S. Chien, S. Choo, M. A. Schnabel, W. Nakapan, M. J. Kim, S. Roudavski (eds.), *Living Systems and Micro-Utopias: Towards Continuous Designing, Proceedings of the 21st International Conference of the Association for Computer-Aided Architectural Design Research in Asia CAADRIA 2016,* 333–342. © 2016, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

TANGIBLE MIXED REALTY

Interactive augmented visualisation of digital simulation in physical working models

GERHARD SCHUBERT, BENJAMIN STROBEL and FRANK PETZOLD
Technische Universität München, Munich, Germany
{schubert, benjamin.strobel, petzold}@tum.de

Abstract. The implications of architectural design decisions are in many cases hard to predict and envisage. As architectural tasks grow more complex and the design of architecture shifts away from the design of end products towards the steering of dynamic processes, new ways of coping with complexity in the design and planning process are needed. Taking this as its starting point, as well as the need for architects to use familiar, established design tools, the CDP research group is working on new ways of supporting the design decision-making process with objective information so that designers are better able to manage these complexities. The focus of the group lies on directly coupling interactive simulations and analyses with established design tools. This paper discusses a central problem in this context: how to present complex calculation results directly within a physical 3D-model. The approach described, as evidenced by the realized prototype, shows clearly that directly coupling real and digital information using interactive augmented visualization presents immense possibilities for managing the complexity of planning processes.

Keywords. Design support, simulations, computational design, urban planning, augmented reality.

1. Introduction

The larger the construction project, the more complex the interactions between its technical, social, planning and design aspects. As large construction projects become more widespread, the building sector is confronted with increasingly difficult challenges. Planners are faced not only with dealing with a multiplicity of static conditions but also with changing situations resulting from dynamic processes. Today's designers, as Wood (2007) has remarked, need to "become the facilitators of flow, rather than the originators of maintainable 'things' such as discrete products or images". In this context, we need to find new ways of planning that help us to visualise and understand complex interactions, implications, interdependencies and processes. Given that the designer's influence in the early design stage is high and decisions made in these stages have a significant impact on later design stages, the building cost and its lifecycle (Paulson, 1976), it is important to take into account such factors from a very early stage in the design process.

A key approach to dealing with these new challenges is the use of Design Decision Support systems that assist architects and planners by providing objective design criteria at appropriate points in the design development process. They allow designers to see the impact of complex, dynamic concepts in the form of objective information. The earlier this information can be made available in the design process, the greater the impact it can have – if taken into account – on the planning outcome. The main question here is: how can digital content be incorporated into existing established ways of working in a form that is useful and does not interrupt the working process? The intention here is not to replace established ways of working, such as models and hand-drawn sketches, with computerised methods, but instead to find ways of combining the two worlds in a single system.

2. Approach

Starting from this position and the requirements of Design Decision Support in the early creative phases, the "CDP // Collaborative Design Platform" research project examines ways of seamlessly integrating interactive simulations and analyses in the creative architectural design process (Schubert, 2014). The approach taken here is to explore how established design tools, such as physical working models and hand-drawn sketches, can function as tangible interfaces within a digital environment. Over the past few years, several approaches to integrated human-computer interfaces have been researched and implemented as prototypes for solving urban design problems at a scale of 1:500 e.g. in (Schubert et al, 2011; 2012; 2014). The seamless integration of established design tools into a digital system makes it possible for designers or planners to continue working with familiar design tools while simultaneously making available interactive simulations and analyses within the physical model. Designers can then see the implications and effects of design decisions in the early creative planning phases, and respond to them accordingly. A key aspect of this is the use of information visualisation as a direct means of feedback directly within the actual physical model. Such information needs to be presented in a way that is simple to understand and that does not interrupt or detract from the process of visual thinking but enriches it with underlying objective criteria. This must be considered at both a technological as well as a conceptual level. The fact that not just the physical model but also the resulting digital computation model as well as the results of the calculation are all three-dimensional leads to the question of how best to display 3D simulation results in the physical model?

This paper describes an interactive mixed-augmented reality (AR) application that was developed and implemented – based on the prior system design – to improve the integrity of the digital authenticity in the physical model. By means of a tablet or see-through glasses, the new extended setup allows users to view interactive simulation results such as shadows cast over the course of the year, wind currents or even statutory regulations (inter-building distances and areas or construction volumes) in three-dimensions that augment the physical working model in real time.

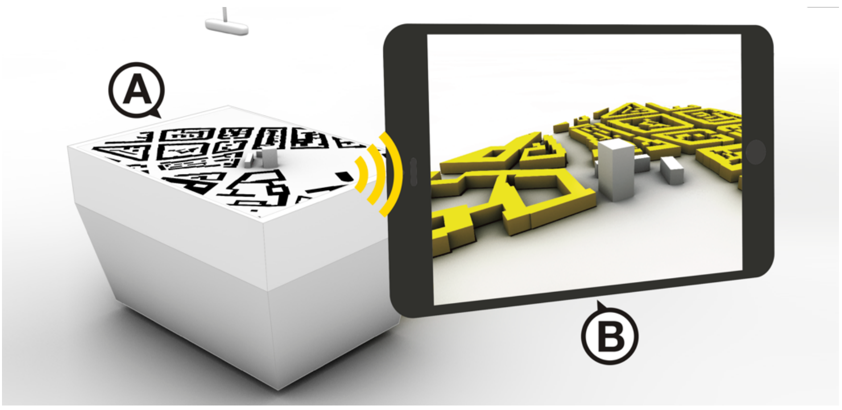

Figure 1. System setup showing both parts of the system: the design platform and the AR application. A network protocol links the physical model placed on a display of the design environment (A) with the display on the AR-device (see-through glasses or tablet) (B) in real time. The physical model placed on the table in combination with a digital map is augmented with a 3D visualisation of the surrounding architecture and interactive analyses and simulations.

The seamless coupling of physical model and simulation means that this method is not limited to the static representation of results. Changes in the working model (shape, position, orientation...) have a direct impact on the computational base and therefore also on the simulations and their display in the AR application: design and analysis merge into a single creative cycle.

2.1. USER SCENARIO

The chosen user scenario is an urban design planning project for an urban quarter extending over several hectares. The project manager, planning team and members of the planning authority meet up to discuss possible approaches. Instead of sitting down facing a beamer projection, they stand around a large multi-touch table. The surface of the table shows a digital plan of the surrounding urban grain. Various Styrofoam blocks have been placed on the site in the map on the table showing a possible urban arrangement for the quarter. The project manager explains the architectural concept and shows how care has been taken to avoid buildings shading each other. To illustrate this, he activates a solar-envelope analysis and the results of the calculations are shown directly as shaded areas on the plan on the table. For an improved impression of the shading, the participants put on transparent glasses. Immediately, the participants see the solar envelope as a 3D projection embedded within the view they are seeing. They can move around and view the scene from different perspectives and see how this will change with the successive phases of the project. One of the participants has an idea and removes a block from the model, trims it to a new shape with a cutter knife, and places it back in the model. The results of the solar-envelope simulation adjust in real time to match the new situation, and the augmented image seen through the glasses changes accordingly. It is immediately apparent to all that the change represents an improvement. The project manager changes the simulation to show wind flow patterns in the new situation. The glasses now overlay the scene with a 3D vector simulation of the wind flow. It's immediately clear where the effects of wind will be felt most. Over the course of the meeting, the participants discuss various aspects and adjust the concept, taking into account the objective feedback provided by the simulations.

2.2. RELATED WORK

Various teams have investigated ways of presenting digital information in physical contexts or physical models and various different approaches can be identified. The URP (Underkoffler and Ishii, 1999) is a further project which uses a multi-touch table in combination with marker tracking to present interactive simulations and to control these with models. The presentation on the multi-touch table shows the results only in two dimensions. Three-dimensional information can only be represented in an abstract form. Another approach, this time from the field of geography, is taken by the Sandscape project (Ishii et al, 2004). The concept makes it possible to model landscapes using sand. The resulting surfaces are scanned in three dimensions, providing the basis for calculating relevant information for the planning process.

The resulting information is projected directly onto the model from above. This process permits a degree of interactive feedback with the model, or the model's surface. One problem with this approach is shadows cast by the user or the user's hands. In addition, it is not possible to present information in three-dimensional space. The "Sketchand+" project (Seichter, 2003), for example, employs an AR application to display digital design variants embedded in a physical model of the urban environment. Different variants can be examined using Fiducial marker tracking. The evaluation of the relative advantages or disadvantages is purely subjective. Simulations and analyses are not shown in the context of the project. A similar approach, this time at the scale of a building, is taken by "MxR" (Belcher and Johnson, 2008). Using AR, a physical model of a building is augmented with digital information such as architectural elements as well as simulations. A further approach can also be seen in the "Magic Meeting" project (Regenbrecht et al, 2002). Here the system setup makes it possible to collaboratively view and interact with a mixed-reality environment using a centrally-placed marker. Additional functional markers are used to control the clipping and illumination of the model. With the exception of notes, however, it is not possible to directly change the model, or to make use of analyses and simulations. "ARTHUR" is a further mixed-reality system that makes it possible to display digital models on a table top using a head-mounted display (Penn et al, 2004). This makes it possible for people to collectively see the results of a pedestrian simulation according to certain objective criteria. Compared with a physical model, the ability to interact with such entirely virtual scenarios are considerably more limited.

3. System Setup

To implement the extended approach outlined above, the existing system setup is extended to include an AR application. The existing system comprising a large multi-touch table with integrated 3D object recognition forms the technological basis of the implemented design platform (Schubert et al, 2011). The table surface serves as the planning base and incorporates a digitized city map. In combination with 3D object recognition in real time, the system allows the user to design interactively within the digital map by means of physical models and sketches. The reconstruction is achieved by combining two connected systems using a 3D on-top depth camera and the object footprint. Tracking markers are not required. Two algorithms have currently been developed that support the use of both rectangular blocks as well as freeform bodies (Schubert et al, 2013). All design ideas in the form of a physical model placed on the table are reconstructed in three-dimensions in real time, and serve as the basis for computing decision support simulation and analysis. To meet the various needs of design tasks and design ideas, the software setup cannot be a fixed system but must provide a flexible, individually extensible structure. The software framework therefore employs a plug-in architecture comprising two sub-systems: Firstly, the host application that provides all system-relevant functions, including the semantic GIS data basis, the interaction possibilities and output of the results on the different devices. And secondly, the plug-ins which can be used in different combinations as required, providing a flexible toolkit of different design-supporting tools such as complex and dynamic calculations, analyses and simulations (e.g. wind simulations, shadow projections, process simulation, route analyses, etc.).

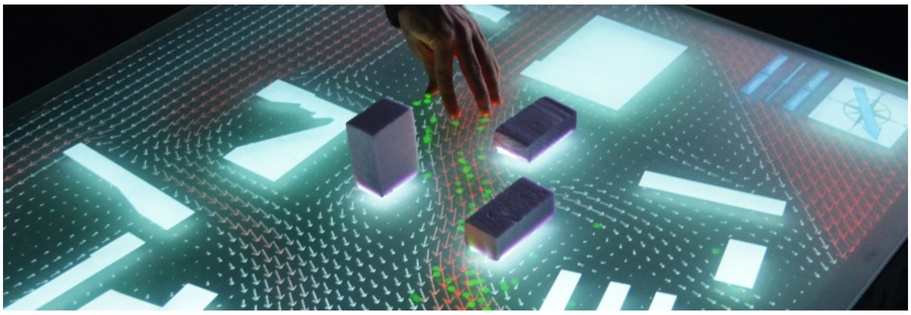

Figure 2. 2D presentation of simulation results on the table surface – seamlessly connected to the physical working models.

The system setup makes it possible to display the results of a simulation directly on the surface of the table in the plan presentation. This form of presentation on a planar surface is, however, necessarily only a 2D visualisation of the information. Studies have shown that this pure 2D feedback is, in many cases, not sufficient to convey the complexity of information contained in the simulations. Given that the basis for the computation and the computation itself is based on 3D- data, this artificially constrains the information simulation possibilities. To alleviate this discrepancy, additional methods for visualising 3D information in a physical context were examined and implemented as part of a sub-project, that is presented here. The approach is based on an AR application that allows one to see design decision support information using see-through glasses or a tablet device. The three-dimensional representation of the digitally computed three-dimensional information is presented superimposed over the view of the model with the result that it appears embedded within the physical model. The requirements for realising the concept can be defined as follows:

- Display of the simulation results in real time
- Tracking without markers in response to a dynamically changing scenario
- A simple means of extending the system for use by multiple users
- Flexible use of clients to show different simulations and analyses

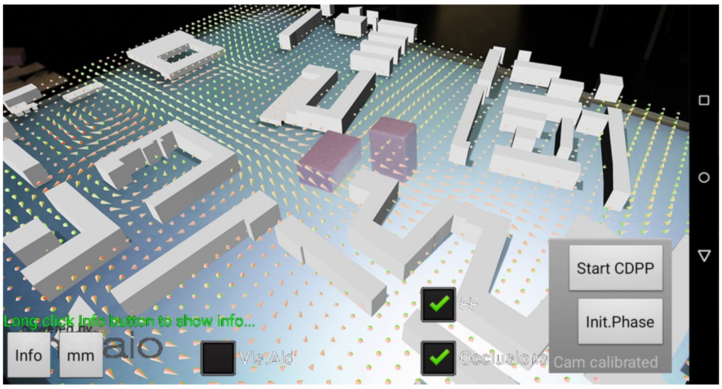

Figure 3. 3D presentation of simulation results and urban context via augmented visualisation directly in the physical model. Physical model (purple), digital model (grey) and digital simulations (wind) are merged interactively (first prototype).

3.1. IMPLEMENTATION

The prototypical implementation of the software side of the system is based on a server-client architecture. It comprises the design platform consisting of a multi-touch table and info panel that serves simultaneously as the server. To view the results in the physical model via an AR application, a separate application for mobile devices that has been developed in a previous subproject has been improved (Schubert et al, 2015). The metaio SDK was used to create the application (Metaio GmbH, 2015). The priority here was to ensure the display of simulation results in real time and the ability to respond to and display changes in the design scenario. The most important components here are the tracking and the custom-developed TCP/UDP protocol for transferring simulation results to the AR client.

3.2. TRACKING

Given the requirement for a flexible, markerless tracking system, we employ a feature tracking approach. This works by tracking prominent edges in the stream of images. The plan drawing shown on the table's surface serves as a good reference for basing the tracking system on. Because we can ascertain the position of the camera from the plan, we can calculate the position and perspective of augmented objects. This makes it possible to track an overall scenario even as the scene changes as a result of changes to the physical model. The system also affords a degree of tolerance in recognising features, even when they are not all visible.

3.3. SIMULATIONS

Using the server-client architecture, the design platform itself functions as the server. The individual AR applications for presenting the different kinds of simulation results are linked to the system as clients via a network connection. The basis of this is a specially developed TCP/UDP network protocol for the transmission of data between both partners (Goldschwendt et al, 2014). The AR application receives simulation results as well as digitized object geometries in real time from the design platform. Both the design platform as well as the mobile application employ the TCP/UDP protocol to communicate with each other, facilitating real-time communication between server and client. This also makes it possible to extend the system to accommodate multi-user scenarios without having to change the internal system – new clients simply connect to the server application. The different presentation perspectives and contents are computed individually and displayed by the respective client. This setup also makes it possible to communicate simulations centrally. The results are then streamed to the clients, which significantly reduces the computational demand on the client application. To establish and maintain communication between two system peers, several so-called control messages are defined within the protocol. After the successful connection of two peers, the collaboration starts.

To communicate the results of the calculation taking into account the flexible connection of different simulations, a corresponding concept was developed for the TCP/UDP protocol. The data communication between table and app works as follows: the physical and virtual buildings on the table setup are processed and represented in a binary format to send them as a TCP/UDP message to the application. These messages are in JSON format with corresponding predefined elements and properties which affords greater flexibility as JSON messages provide a convenient way to send arbitrary data via the protocol. This makes it possible to send new data without having to adapt the protocol. It is only necessary to parse the new data on the sender/receiver side. By way of example: the table creates a JSON message for different primitive objects, such as spheres or arrows and then sends the JSON message to the application. The protocol is unaware of the content of the message. The app receives the JSON message and parses it to reveal the content. Finally, the app visualises the received primitive objects.

4. Discussion

The previously developed concept in combination with the new implemented prototype of the AR application permits the interactive and direct three-dimensional representation of computed simulations and analyses in physical models. The integrated approach of using physical models along with an AR application on a tablet device or see-through glasses makes it possible to interact with established design tools while concurrently displaying digital models of the surrounding buildings as well as digital supporting information directly in the physical model. The physical and digital realms are closely connected with one another. As such, the designer can incorporate objective information in his or her design explorations in the early design phases. The server-client software architecture also allows the prototypical implementation to be easily extended to cater for multi-user scenarios, so that several participants can work interactively with the model to discuss a design scenario and use the simulations to assess the implications of design decisions. The use of the JSON format for data communication also makes it possible to flexibly extend the system to accommodate future design-supporting plug-ins with simultaneous display on the table and in the AR view. The use of feature-based tracking using the plan drawing on the table enables markerless tracking. Tracking problems only occur if the display quality is not good (for example low contrast or poor or skewed visibility of the plan on the table), and are most noticeable when changing the direction of view. In addition, the need for an AR device is not ideal. Holding a tablet for example, limits one's ability to simultaneously interact freely with the physical model. The use of see-through glasses is better in this respects, as it leaves one's hands free, but the ability to interact with the GUI of the AR-view is more limited than when using a tablet.

5. Summary and outlook

The expanded setup and prototype described in this paper enables simulations to be presented no longer purely in 2D but also to portray complex 3D-content, which expands the usefulness of analyses and simulations considerably. The system helps the user to see and understand complex, 3D-relationships and their implications. This is especially relevant in the context of ever more complex construction tasks, and the nature of architectural projects as dynamic processes rather than the production of final products. Future work will concentrate in particular on how to present separate content to specific users, for example different degrees of information for specialist planners or laypersons. In addition, different ways of interacting with the GUI using see-through glasses will be examined and implemented.

References

Belcher, D. and Johnson, B.: 2008, MxR: A Physical Model-BasedMixed Reality Interface for Design Collaboration, Simulation, Visualization and Form Generation, *in* A. Kudless, N. Oxman and M. Swackhamer (eds.) *Proceedings of the 28th ACADIA*, Minnesota, 464–471.

Goldschwendt, T; Anthes, C; Schubert, G; Petzold, F. and Kranzlmüller, D.: 2014, The Collaborative Design Platform Protocol: A Protocol for a Mixed Reality Installation for Improved Incorporation of Laypeople in Architecture (Poster), *in* R. Lau (ed.) *Proceedings of the 20th VRST*, ACM, Edinburgh.

Ishii, H; Ratti, C; Piper, B; Wang, Y.; Ben-Joseph, E.: 2004, Bringing clay and sand into digital design: continuous tangible user interfaces, BT Technology Journal, **22**(4), 287–299.

Metaio GmbH: 2015, "Metaio | SDK". Available from: <http://www.metaio.com/sdk/> (accessed 2 Feb 2015).

Paulson, B.C.: 1976, Designing to Reduce Construction Costs, Journal of the construction division, 587–592.

Penn, A; Mottram, C; Fatah gen. Schieck, A. Wittkämper, M; Störring, M. Romell, O. and Strothmann, A. Aish, F.: 2004, Augmented Reality Meeting Table: a Novel Multi- User Interface for Architectural Design, *in* J. van Leeuwen and H.J.P. Timmermans (eds.), *Recent advances in design and decision support systems in architecture and urban planning*, Kluwer, Dordrecht, Boston, 213–231.

Regenbrecht, H.T; Wagner, M.T. and Baratoff, G.: 2002, MagicMeeting: a Collaborative Tangible Augmented Reality System, *Virtual Reality*, **6**(3), 151–166.

Schubert, G.: 2014, Interaktionsformen für das digitale Entwerfen: Konzeption und Umsetzung einer rechnergestützten Entwurfsplattform für die städtebaulichen Phasen in der Architektur, Dissertation, Technische Universität München.

Schubert, G; Artinger, E; Petzold, F. and Klinker, G.: 2011, Bridging the Gap: A (Collaborative) Design Platform for early design stages, *in* T. Zupančič-Strojan, M. Juvančič, Š. Verovšek and A. Jutraž (eds.), *Proceedings of eCAADe 2011*, Ljubljana, 187–193.

Schubert, G; Artinger, E; Yanev, V; Petzold, F. and Klinker, G.: 2012, 3D Virtuality Sketching: Interactive 3D-sketching based on real models in a virtual scene, *in* M.J.J.K. Cabrinha and K. Steinfeld (eds.), *Proceedings of the 32nd ACADIA,* San Francisco, 409–418.

Schubert, G; Riedel Sebastian and Petzold, F.: 2013, Seamfully connected: Real working models as tangible interfaces for architectural design, *in* J. Zhang and C. Sun (eds.), *Proceedings of CAAD Futures 2013,* Springer, Berlin, Heidelberg, 210–221.

Schubert, G; Schattel, D; Tönnis, M; Klinker, G. and Petzold, F.: 2015, Tangible Mixed Reality On-Site: Interactive Augmented Visualisations from Architectural Working Models in Urban Design, *in* G. Celani, D.M. Sperling and Franco, Juarez Moara Santos (eds.), *Proceedings of CAAD Futures 2015*, Springer-Verlag New York Inc, 55–74.

Schubert, G; Tönnis, M; Yanev, V; Klinker, G. and Petzold, F.: 2014, Dynamic 3D-Sketching: A design tool for urban and architectural design, *in* N. Gu, S. Watanabe, H. Erhan, M.H. Haeusler, W. Huang and R. Sosa (eds.), *Proceedings of CAADRIA 2014*, Kyoto, 107–116.

Seichter, H.: 2003, Sketchand+ a Collaborative Augmented Reality Sketching Application, *in* A. Choutgrajank (ed.), Proceedings of CAADRIA 2003, Bangkok Thailand, 209–222.

Underkoffler, J. and Ishii, H.: 1999, Urp: A Luminous-Tangible Workbench for Urban Planning and Design, *CHI 99*, 386–393.

Wood, J.: 2007. *Design for Micro-Utopias: Making the Unthinkable Possible*, Aldershot, Gower.