with different professional skills, backgrounds, methodologies, and communication cultures. In practice, the flow of information between these professionals is often temporally displaced. As a result, feedback and the exchange of ideas is not direct and immediate. By improving communication, we can also improve the design process workflow. By improving the workflow of the design process, we might improve the quality of the design itself.

Decisions made in the early design phases are particularly important. These decisions can have a far-reaching impact. If problems are discovered late, adjustments and corrections can have significant temporal and financial implications. To ensure that all professionals involved can contribute their expertise in the most effective manner, a workflow and communication process must be established that provides a common platform for the exchange. In practice, this often proves difficult: The professionals involved usually have different working conventions, terminology, and toolkits, which hinders seamless communication. Some professionals are only involved at a later stage of a project and cannot contribute to decision making in the early design phases.

To improve the efficiency of AEC processes, a central integrative communication platform is necessary. Such a platform must be centred around early design tools, ensuring the highest impact of informed decisions. The most formative of early design methods is sketching. Sketching is the earliest stage in the iterative process of architectural form-finding. It involves a multitude of techniques beyond the commonly associated pencil-on-paper modus. Sketching is fast, immediate, and expressive, it is a strategy, a selection procedure, and a form of communication. It is more than just a design tool. Sketching is thinking: thinking about form, about shape and about different realisations thereof. To truly enable thinking about form, sketching should not be limited or hindered by its tools.

A truly impactful tool for architectural design is one that allows the creation of informed sketches: unhindered expression of form, enriched with domain expert feedback to supplement decision making. Considering this, we propose the creation of a sketching application that can act as a central integrative platform throughout the entire design process. Our goal is to seamlessly integrate and visualise domain expert feedback on the feasibility, cost-effectiveness, and potential uses from different AEC professionals in the earliest stages of design. With the help of domain expert feedback, we can offer alternatives and new form concepts from the first draft iteration, which the designer can consider when developing the project. Creating sketches directly in 3D space offers significant advantages in individual form finding work, making extent and shapes immediately discernible by providing a sense of spatiality. It is of even greater value in a collaborative workflow. With spatial visualisation, the design can be better communicated to other stakeholders.

There are established best practices for communicating spatial data across multiple applications, like computer aided design (CAD) and building information modelling (BIM). However, the tools of 3D CAD modelling hinder the advantages of sketching, losing its immediacy, spontaneity, and unobstructed expression. The "sketching is thinking" paradigm cannot be achieved through the mediation of such instruments. In these paradigms, freehand drawing and the creation of a spatial model are two separate work stages, and the feedback into the iterative form-finding is not directly coupled.

Our proposed sketching application aims to bridge this gap by incorporating interaction paradigms that enable the creation of spatial models with the immediacy of freehand drawing. The application can be used primarily on portable devices. The primary stylus-on-tablet input method provides intuitive stroke control, with a familiar sketching experience that is similar to the still ubiquitous pencil-on-paper paradigm.

2. Related Work

2.1. Digital Sketching in Three Dimensions

Digital sketching in two dimensions (2D) is available in multiple commercial and open-source applications. Sketching in three dimensions (3D) is an ongoing research topic, as there are still difficulties to solve: How to use 2D input devices for sketching directly in 3D? How to create sketches with a context of real objects? To use 2D input devices (stylus-on-tablet), several approaches create a canvas (e.g., planes or curved surfaces) in 3D and project the 2D strokes onto the 3D canvas [4; 8; 17]. Some approaches track the location and orientation of the input tablet device to generate a 3D canvas [9]. Others use hand tracking to define a 3D canvas [7]. Sketching applications using a virtual reality paradigm rely on 6 degrees of freedom (DOF) tracked input devices. Google Tilt Brush [6] became well known for allowing 3D painting in virtual reality

(VR) with inputs via tracked VR controllers. An overview of several painting applications in VR is given by Ramsier [11]. Arora et al. [2] have shown that a challenge for precise drawing in 3D is the lack of haptic feedback. Müller et al. [9] address this issue by using a Phantom device. Drey et al. [5] propose a design tool for 3D VR sketching with a hybrid stylus-on-tablet and 6DoF tracked pen interaction.

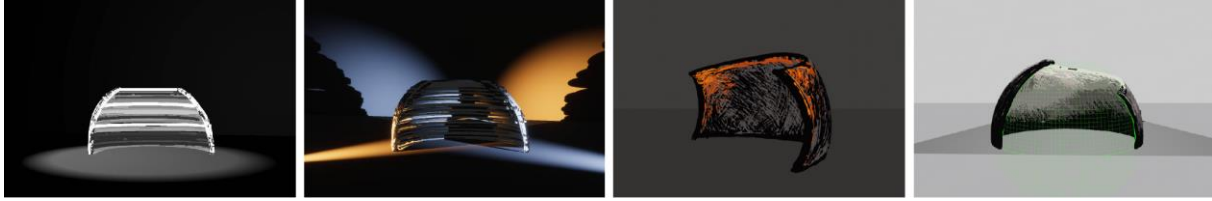


Fig. 1. Form study of curved walls in the sketching application.

2.2. AR Paradigms for 3D Sketching

A crucial hurdle in allowing sketching 3D content on a 2D surface is to define the plane (or, more generally: the surface) where the sketched lines are inserted into 3D space. Xin et al. [15] propose a handheld AR system for 3D sketching using stylus input and marker tracking. Their approach involves an intermediate, separate canvas definition step before drawing. Arora et al. [1] describe a technique for combining 2D and 3D sketching for in-situ design. They too propose a 2-step solution. First, the designer defines a drawing canvas as a patch surface fitted to multiple freeform 3D mid-air sketch lines created via a 6 DOF motion tracked pen. In the second step, sketching onto the tablet surface projects the sketched lines on the predefined drawing canvas. Yee et al. [16], Berging et al. [3], Paczkowski et al. [10] and Wacker et al. [14] provide further examples of sketching within a context using augmented reality (AR) techniques.

3. The sketching application

3.1. 3D sketching

Drawing directly into 3D space presents the aforementioned challenges. To draw without obstruction, the designer must be always aware of two factors: Where are they located, how are they oriented in space (viewport pose) and where exactly will the pen stroke be inserted into space (line input pose)?

We propose a novel solution for this challenge: the use of viewport-affixed drawing surfaces (canvases). The method is based on affixing a surface in front of the viewport (camera) at a certain default distance. We refer to this surface as the drawing canvas, because during sketching, lines drawn onto the surface of the tablet device are projected onto the virtual surface of the canvas geometry.

To make the spatial relationship between the drawing canvas and the viewpoint evident, we use different interaction techniques, such as canvas-centric spatial navigation, direct canvas control and different canvas visualisations (semi-transparent grid, intersection highlighting). The application includes multiple scalable canvas geometries (plane, sphere, cube) and allows the import of arbitrary meshes to use as canvas. To support the user's spatial confidence, the application provides intuitive camera control schemes, including interactions based on mixed reality paradigms.

3.2. Mixed reality techniques

We implemented two distinct mixed reality interaction modes. The viewport-affixed drawing canvas can be used in augmented reality (AR) mode. In this mode, the camera position is adjusted via 6 DOF inside-out tracking using the built-in LiDAR scanner of the tablet device. Drawing canvas visualisations and control are still available in this mode.

The LiDAR scanner also enables spatial mapping and meshing the geometry of the physical environment. In this mode, the geometry of the scanned physical environment provides the surface for sketching. This

allows the designer to draw directly over physical objects. Akin to the tangible user interface paradigm, physical objects can be used as drawing guides.

We use additional MR, AR and VR platforms and techniques to visualise sketches at different scales and in different contexts. Our application supports collaborative design and visualisation tasks, allowing room-scale visualisations of 3D architectural sketches previously created via stylus-on-tablet interaction.

3.3. Central integrative platform

We are creating experimental implementations of the above techniques with the aim of providing tools for designers to directly generate data that enables real-time, instantaneous exchange. Processing, transforming, serialising, and transferring 3D sketches is a significantly simpler task than converting a two-dimensional freehand drawing into a 3D model in an intermediate step.

In terms of data exchange, two main challenges were identified: on the output side, the serialisation and transmission of sketch lines created in the application. On the input side, the reception, processing, and visualisation of mesh geometries. Based on the preliminary requirement analysis, we implemented proof-of-concept data exchange solutions for two popular applications. We integrated the Rhino/Grasshopper (GH) parametric modelling software and its headless Rhino.Compute REST geometry server, to generate parametric geometries from freehand drawing lines, and Blender, an open source 2D/3D content creation software, which serves as an intermediate data exchange platform and meshing tool.

4. Exemplary workflow

In this section, we show how our application can be used to conduct a specific exemplary workflow on the basic spatial element of a transformable kinetic wall. In this example, the designer is supported by immediate feedback from mathematician and digital manufacturing domain experts. We describe the specifics of the integration with Rhino/GH, including data processing, generation of a specific quadrilateral mesh type, the visualisation of the resulting expert feedback (geometry) and the preparations for digital manufacturing.

4.1. Sketching lines

Using our sketching application, the artist can create the first sketches of the wall directly in 3D space. To generate the quad-mesh, three planar curves must be provided as input. We send these curves to Rhino/GH using real-time network data exchange. The quad mesh generated via the GH script is sent back and visualised in the sketching app, where the designer can make immediate refinements.

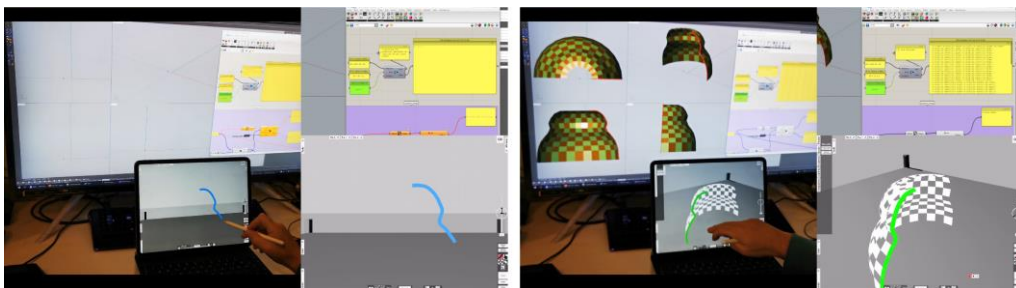


Fig. 2. Real-time data exchange between the sketching application and Rhino/Grasshopper. The designer sketches a curve on the tablet. A Rhino/GH instance running on a desktop computer receives the data, processes it, and generates a mesh. The mesh is then sent back and inserted into the sketch scene

4.2. Mesh generation for a kinetic wall

In this section, we give a rough introduction to the functionality of the GH plugin “Scutes”. It allows the designer to create a special class of flexible quadrilateral meshes known as T-hedra. Moreover, we point

out some features of the plugin facilitating the construction process of physical models. Finally, we make some comments on the usability and performance advantages of “Scutes”.

Triangulated meshes, in general, have several DOF, while a generic quad-mesh with planar faces, hinged by rotational joints in the combinatorics of a square grid, is rigid. However, there also exist certain geometries of such quad-meshes allowing a 1-dimensional flexibility. An important class of these flexible discrete surfaces is constituted by trapezoidal quad-meshes, as they allow direct access to their spatial shape, which makes them suitable for design tasks. These so-called T-hedra can be considered as a generalisation of discrete surfaces of revolution so that the axis of rotation is not fixed at one point but sweeping a polyline path on the base plane. Moreover, the action does not need to be a pure rotation but can be combined with an axial dilatation. After applying these transformations to the breakpoints of a particular discrete profile curve, we obtain a flexible mesh with trapezoidal faces. Therefore, the design space of T-hedra also includes discretised translational surfaces and moulding surfaces. These subclasses, beside the already mentioned rotation surfaces, are all widely used in the application context. For a more detailed geometric description of T-hedra we refer to [12; 13].

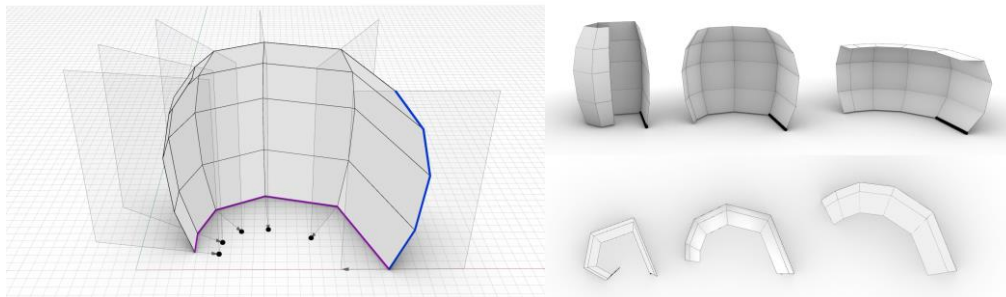


Fig. 3. (a) T-hedron of the most general type. Profile curve (blue), trajectory curve (purple), and direction points (black dots), (b) T-hedron and its relative motion into flexion limits regarding the fixed edge (thick black segment) on the base plane.

“Scutes” is an interactive plugin for Rhino/GH implemented in C#, which makes the design space of T-hedra accessible for designers. It enables the user to design a T-hedron interactively and visualise its deformation in real-time. The visualisation is updated based on a recursive parameterization of the quad-mesh vertices under the associated isometric deformation. The main mesh-generator component generates a T-hedron based on two planar boundary polygons (the so-called profile and trajectory polyline (cf. Fig. 3.a) and a list of direction points identifying the carrier planes, which are orthogonal to the base plane of the stretch-rotated/translated profile). Moreover, “Scutes” visualises the flexion of the T-hedron as set by a deformation parameter slider. For more details on “Scutes”, we refer the interested reader to [13], where features are explained in greater length (e.g., the visualisation of the closeness to flexion limits or of the force transmission throughout the quad-mesh).

To facilitate the construction process of flexible physical models, we implemented additional features/components, such as the output of minimum and maximum dihedral angles for customised hinges with rotational restriction, edge selection of the trajectory polyline, which remains fixed under the deformation (cf. Fig. 3.b), and computation/visualisation of the resulting path-curves of points of the trajectory polyline, which is used for guiding rails.

As a conclusion of this exemplary workflow, we now provide details on the realisation of the designs created with our sketching application, for which we employed digital fabrication technologies.

4.3. Digital manufacturing

To digitally manufacture a movable flexible scale model of the sketched and computed, it was necessary to extract the information required for manufacturing from the virtual 3D model. Each face in the 3D model has zero material thickness, is unique in geometry and additionally each element in space has a different position in relation to adjacent elements. The first step of manufacturing is defining a material with a specific thickness and designing hinges for a smooth transition from the start to the end position. We chose

opaque acrylic glass with 3mm thickness for the scale model (consisting of twenty faces) due to its high stiffness and ability to be laser cut precisely. We developed mass customised hinges to use as connectors between the faces.

To ensure that the hinges can move properly, we made a GH definition containing the real material thickness and our hinge design. Using a virtual 3D movable model, it was possible to detect collision problems in the movement caused by material thickness and the restriction in the rotation range of the hinges. We extracted the geometry and position of each face within the mesh. To achieve an undistorted contour curve of each planar face, we developed the 3D mesh into a 2D line drawing and orientated it onto the XY plane. All faces were offset by a safety distance of 2.5 mm towards the inside (red) to avoid collision with adjacent faces. We labelled each face with an ID (blue), marking its orientation for easier assembly (cf. Fig. 4).

In the next step, we used the GH definition to determine the minimum and maximum position of each hinge. For this model, the rotation angles range from 0.3° to 87.77° . Parametrically constructed hinges allowed the implementation of the boundary values as physical boundaries for each hinge. Material thickness, hinge mounting, and the diameter of the rotating part of the hinges had to match precisely, as any other position of the rotation axis would have caused the mesh to block. We designed the hinges under the constraint that the axis of rotation must be positioned exactly along the interior edges of the mesh. A total of thirty-one hinges were needed to connect all faces together as well as one large hinge to connect the first face, the lower edge of which is fixed in position. All other elements have a complex relative motion to the ground plate. We custom manufactured each hinge from grey coloured ABS filament using a 3D printer. We made the ground plate with four slits acting as guiding rails for the physical model using a laser cutter. These rails were generated by the path-curves of the midpoints of the four non-fixed edges of the trajectory polyline. We added small pivots in the form of pins to these midpoints. Note that the proposed construction takes advantage of the fact that the trajectory polyline remains planar during the deformation.

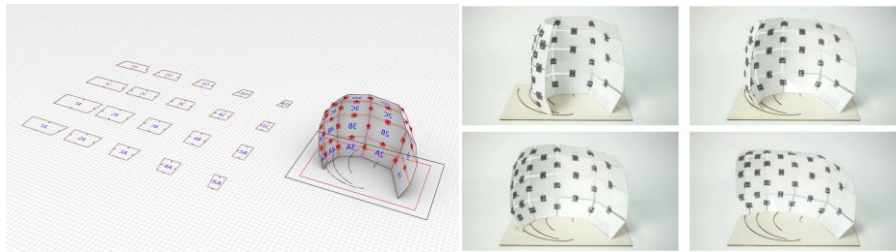


Fig. 4. (a) Drawing of extracted geometry and additional IDs ready to be laser cutted, (b) Picture of the physical model

5. Conclusion and future work

Improving communication between domain experts with different professional languages leads to an increase in the quality of the design process and subsequently to an increased quality of the design itself. Our integrative mixed reality sketching application provides a solution to achieve this improvement. We have created an experimental implementation and assessed its integrative capabilities on a use case aimed at designing a kinetic wall structure. We realised and described an experimental design workflow in which architects, mathematicians and digital manufacturing experts can communicate through a central integrative platform. With the help of our 3D sketching technique, the designer can create spatial freehand sketches in an immediate and intuitive manner. These sketches can be used as input for parametric design methods. We have shown that through real-time data exchange, immediate domain expert feedback can be provided to the designer. This helps to involve experts from across the AEC workflow in the earliest phases of a design project. Our experimental workflow shows improved professional communication from the first stylus strokes to the manufacturing of a physical structure.

We are in the process of conducting user evaluation with architecture students. The evaluation is based around performing specific design tasks and reporting user experience about form-finding, expression, and communication of design ideas. In this step, we are evaluating the 3D sketching aspect of our platform. The

usability and design-related potential of the "Scutes" plugin was also evaluated in a seminar course for architectural students, with favourable feedback. Following evaluation rounds will involve students and professionals from different domains and will concentrate on interdisciplinary communication.

The exemplary workflow presented in this paper is one of the many integration possibilities that we are exploring. We aim to find and characterise communication bottlenecks in AEC processes and provide integration solutions to alleviate them. We are developing cross-platform annotation tools to enrich sketches with semantics. Our research project continues to explore, develop, and evaluate experimental tools for computational design, AEC communication support and mixed reality techniques for early architectural design contexts.

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