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Augmented reality and tangible user interfaces as an extension of computational design tools

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Abstract: The paper envisions the use of Augmented Reality (AR) as an interactive and communication tool utilized in the architectural design research, education, and practice. It summarises the current knowledge and various applications of this immersive technology in both the theoretical and practical field and focuses on a particular type of the AR implementation – tangible user interfaces (TUI) – in a computational design context. The outcome of the research is an adaptation of the originally GRASS-GIS-powered Tangible Landscape tool into Grasshopper 3D environment, which is more accurate and suitable for the architectural design workflow with respect to 3D computation, algorithmic modelling and different scale management. The newly prototyped tool is reactive to the modifications of the physical model and projects the computed additional information on it in real time and thus can communicate with the designer or observer, which results in a more interactive, haptic man-machine interface. The projected and visualised data on the physical model are the outcome of the computing algorithm designed in Grasshopper that allows for a wide range of applications, including the visualisation of shadows and solar potential analysis and thus depicts the physical model in multiple dimensions. Furthermore, the article discusses the potential and further development of this tool as well as the possibilities of layering different AR technologies in the subsequent research.

Keywords: mixed reality, tangible landscape, augmented reality, virtual reality, computational design, modularity

INTRODUCTION

Tools of architecture have been naturally evolving hand in hand with technology advancements. More than half a century ago, the first tool of computational design was introduced in the automobile industry. This tool was created to fulfil the need to make the notation of smooth geometries, initially splines, more exact and accessible for vehicle designers and draftsmen. In the 1990s, spline modelling tools were included in the early computer-aided design (CAD) software inside its graphical user interface (GUI). Designers and architects could intuitively model complex, continuous curves and surfaces defined by parametric equations, simply by manipulating the control points with a mouse. Parametric representations of those geometries were automatically computed and rendered on a computer screen. (Carpo, 2014)

Simplification and automatization of conventional design processes using CAD tools quickly became an industry standard. Further development of their role in the design process exceeded the purpose of automatization of the conventional design and marked an era of computational design. Spline-modelling tools have dominated the past 20 years of architectural design aesthetics and created the today's mainstream parametric architecture trend. Nowadays, designers can access huge amounts of data and utilize complex computations like never before. Analytical and optimisation tools can inform and create guidelines for the design. Parametric tools and more autonomous, generative algorithms have potential to be used in the whole design process from form-finding to fabrication.

The research of possibilities offered by technological advancements and its implementation in the context of architectural design can have as great aesthetical and conceptual impact as the implementation of a simple spline-modelling tool. Embedding of data created in computational-design workflow into AR software and making them tangible in the physical world creates new interaction opportunities between computational design tools and designers. In this research, we explore how tools paired with innovative user interfaces beyond GUIs can yet again challenge the ways the future of design methods might look like with even closer human-machine cooperation.

SYNOPSIS OF DIFFERENT REALITIES' CONNOTATIONS

"Architecture begins with a drawing: this is a starting point for an object that constantly lacks the third dimension in all of its aspects, though it is part of architecture as a discipline, different from the act of building. As Robert Evans pointed out: Architects do not make buildings, they make drawings of buildings; the transformation of a drawing into the building is always a challenge." (Tichá, 2006, p. 67) Representations of future buildings were, and still are the primary task of architecture, whether these are 2D drawings, physical or digital models. There is a constant challenge in displaying the design in the most legible, natural and descriptive way, while overcoming problems of the latest tools available, such as rigidity and different scale of physical models, limiting 2D nature of drawings and screens, or still unnatural and too individual virtual reality headsets.

As Schnädelbach's research in this area was focused on the most natural blending of representations of flexible human social interactions with rigid physical spaces (Schnädelbach, 2007), a similar approach was already achieved in experiments blending physical and digital representations of the designed spaces to provide viewers with sufficient information in a more natural way (Kymäläinen, Siltanen, 2012). These older approaches still open paths for further research as current technology is swifter and more ubiquitous. Nevertheless, the terms and definitions for the blurred line between real and virtual are already almost 30 years old, as they emerged when the digital paradigm blossomed in architecture in the mid 1990s. In 1994, Milgram and Kishino proposed a diagram that incorporated all these ideas into one definition of virtuality continuum (Fig. 1). In their diagram, Milgram and Kishino placed real environment and virtual environment as two extreme opposites in the gradient of mixed reality (MR), which contains various "mixtures" of those aspects. It was an explanation of situations in which real elements may appear in a virtual environment to create an augmented virtuality (AV), or to place virtual objects in a real environment to create an augmented reality (AR). Both these terms have been often referred to as augmented reality, despite the differentiation between them. (Milgram, Kishino, 1994)

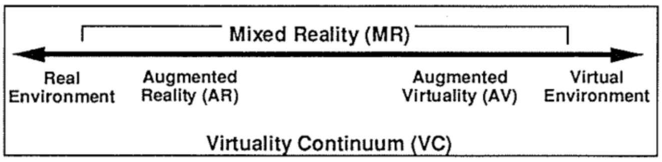

Fig. 1. Diagram of Virtuality Continuum. (Source: Milgram, Kishino, 1994)

In 2007, Schnabel, Xiangyu, Seichter and Kvan by developing the diagram of Milgram and Kishino, added the terms such as Amplified Reality, Mediated Reality and Virtualized reality. Amplified reality only amplifies the real properties of physical objects, instead of superimposing additional virtual properties on them, as is the case in augmented reality. The Mediated Reality deliberately diminishes the perception of reality, for example, by removing a collection of objects, which are then replaced with a more appropriate background image and adjusting the light and perspective – which are techniques usually used in architectural visualizations. Virtualized Reality virtualizes real-world scenes by capturing them from different angles and then reconstructing them in a computer as 3D scenes. The authors have placed these newly defined concepts on a similar spectrum of realities from real to virtual. (Schnabel, Xiangyu, Seichter, Kvan, 2007; Fig. 2)

In 2013, Steed, revisiting the Milgram and Kishino's taxonomy, stated that even within a "standard" virtual environment, there are often used links to the real world, as a result, what an observer sees in the virtual reality might reflect some aspects of the current state of the real world. This situation could be observed by means of using body avatars or real objects' representations in the complete virtual environment. These links to the real state of the world are built on the already experienced images from the real world and evoke similar connections and emotions. They are often used to make the virtual environment more familiar for the visitor, which simplifies the orientation and interactivity. (Steed, 2013) In 2022, Philipp A. Rauschnabel's research pointed out an ongoing confusion in the terminology. In his most recent paper on this topic, theoretical definitions are confronted with current industry practices. Rauschnabel acknowledges the ideas of Milgram and Kishino, resp. Schnabel and Seichter, along with various other viewpoints, labels their approach as "MR-centred view" and brings up its potential problems. He argues that AR and VR have opposing designer goals and user experiences, therefore cannot be united under one term. (Rauschnabel, 2022; Fig. 3)

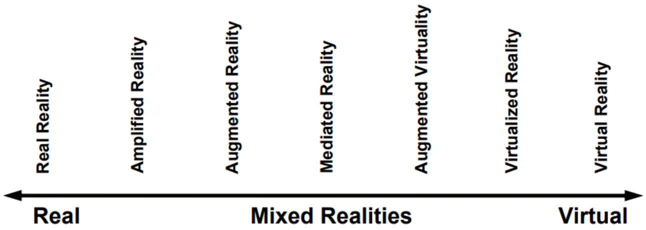

Fig. 2. Broadened spectrum of realities from real to virtual. (Source: Schnabel, Xiangyu, Seichter, Kvan, 2007)

The use of the term xRealities (XR) as an umbrella term for AR and VR was proposed, however, Rauschnabel cautioned about the interpretation of this abbreviation using the term "extended". VR is not by definition an extension of reality rather than a replacement of one. Instead, the interpretation of the letter "X" is proposed as a placeholder of either Virtual or Augmented (Fig. 4). This claim is backed by interviews with experts conducted as part of a study with the conclusion that XR users can either be situated in a physical space in which they can observe additional virtual augmentations or be immersed in another, virtual space separating users from perception of physical environment distractions. The idea of blended spaces is built upon the 1993 "conceptual blending" theory of cognition developed by Gilles Fauconnier and Mark Tunner (Tunner, Fauconnier, 2009), extended with human-computer interaction and software engineering concepts of Manuel Imaz and David Benyon (Imaz, Benyon, 2007). Blended space presents a concept in which the physical and virtual environments are closely integrated to provide the experience of presence in such a space. The simplest form of blended spaces consists of two main features – input to virtual space and response from virtual space, with input ranging from tactile to environmental changes and response ranging from visual notifications to olfactory senses (Fig. 5).

Despite the long history behind the idea of XR, the concept itself was not feasible until recently, mainly because of unavailability of underlying technologies, including necessary processing power and sensors and because of the high cost of licensing of existing toolsets. Widespread use of handheld mobile devices such as smartphones and tablets possessing some of the necessary technologies, including orientation sensors, high-quality cameras and microphones and location-based technology, has led to increased availability and affordability of XR-based tools.

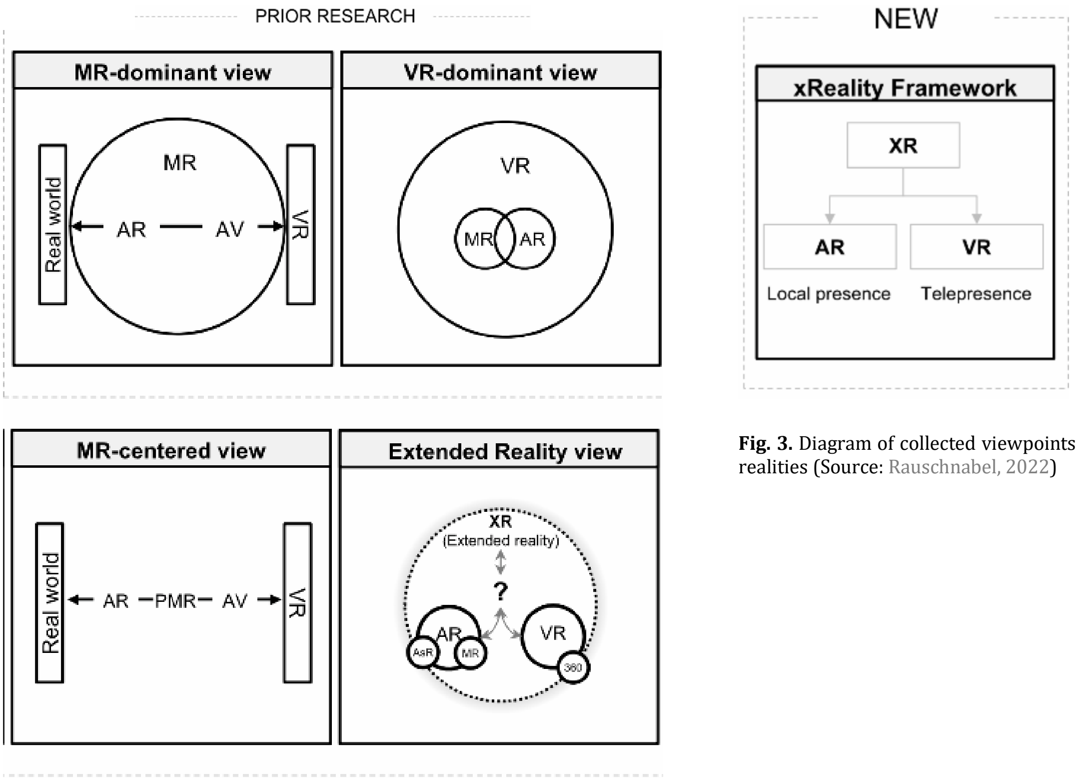

Fig. 3. Diagram of collected viewpoints (prior research vs. new) on different realities (Source: Rauschnabel, 2022)

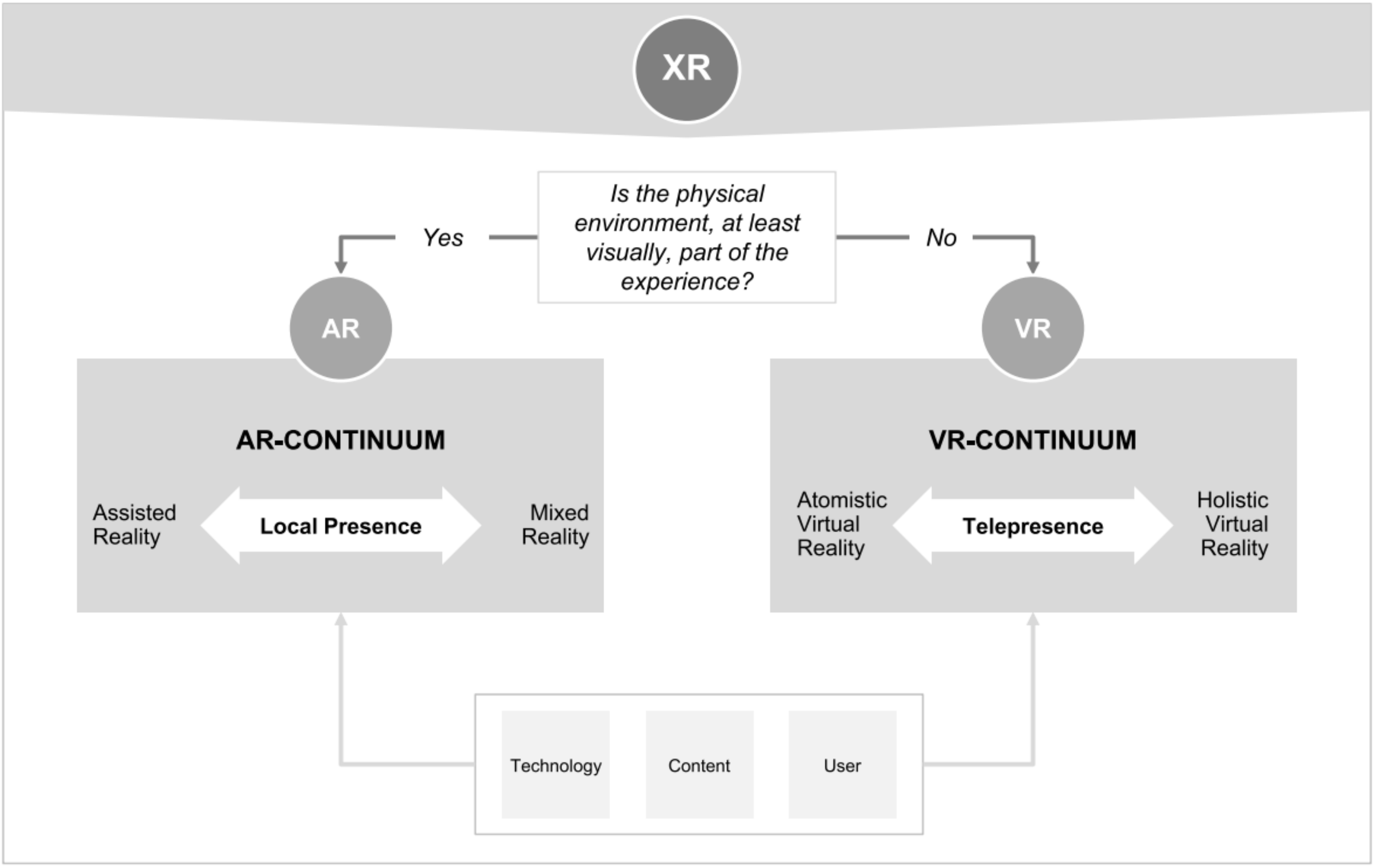

Fig. 4. Diagram of xReality framework proposal. (Source: Rauschnabel, 2022)

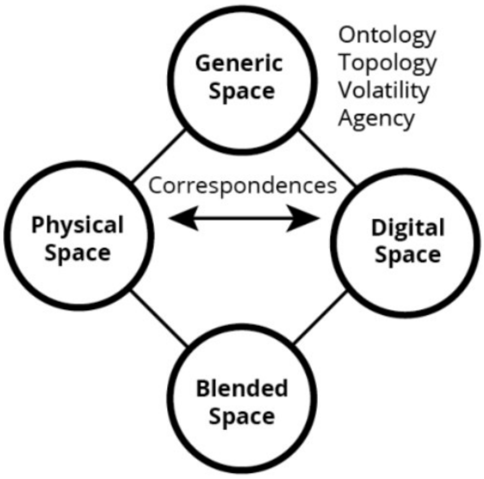

Fig. 5. Basic structure of blended spaces (Source: Benyon, Resmini, 2017)

BASIC FORMS OF AR

One of the simplest forms of AR is optical tracker-based and image-based recognition. This relatively simple to compute solution enables real-world object tracking even to lower-end devices without special sensors. Objects are tracked using QR or ArUco markers of defined real-world size or predefined image patterns are used. Those are pinned to the virtual representation of such a marker. This solution is simple but lacks the awareness of the world around the viewport. Smartphones and tablets utilise a multitude of technologies that provide information about their position in the real world, thus enabling them to provide an interface between physical environment and virtual environment at different levels of experience and integration.

A more immersive type of AR includes mediation devices such as Microsoft HoloLens, a headset with semi-transparent displays used to project digital information before spectator's eyes and seamlessly extending human vision while retaining the ability to manipulate objects present in the physical world. It adds a layer of perception and complements environment. (Sebeom, Bokijonov, Choi, 2021) This is very similar to VR technology with the only difference of VR being fully immersive. When combined with marker-based tracking technology, trackers can be used to inexpensively address real-world object location, rotation and scale. Software tools such as Fologram (Jahn, Newnham, van den Berg, Beanland, 2019), a mobile handheld and HoloLens application can be used in combination with computer modelling (Rhino 3D) and parametric computational software (Grasshopper) for environmental simulations (Ladybug, etc.) or form-finding.

A combination of GPS sensors and AR image tracking merges into location-based AR. It allows AR-specific elements of real-world environment to be enhanced or supplemented with computer generated content. (Chou, Chanlin, 2014) Tools like this help spectators understand spatial, environmental, and historical contexts more seamlessly and in the physical world scale. During the COVID pandemic, visiting inaccessible places through XR virtual tours presented a new way of thinking about what is possible within spaces normally bound by strict rules, providing visitors access to inaccessible or even forbidden places. (Allal-Chérif, 2022)

XR in AEC

A 2020 Davila Delgado study (Delgado, Oyedele, Demian, Beach, 2020) aims at creating a comprehensive overview of the status of XR usage within the Architecture, Engineering and Construction (AEC) sector. Different levels of real-world separation provide endless possibilities of presentation, visualisation and examination of proposed projects. The study also addresses current limits of XR technologies. AR and VR, while sufficient for visualisation and exploration purposes, are not yet reliable, robust and user-friendly enough to be fully implemented with real-life industrial requirements in mind. (Palmarini, Erkoyuncu, Roy, Torabmostaedi, 2018)

A list of six general use-cases has been assembled using a combination of qualitative and quantitative data collection methods: (1) Stakeholder engagement, (2) Design support, (3) Design review, (4) Construction support, which has four subcategories: construction planning, progress monitoring, construction safety, and operative support; (5) Operations and management, and (6) Training. AR and VR can be used to extend presentation experience, project analysis and form-finding. (Devagiri, Paheding, Niyaz, Yang, Smith, 2022)

Some of the tools mentioned above are used in commercial and educational environment. HoloLens and multiple current smartphones can be used as localization and spatial mapping tools in prototyping autonomous vehicles (Moezzi, Krcmarik, Bahri, Hlava, 2019) or as an augmented fabrication assistant. (Jahn, Newnham, van den Berg, Beanland, 2019) Another system uses MR to sync physical world changes to the BIM model of the project such as furniture location planning or HVAC pipe inspection. Various MR technologies have been used to visualize data for regular users, including street and indoor navigation.

XR AS AN EDUCATIONAL TOOL

The authors explore possibilities and ways of encouraging students and the public to use and create their own AR experiences using freely available tools. Multiple libraries, SDKs, tools are available with varying degree of usability, adoption, availability, and cost. Currently, multiple tools for creating XR experiences with varying degrees of creative freedom and learning curves are freely available. Multiple toolkits, such as Vuforia, AR Toolkit, or various software development kits (SDKs), including those of Oculus Rift or HoloLens, enable the highest level of modification and integration, with the main drawback being the need for highly advanced programming skills.

Streamlining the process, with Unity as a gaming engine with its integrated tools, makes it possible to develop a range of XR experiences from simple to the most complicated, without the inherent need for programming language knowledge. With little effort, it also enables sending XR experiences to multiple end devices, including mobile, desktop and web-based applications. The main drawback of this software is its relatively steep learning curve. (Barroso, Gutiérrez-Castillo, Llorente-Cejudo, Ortiz, 2019) One alternative to these highly specific tools is Spark AR, with its underlying ecosystem. It is primarily used as an entertaining way for users to interact with social networks. However, it can also be used as a simple introductory tool for teachers to create immersive educational XR experiences using node systems logic programming for their students without needing to have any programming skills.

Both AR and VR help contextualize small scale ideas, explore proposed urban planning, and garden architecture scenarios on-location (Cirulis, Brigmanis, 2013), or visualize final concepts as a form of presentation. MR as a tool inherently introduces gamification aspects into its operation. Malone (1981) focuses on what makes games fun, categorising his findings into three categories: challenge, fantasy, and curiosity. By applying gamification aspects to MR workflows, higher engagement and learning rewards can be achieved. Despite the useful capabilities MR technologies, it is crucial to ensure that user's cognitive overload is prevented. During a typical AR or VR experience, users are required to simultaneously interpret content, manipulate the device and objects, and collaborate with others. (Dunleavy, 2014) Large data set aggregation, processing, and subsequent interpretation through the computational-design workflow can help to visualize data by embedding them into AR software and orienting them in a physical world, which creates new interaction opportunities between computational design tools and designers. In combination with AI, increased workflow efficiency can be achieved.

TANGIBLE LANDSCAPES

Natural interaction between the user and computational design tools has been further improved with the use of Tangible User Interfaces (TUI). The study on TUI by Kim and Maher (2008) compared it with GUI and explored its impact on collaborative and participative design. The study found that the physical interaction with objects in TUIs improves designers' spatial cognition and offloads the designer thinking. The naturalness of the direct hands-on approach helps designers' immersion in designing, thus allowing them to perform spatial reasoning more effectively. In 2011, a study on TUIs paired augmented reality with tangible interaction and compared it to conventional interaction via GUIs, while it encouraged designers to engage in more exploratory design actions, creative interpretations, enhanced communication, and overall experience in collaborative design tasks while working in groups. (Gu, Kim, Maher, 2011)

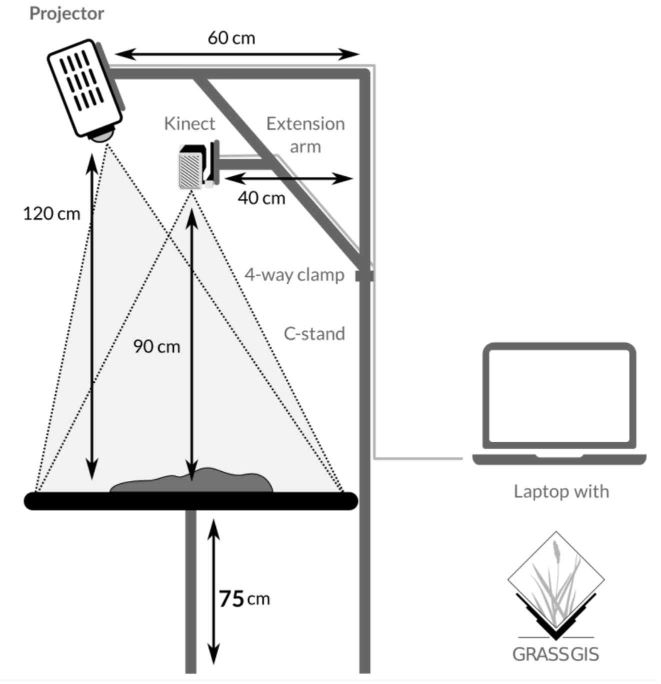

Fig. 6. Setup of tangible landscape (Source: Millar, Tabrizian, Petrasova, Petras, Harmon, Mitasova, Meen-temeyer, 2018)

A recently popular and widely used special type of tool combining AR and TUI in the collaborative modelling is tangible landscape. As a study (Millar, Tabrizian, Petrasova, Petras, Harmon, Mitasova, Meentemeyer, 2018) explains, tangible landscape allows users to model the scaled landscape by hand physically, 3D-scan it and virtualise it in a computer. The virtualised model can be used for various analyses or computation, which may be processed and then visualised back on the physical model, giving the users instant feedback. As the name of this tool indicates, it is mainly used for landscape and geospatial modelling and simulation. The tool is assembled with a mass for physical modelling – mainly kinetic sand, projector, 3D scanner and a computer (Fig. 6). As this setup with only one projecting and one scanning device allows sufficient scanning and projecting only on 2.5D objects, it is suitable for use in large-scale landscape modelling. As it enables a very natural interaction between the users modelling their common design, and is completely open-source, tangible landscape has quickly gained a community of users across the world.

TANGIBLE LANDSCAPE AS ARCHITECTURAL DESIGN TOOL

The research in this article explores the possibilities of extending the utilisation of the tangible landscape tool beyond the large-scale planning, into the architectural and urban planning domain. The use of different, more suitable software for architectural profession was a key factor in the adaptation of the tool for architectural use, as the originally-used GRASS GIS software was developed mainly for large scale geo-modelling. The originally used GRASS GIS software is a powerful computational tool with a robust open-source community; however, it was developed mainly for large scale geoinformation systems, not for detailed 3D modelling on the architecture scale. From the wide range of the architectural software tools the program Rhinoceros was chosen, as it is widely used by architects, and it is capable of the algorithmic modelling with the Grasshopper extension with plenty of plugins and pre-made scripts.

The rest of the setup of the first prototype constructed at the Faculty of Architecture and Design of the Slovak University of Technology in Bratislava, Slovakia, (FAD STUBA) is very similar to the original product of the aforementioned study (Millar, Tabrizian, Petrasova, Petras, Harmon, Mitasova, Meentemeyer, 2018). The main difference is a projector, which is able to project the bottom border of the image in the plane of its base, which allowed simplification of the stand holding it and a 3D scanner. Azure Kinect DK with 4096 × 3072 px resolution was used as the 3D scanner, mounted directly on the projector (Fig. 7). In Grasshopper, the script for 3D scanning with Azure Kinect GH plugin was prepared (Ahn, 2022). The outcome of the scanning are 3D points in a proper scale, which are subsequently automatically filtered and adjusted. The 3D points then serve as an input for computation and data visualisation. The current prototype is capable of point-depth colouring, preparing animation visualisation and constructing mesh geometry. The resolution of constructed mesh from scanned points is provided in Fig. 8.

Mesh constructed from points allows further analysis, such as contour line visualisation (Fig. 9), and shadow or solar irradiation analysis with Ladybug plugin. These computed data were afterwards projected back on the physical model, giving feedback to the designer. The scanning and computation were performed on physical models from different materials, in different scales - the model of an urban neighbourhood designed as a solar envelope, the lasered plexiglass urban area model, the 3D printed model of a residential building and on models made from kinetic sand, modelled by visitors to the Night of Researchers event in Bratislava, Slovakia. The solar irradiation analysis is currently performed with the tool and computations done annually, using a discretized model of the sky dome made of 145 patches based on Tregenza subdivision (Tregenza, 1987) with calculated annual solar radiation for each patch.

The model is based on Perez formulas for sky luminance distribution (Robinson, Stone, 2004; Perez, Seals, Michalsky, 1993). The algorithm GenCumulativeSky in Ladybug calculates the irradiations of sky patches from direct normal and diffuse horizontal irradiance values noted as measured values in a list as part of EnergyPlus Weather file - reference climate data per one year, in a specific place (Energyplus, 2020; Radsite, 2020). The current prototype of tangible landscape uses the location of Bratislava but it is possible to easily change it to other places with available EnergyPlus Weather file. The projection of the solar irradiation analysis is in Fig. 10. All those visualisations run on the single push of the button, without any digital modelling or scripting knowledge required on the part of the user. Every operation took different time to compute, allowing interaction with the tool in real time, or interaction in time intervals (Tab. 1).

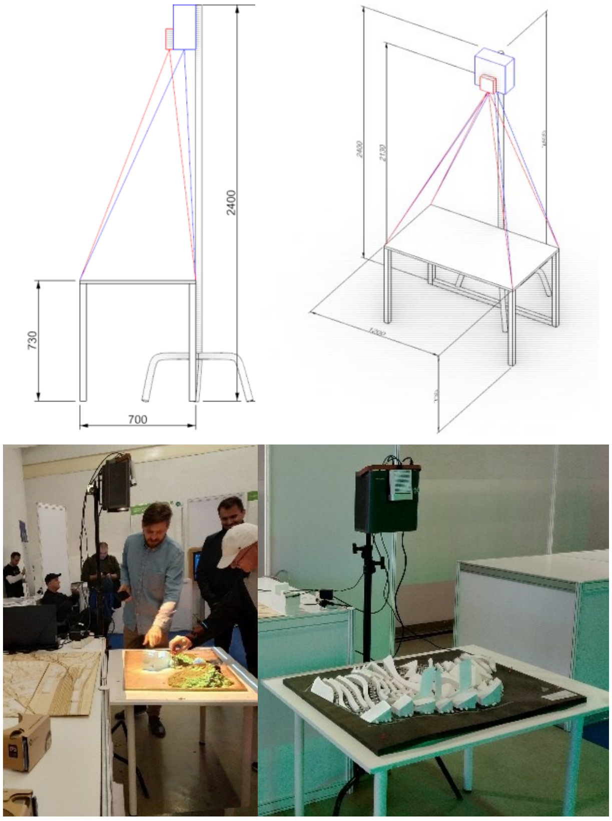

Fig. 7. Setup of the tangible landscape at the Faculty of Architecture and Design, Slovak University of Technology in Bratislava, Slovakia (Model: students Daniela Martinkovičová, Mária Mihaľková, supervised by Julián Keppl and Klára Macháčová; Source: Uhrík, Kupko, Krpalová, Hajtmanek - authors)

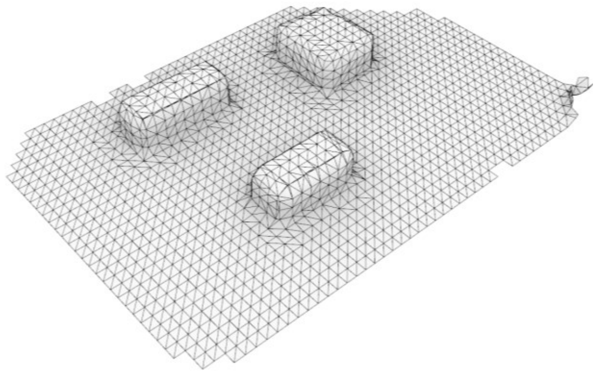

Fig. 8. Reconstructed mesh from 3D scanned points. (Source: Uhrík, Kupko, Krpalová, Hajtmanek - authors)

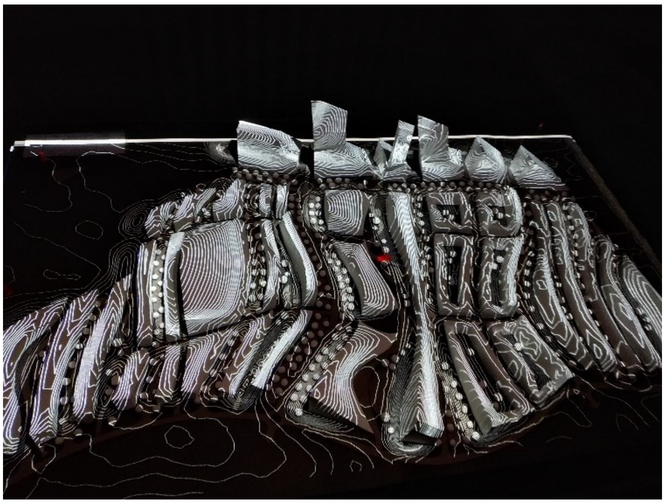

Fig. 9. Contour lines visualisation on the physical model of an urban area. (Model: students Daniela Martinkovičová, Mária Mihaľková, supervised by Julián Keppl and Klára Macháčová; Source: Uhrík, Kupko, Krpalová, Hajtmanek - authors)

Fig. 10. Top – solar irradiation of the urban area. Bottom left – solar irradiation of the residential building – 3D printed model. Bottom right – scanning and modelling with kinetic sand by visitors to the Night of Researchers event in Bratislava, Slovakia. (Model: students Daniela Martinkovičová, Mária Mihaľková, supervised by Julián Keppl and Klára Macháčová; Source: Uhrík, Kupko, Krpalová, Hajtmanek - authors)

Tab. 1. Time of computation – responsiveness of the system. (Source: Uhrík, Kupko, Krpalová, Hajtmanek - authors)

Type of computation	Required time
Points depth colouring	under 100 ms
Prepared animation	under 100 ms
Constructing mesh	circa 2 s

Shadow analysis	circa 6 s
Solar analysis	circa 8 s

DIGITAL DATA AS TANGIBLE PARTS

Non-parametric computational design strategies

The ways in which architecture is notated, and the use of tools may influence fabrication methods as well as its conceptual and aesthetical aspects. Professor of Architectural Theory and History, Mario Carpo, examines in his work how the evolution of computation has been affecting contemporary architecture. He describes the use of parametric tools that initiated the boom of the parametric architecture movement as *"The Digital Turn in Architecture"*. (Carpo, 2014) For the past 10 years a shift in the paradigm of computational design has become more pronounced. Carpo initially identified this phenomenon as a discontinuity between the mainstream and the academic aesthetics. The general image of designs produced by computational design tools follows the style of parametric architecture, which is smooth, curvy and continuous. However, nowadays, the designs created at school and in some experimental projects are *"disjointed, disconnected and fragmentary – often voxelized, filamentous or chunky"*. (Carpo, 2019)

This shift, labelled by Carpo as *"The Second Digital Turn"*, introduced the then-new, emerging discrete architecture movement. Their attitude towards notation of architectural designs has been changing. Computational designers aspire to create a setting where digital design and fabrication processes stem from close human-machine cooperation. With the utilization of robotics and tools of digital fabrication, the data do not require a notation understandable to the human mind. The notion of discrete comes from the mathematical term that means being individually separate and distinct. The digital notation of raw data used by computers utilizes the format of discrete mathematics that describes objects as countable, finite sets, as a list of the positions in space (x-, y-, z-coordinates). That opposes the previously compressed and simplified data recorded using the human logic of parametric equations. In conclusion, the revised model of computation logic has resulted in research of non-parametrical design strategies.

Fig. 11. Block' hood project. (Source: Sanchez, 2016)

"It asserts that a digital form of assembly, based on parts that are as accessible and versatile as digital data, offers the greatest promise for a complex yet scalable open-ended and distributed architecture." (Retsin, 2019a) This development opens the discussion on how tools and devices can support such cooperation in architectural design. Jose Sanchez has introduced an approach named combinatorial design and outlined how this approach can be utilized in practice. Combinatorial design is an approach that uses modular, discrete elements and combinatorial algorithms that compute their possible aggregation. (Sanchez, 2016) Such an approach has been illustrated within VR environments trough gamification. The first illustrative project was a Block'hood game (Fig. 11), a video-game interface that was used in the study of collective architectural engagement using real-time interactive platforms. The study indicated that interactive platforms facilitate an enhanced decision-making process, one in which human intuition is coupled with algorithmic intelligence. (Sanchez, 2016) In the following project, Virtual warehouse facility (Fig. 12.) interface allowed users to design and simulate the fabrication of Discrete Architecture Projects. (Sanchez, 2019)

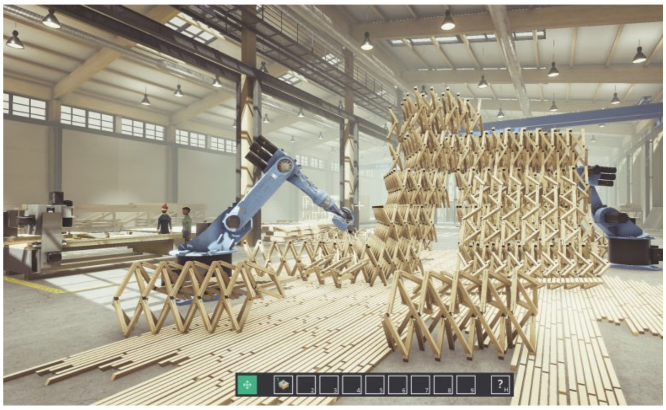

Fig. 12. Virtual warehouse facility project. (Source: Sanchez, 2019)

Prospects of human-machine cooperation

In academia, Bartletts', UCL Research Cluster 9 (RC9) led by Soomeen Hahm (Fig. 13) and Alvaro Lopez Rodriguez, has outlined ways in which AR and tangible elements can be involved in the computational design process. The recurring theme of the use of XR devices is present in the projects of RC9, with the focus on redefining the role of humans, machines, and computers. Researchers propose a workflow, where humans use AR devices to design and assemble models. In this case, discrete parts have become the tangible interface of combinatorial design tools. *"This is to propose an alternative to reducing construction to fully automated assembly of simplified/discretized building parts, by appreciating physical properties of materials and nature of crafting processes."* (Hahm, 2019) In 2019, Gilles Retsin demonstrated the potential of discrete design and fabrication through the use of an AR tool, fologram and combinatorial algorithm in a real-life scale prototype (Fig. 14). *"We used AR to send instructions directly from the digital model to the team working on site. AR therefore helps us understand what a fully automated construction process would look like, where a digital model communicates directly with people and robots on site."* (Retsin, 2019b)

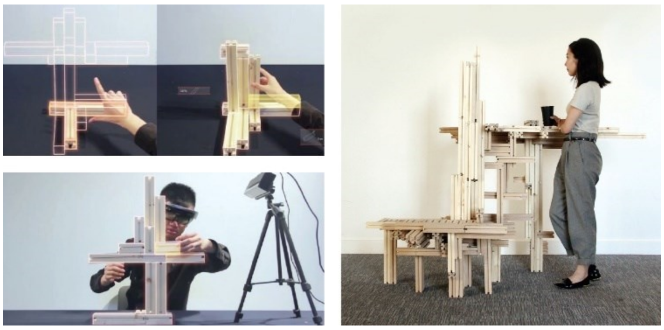

Fig. 13. iBrick project. (Source: Hahm, 2019)

Authors of this paper have also been participating in an ongoing project Monoceros, which has resulted in a combinatorial design toolset similar to those mentioned in earlier examples (Subdigital, 2021). The Monoceros project (Fig. 15) is a suite of tools from the Subdigital studio in the form of a freely available plugin for Grasshopper 3D. The plugin is created with an emphasis on computing power, stability and ergonomics of use for designers and architects. Monoceros is an implementation of the Wave Function Collapse (WFC) algorithm. The tool makes it possible to digitally design and materialize composite objects in scales ranging from jewellery, through spatial installations to urban structures from a limited number of repeating elements or modules. With a limited number of modules, it is possible to create an unlimited number of unexpected objects that will have the expected aesthetic, qualitative, functional and structural properties. With its simple use and adaptation for the purposes of architectural design, it democratizes and makes the otherwise complicated WFC available for the purposes of computational design. Further development of this universal toolset and its implementation in XR environments could result in multiple projects with various uses.

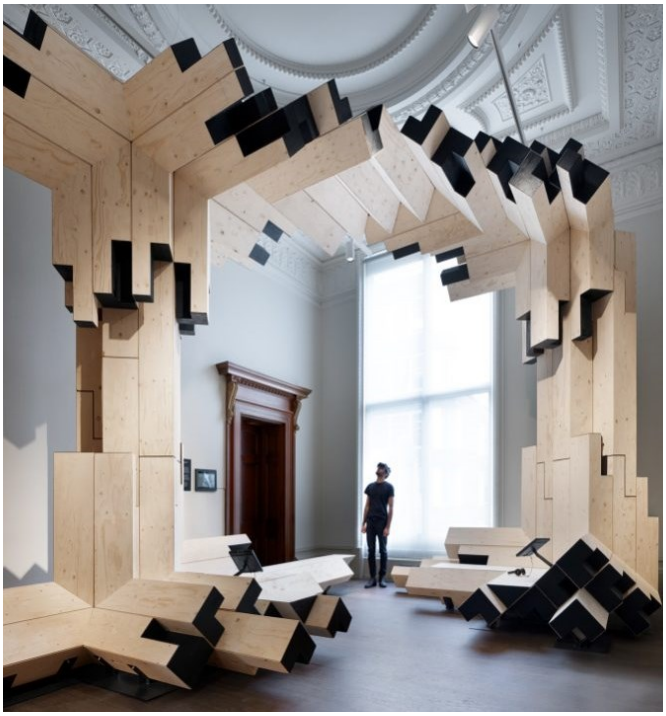

Fig. 14. Real Virtuality Project. (Source: Retsin, 2019b)

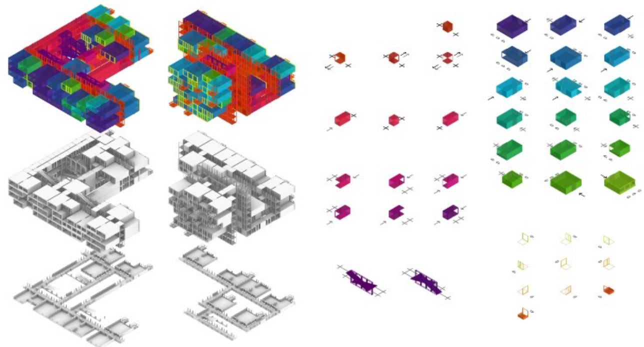

Fig. 15. Monoceros housing study. (Souce: Subdigital, 2021)

CONCLUSION

Computational tools are powerful aid to design; nevertheless, their popularity is currently decreasing. Young authors rather prefer easy-to-learn and intuitive tools. In the current fast-forward world, nobody has time to learn slowly. An easy-to-use interface and attractive envelope are as important as the tool's capabilities. Exploring new interfaces, such as TUI or XR may make those tools more human and bring them closer to their users. That was also the aim of the prototype of the tangible landscape at the FAD STUBA. The use of the prototype has already shown that it can improve communication during the collaboration as it blends the physical 3D and digital layers. As a result, the design is more legible and design decisions are more intuitive. The plan for follow-up research is to pursue its utilisation in modular and discrete architectural projects using components and designing from inside out, with possible implementation of the Monoceros tool (Subdigital, 2021).

Another aspect of the tool is its educational potential. Interactive engaging of the touch and visual senses has led to better understanding and remembering of the concept mainly with the younger audience from secondary schools, who saw the tool at the Night of Researchers event in Bratislava Slovakia. Despite the benefits of the prototype, new areas for improvement have been identified. As the current setup of the tangible landscape 3D-scans only the depth of the physical model, it captures the facades insufficiently. The plan is to enhance the prototype with with more 3D scanners on the sides of the table to capture also facades of the objects. The planned improved version is in Fig. 16.

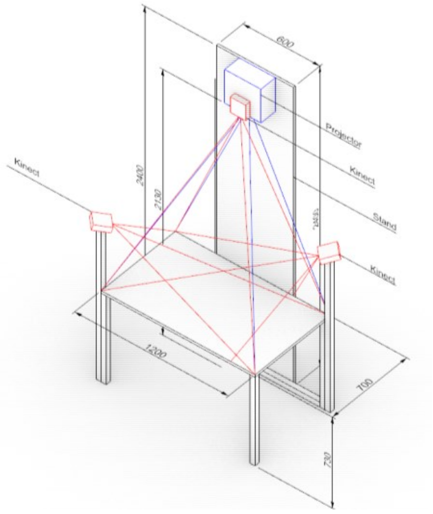

Fig. 16. An improved planned version with three 3D scanners. (Source: Uhrík, Kupko, Krpalová, Hajtmanek - authors)

Another improvement is that the main scanning Kinect, above the model, will be mounted at different height, as the current resolution of scanning is not sufficient. The projector will be placed higher, which will eliminate shadows produced by projecting. The use of Grasshopper has shown that the scanned model could be further modified with its large library of plugins, or in a 3D environment of Rhinoceros, well-known to architects. Nevertheless, the Grasshopper's computation times of some operations are too long for the intuitive interaction. The next plan is to experiment with Blender as an opensource engine for running 3D scanning and computation with its extensions Geometry Nodes and plugin Sverchok with Ladybug toolset. As Blender is usually used as animation software for high-poly scenes, it may increase the speed of the Tangible Landscape and its interaction with users.

The tool was tried with different materials used for the physical models. This experimentation has revealed that kinetic sand is less suitable for modelling buildings or spaces than for modelling landscapes. This mass is too liquid, which means it is only possible to model urban area models in scale 1:1000 or 1:5000. The materials usually used for analogue architectural models – paper, cardboard and 3D printed matt PLA – were used by the tool without any problems. On the other hand, the use of plexiglass revealed that the scanning did not work as expected, and the reflections and plexiglass blocks were scanned as holes in the base board. 3D print from highly reflective PLA might also have this problem.

Nowadays, even larger architectural offices rather prefer to use simplistic, easy-to-learn design tools, e.g., SketchUp, instead of BIM, even in the execution phases, as their dynamic teams and interns learn to use the tools quickly, during their work, without the need for additional investment into their training. It seems that even if mistakes emerge in this process, it is inexpensive in comparison to the investments into the education and training of employees needed for more powerful software in terms of computation, automation and design analysis. This is probably the face of the new fast architecture. Making the computational tools more accessible and intuitive for everyone is a way to use different approaches to design more widely and to be more original, or to evaluate the outcomes during the design, and thus bring more efficient and meaningful solutions.

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