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Integration of Augmented Reality for Enhanced Visualization and Analysis in Bridge Engineering, Towards Real-Time Optimization in Structural and Architectural Design

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Abstract

Augmented Reality (AR) can create a live visualized design and analysis system of adjustable geometry regarding structural analysis and site conditions. In contrast to conventional methods, the aim is planning directly in situ to generate desirable geometry for different constructions. By considering the potential of Augmented Reality (AR) through a bridge example, the current study proposes a step-wise algorithmic approach for live planning. In this regard, using AR glasses, the site environment is initially scanned to create a basis for planning, which enables allocating the controlling and supporting points as holograms. Then, the algorithm configures the geometry of the initial bridge, minding the arch line, and a parametric cross-section is calculated. By the user interface, the on-site operator can adjust all geometrical parameters (e.g., span, height, and section). The simultaneously visualized bridge geometry and calculation results (diagrams in the natural environment) enable the operator to design optimum geometries regarding the structural and architectural criteria. Furthermore, some more details and calculations, including the construction process (e.g., the segmentation) and the financial measures (e.g., the material amounts), were also considered. In addition to designing optimum geometries, in situ planning can quickly identify geometrical problems, accelerate the process, and make a 3D model of the structures in the natural environment. The successful operation shows that this closer link between digital planning and actual construction states in further steps can be applied to different, more complex structures with a higher element number.

Keywords: Digital planning, Live analyzing, Augmented reality, On-site, Segmental bridge

1. State of the Art:

Augmented Reality (AR) immerses users in a blend of computer-generated content overlaid onto their real-world surroundings. As AR technologies advance, they offer diverse and increasingly popular applications across various fields, including education [**1**], design, manufacturing [**2**], and entertainment [**3**]. Recent advancements in Information and Communication Technologies (ICT) promise to generate business value by facilitating data-driven manufacturing and autonomous supply chains [**4**]. These technologies facilitate smooth data transmission and connect information to the movement of goods and materials [**5**]. This growing trend underscores the immense potential of AR to enhance existing technologies and elevate overall quality of life.

Extended Reality (XR) encompasses a range of immersive technologies designed to enhance user experiences and evoke heightened sensations. XR comprises Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). Virtual Reality (VR) aims to create a fully immersive digital environment that disconnects users from reality. In contrast, Augmented Reality (AR) and Mixed Reality (MR) focus on integrating virtual elements into the real world. AR emphasizes overlaying virtual elements onto the real environment, while MR enables seamless integration of virtual and objective elements. With MR, users can interact with virtual and real-world elements simultaneously, facilitating interaction and integration between the two environments [**6**].

Likewise, these techniques hold significant promise in structural and construction engineering, offering innovative solutions to enhance design, construction, and maintenance processes. In structural engineering, AR can visualize complex structural models in real-world environments, facilitating better understanding and decision-making during the design and analysis stages. Construction engineers can benefit from AR by overlaying digital models onto physical construction sites, enabling precise alignment of components and accurate visualization of project progress [**7**]. Additionally, AR can improve on-site safety by providing real-time contextual information and guidance to workers, reducing errors and enhancing efficiency. Overall, AR technology has the potential to revolutionize how structural and construction engineering projects are planned, executed, and maintained, driving efficiency, accuracy, and safety across the industry [**8**].

A recent study explores the trans-formative potential of AR, taking it beyond traditional applications in 3D visualization and assembly guidance. By coupling AR with Vector-based Graphic Statics (VGS), researchers have developed a workflow that allows for real-time manipulation of both form and force diagrams, Fig.(1). This approach was effectively demonstrated in the construction of a 4×2-meter table, highlighting AR's pivotal role in facilitating dynamic adjustments and guiding precise construction tasks. The study not only showcases how AR can enhance collaborative efforts in multi-user environments but also critically examines the challenges and future directions for integrating VGS with AR [**9**].

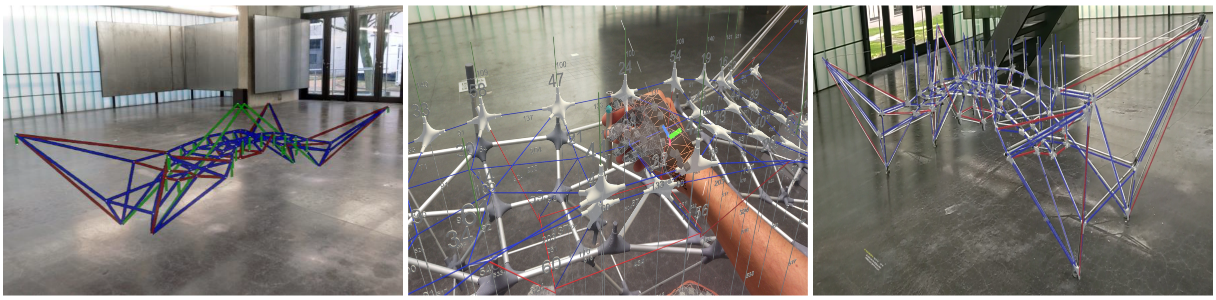

Figure 1: Left) In the AR Environment, when a node in diagram is moved using Microsoft Hololens gestures, Mid) The adjustment of the nodes by the operator, Right) Final assembled substructure [**9**].

One of the prominent features of AR technology is the combination of virtual and natural objects. Traditionally, VR has been used to visualize construction processes [**10**] and [**11**]. The core of VR implementation in construction is detailed 3D CAD modeling of both the project and the environment [**12**]. The input of detailed environmental information is also required for VR implementations [**13**]. However, the requirements for detailed models become impractical as the complexity of the construction process increases [**14**]. With AR technology, the virtual construction plan and the actual construction site can be combined and visualized to engineers and workers in real-time, leading to increased accuracy and efficiency [**15**]. Applying AR in life-cycle construction site planning can help keep the project within budget and avoid process errors or additional time. AR does not require detailed modeling of the environment or existing project flow [**13**].

Despite the mentioned investigations and achievements in the utilization of augmented reality and, from the other side, development in structural engineering, especially in computational technique and progress in the software, different aspects of designing the structures have not been addressed appropriately. The aspects include the architectural and structural points of view. For instance, no one of the studies addressed the application of AR (e.g., utilizing HoloLens) in the live design of a structure in the real environment. AR seems to have the potential to enable the operator to simultaneously visualize and decide about the geometry of the structure based on the force amounts (structural) and how the geometry in the final location looks (architectural) while manipulating the geometry (e.g., spans and sections). For instance, regarding the difficulties of designing arches and influences of parameters like shape and height to span ratio on their load transitions process [**16**], [**17**], this application quickly designs a desirable pre-model of construction.

2. Application of AR for Live, Parametric Visual Analysis of an Arch Bridge

In this study, the potential of Augmented Reality (AR) is demonstrated through an example involving the live analysis of an arch. A segmented concrete arch bridge located over a river serves as the real-world scenario for parametric analysis. The objective is to achieve live adjustable force and visual analysis while simultaneously displaying the forces and geometry of the bridge in its final location. This enables the operator to select the optimal structures based on various parameters, including height-to-span ratio and the type and number of concrete sections. The process involves the utilization of HoloLens and established structural analysis methods, culminating in a practical example.

2.1. Methodological Framework for AR-Based Optimization of Bridge Design

Augmented Reality (AR) integration signifies a paradigm shift in bridge engineering, fostering a more interactive and iterative design process. This section details the methodological steps employed using HoloLens to achieve a synergistic balance between structural integrity and architectural aesthetics for a bridge over the Oker River Valley in Braunschweig, Germany.

1. Initial Environmental Scanning with HoloLens The design process commenced with a rough environmental scan using HoloLens's advanced spatial mapping capabilities. This comprehensive scan captured the site's topography, generating a sufficient digital terrain model (DTM). This DTM was a precise foundation for the virtual bridge representation, ensuring an accurate contextual backdrop for subsequent design stages.

2. Virtual Allocation and Preliminary Positioning Leveraging the DTM, virtual structural elements were meticulously positioned within the environment. HoloLens's spatial computing abilities facilitated the placement of holographic elements, serving as a reference for later physical construction. Precise alignment with the natural topography was crucial, considering potential geological and environmental constraints.

3. Real-Time Structural Adjustment and Design Iteration Following preliminary allocation, real-time structural adjustments were conducted using HoloLens. The interface facilitated on-the-fly modifications based on the specific types of analysis, load path calculations, stress analysis, deflection calculations, buckling analysis and forces. In the current example, to simply describe the process, forces based on the next section, static calculations were analyzed. This iterative process enabled rapid fine-tuning of the bridge design to optimize structural performance.

4. Defining Bridge Section Attributes With the virtual model taking shape, attention turned to defining the cross-sectional attributes of the bridge segments. This critical step involved selecting a material and geometric configuration that balanced the strength-to-weight ratio, considering engineering principles and material cost-efficiency.

5. Visualization and Analysis of Structural Forces A key innovation of this methodology was the real-time visualization of forces within the AR environment. As the operator manipulated the virtual model, the AR system dynamically displayed the distribution of forces (tension, compression, shear, bending moments). This crucial feedback loop informed design decisions, enabling early detection and correction of potential structural issues. Specific examples of visualized forces could include color-coded segments highlighting areas of high stress or diagrams overlaying the bridge to represent bending moments.

6. Segmentation of the Virtual Model for Constructability The virtual bridge was segmented to mirror the proposed construction phases, enhancing clarity on constructability and aiding in logistics planning and resource allocation. It also facilitated in-depth analysis of individual segment performance, a feature often overlooked in traditional design approaches but critical for complex structures. In this approach, the number and type of segments required for force analysis and later production are selected by the operator during the live analysis. Primarily, this approach leads to an optimal suggestion for the arch geometry. Despite a final standard analysis being conducted after finalizing the geometry to select the type of concrete and re-bar layout, initial assumptions for the weight of the concrete, similar to regular designs, should be made.

7. Iterative Refinement of Cross-Sectional Parameters The final stage involved iterative refinement of the cross-sectional parameters of the bridge segments. Guided by the goal of optimal structural performance, the operator made data-driven adjustments to segment dimensions, reinforcing steel layout, and material compositions. Through this iterative process, a well-balanced design emerged, ensuring structural integrity while aligning with aesthetic and environmental considerations. Due to the high range of possible geometries for the section and the difficulties of defining the parametric cross-section, to ease the operator's task, in the current example, the type of section was selected from a limited proposed range, such as a voided segmental arch suitable for high axial and lateral-torsional forces.

2.2. Structural Calculations and Definitions:

Before describing the usages of augmented reality in the live design of an arch, to prove the structural calculations and declare how it was coded in HoloLens, the problems and calculations through an example mentioned. Then, in the following section, its proven application in HoloLens will be described, and multiple examples will be made. The discussed approach shows how the live adjustment of the bridge

Seg:	α	$\sin\alpha$	$\cos\alpha$	$x = x' - R/2$	$y = y' - (R - h)$	Δx	V_0	V	N
A	38.57	0.62	0.78	0.00	-	1.28	–	7.32	186.4
1	36.64	0.60	0.80	1.28	0.99	2.66	110.53	9.91	179.9
2	32.78	0.54	0.84	3.94	2.83	2.78	99.48	7.07	174.2
3	28.93	0.48	0.88	6.73	4.49	2.89	88.42	5.00	168.9
4	25.07	0.42	0.91	9.61	5.97	2.98	77.37	3.63	164.2
5	21.21	0.36	0.93	12.59	7.24	3.06	66.32	2.88	160.1
6	17.36	0.30	0.95	15.64	8.31	3.12	55.27	2.65	156.6
7	13.50	0.23	0.97	18.77	9.17	3.17	44.21	2.85	153.8
8	9.64	0.17	0.99	21.94	9.82	3.21	33.16	3.39	151.8
9	5.79	0.10	0.99	25.15	10.25	3.23	22.11	4.16	150.6
10	1.93	0.03	1.00	28.38	10.47	1.62	11.05	5.06	150.2

Table 1: Geometrical Definitions, shear and bending amounts

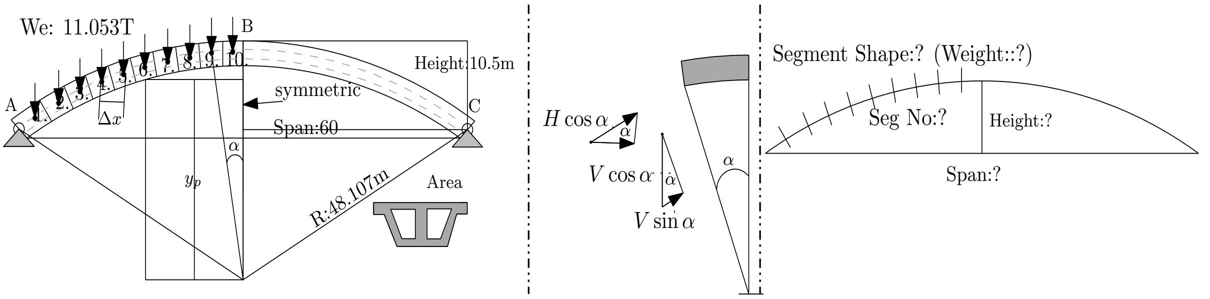

Figure 2: Geometrical definitions of the example

geometry changes the structural forces (inc., bending, shear, and axial loads) and the structure's geometry in the scanned natural environment. This enables the designer to regard the architectural (aesthetics) and the structural aspects of having a structurally optimum and architecturally desirable geometry simultaneously. Since the current study is the first in its field and the target proposes a new approach, a simple example with enough variables was selected to quickly describe the live analyzing technique. In following the calculation method, an example is mentioned, and then the method of its application in HoloLens will be described. Finally, some examples of operation techniques will be addressed.

2.2.1. Definition of the Structural Problem of an Arch:

A wide range of approaches have been developed for finding the optimum form of arches and shells [**18**], [**19**], which are mainly based on optimization algorithms or specific calculations aimed at reducing eccentricities [**20**]. Nonetheless, the current approach is based on the direct engineering judgment of the operator. The first example should be simple but have parameters the HoloLens operator can set. This bridge arch with simple supports (hinged) has symmetrical geometry. The main problem is designing a concrete bridge structure over a natural valley. The dimension of the cross-section of the bridge deck, which is a reinforced cavity cross-section, was chosen as the parameters (setting variables). Nevertheless, the approach can also consider changing the lengths of the section; the length of the bridge segments is assumed to be the same, and the number of segments is considered a parameter. In HoloLens, the arch's span length and height are considered parameters that can be manipulated in the live design. Since, in AR, some diagrams represent the results through the arc, forces in each segment are needed (e.g., shear and bending diagrams). Therefore, the calculation results are described in some tables in this step.

Some assumptions were made in this example to describe the calculation. This example considers the live load (LL) and the self-weight of the voided section ($Weight$), which is the section area multiplied by the concrete weight. The forces are calculated based on the number of segments (Seg), $Weight$, the span ($Span$), and the height of the arch ($Height$), Fig.(2). These independent parameters decide the loading and other geometrical features to be manipulated. In this example, to describe the calculation assumed as Radius of the arch ($R : 48.107m$), $Span : 60m$, $Height : 10.5m$, ($LL + Weight : 11.053T/m$) and ($Seg : 10 \times 2 : 20$). Figure (2) shows the mentioned parameters of the example.

Based on this, the places of the segments can be calculated, which are managed by the HoloLens in the following section. After selecting the arch geometry in each iteration, the places of the nodes (10+2(A+B)) over the arch are selected. In the calculations, it can be applied by the angles and radius ($\alpha + R$) or coordinates (x, y), Fig.(2). Table. (1) displays the geometrical properties of the arch, which are principally decided by the operator's decision. After deciding the coordinates or angles, each segment's center is clear, which calculates the distances between the center of segments for shear and bending calculations. Table. (1) also shows the stepwise load summations, which are equal to the shear

Seg:	$M_i = V.\Delta x$	$M_s(t.m)$	$M'.m$	m^2	$H_A(y)$	M (t.m)
A	141.72	–	–	–	—	–
1	264.87	141.72	-140.04	0.98	148.506	6.782
2	245.82	406.59	-1152	8.03	425.835	19.24
3	223.26	652.41	-2932.4	20.2	675.542	23.13
4	197.49	875.67	-5223.7	35.6	896.571	20.9
5	168.89	1073.2	-7768.1	52.4	1087.92	14.76
6	138.06	1242.1	-10319	69	1248.68	6.629
7	105.21	1380.1	-12656	84.1	1378.24	-1.87
8	70.946	1485.3	-14586	96.4	1475.9	-9.42
9	35.707	1556.3	-15959	105	1541.25	-15
10	–	1592	-16672	110	1574	-18

Table 2: Geometrical Definitions (Imported by the operator)

on the right side of the element (V_0).

For calculating the Horizontal load in the supports the numerical integration can be used [**21**], $H_A = \frac{2\Sigma M'm}{2\Sigma m^2} = \frac{2\times 87390}{2\times 581} = 150.5T$ in which M and m are the bending and the increasing bending rate accordingly, Tab.(2). After calculations of H_A, the axial load ($N = V_o \sin(\alpha) + H\cos(\alpha)$) and the Shear forces in different segments ($N = V_o \sin(\alpha) + H\cos(\alpha)$) can be calculated. The results of the geometrical, axial, and shear forces are shown in Tab.(2). For calculating the bending amount in the arch segments, increasing amounts of bending, which is shear times distances, were initially calculated ($M_i = V.\Delta x$). This amount and stepwise summation of them are shown in Table. (2), in which $M.m$ is the bending moment ($M'.m$) multiplied by differences in y direction. If the $HA(y)$ of all segments are calculated, bending will be equal to $M = M_0 - H_A(y)$, Tab.(2).

To prove the performance of the selected calculation, a comparison with SAP2000 was made, in which the mentioned arches' dimensions and forces were selected. The difference between them is lower than 3% on average. The first reason for presenting the computations is to prove the computational results of HoloLens compared to SAP2000 and then to display later how they can be applied in this virtual tool. This first application of the method requires a simple, well-known computational approach, while this study aims to show how it can be coded in HoloLens. It should be recalled that HoloLens does

Figure 3: left: Operator of HoloLens in Live Analyses of the Bridge-Arch, Right: Site Layout

not have a high computational capacity. This means that this calculation was decided contrary to the experience and preferences of this article's researcher in developing FE models. Using the FE method is not reasonable in this step due to the analysis costs and the type of coding platform available in HoloLends. In further steps and publication, the aim is to convert the geometry into a building structure and connect the HoloLens to another platform on an ordinary computer through a bidirectional data transfer. The regular computer will be used instead of the HoloLens for the massive calculations.

2.3. Application of the HoloLens in Live Analyses of the Bridge-Arch

The process outlined involves a step-by-step implementation of procedures and coding structural calculations, facilitating live parametric analyses of an arch within a real-world setting. Imagine an operator equipped with fundamental structural knowledge donning a HoloLens at the construction site where the bridge is planned. Using intuitive finger gestures within the HoloLens interface, the operator selects ideal support locations (QR Codes) on both sides of the river, adjusts sliders to determine the number of segments, and chooses from a predefined list of section types. During the initial run of the analysis, various forces, such as bending and axial forces, are vividly displayed. Moreover, a crucial metric known as eccentricity (Ecc = Bending / Axial forces) is calculated, providing valuable insights to the operator for selecting the optimal geometry for each arch segment, Fig.4.

Subsequently, in successive iterations, the operator manipulates another slider to adjust the height-to-span ratio, essentially altering the arch's overall height. This dynamic adjustment, coupled with real-time forces updates within each iteration, gives the operator a comprehensive visualization of the structure's final geometry at the site for any chosen parameter. This interactive process empowers the operator to consider structural criteria, aesthetic considerations, and the structure's integration with the surrounding environment. Consequently, it culminates in determining the general geometry of the arch, which, following further standard calculations and design refinements (e.g., re-bar layout adjustments), can

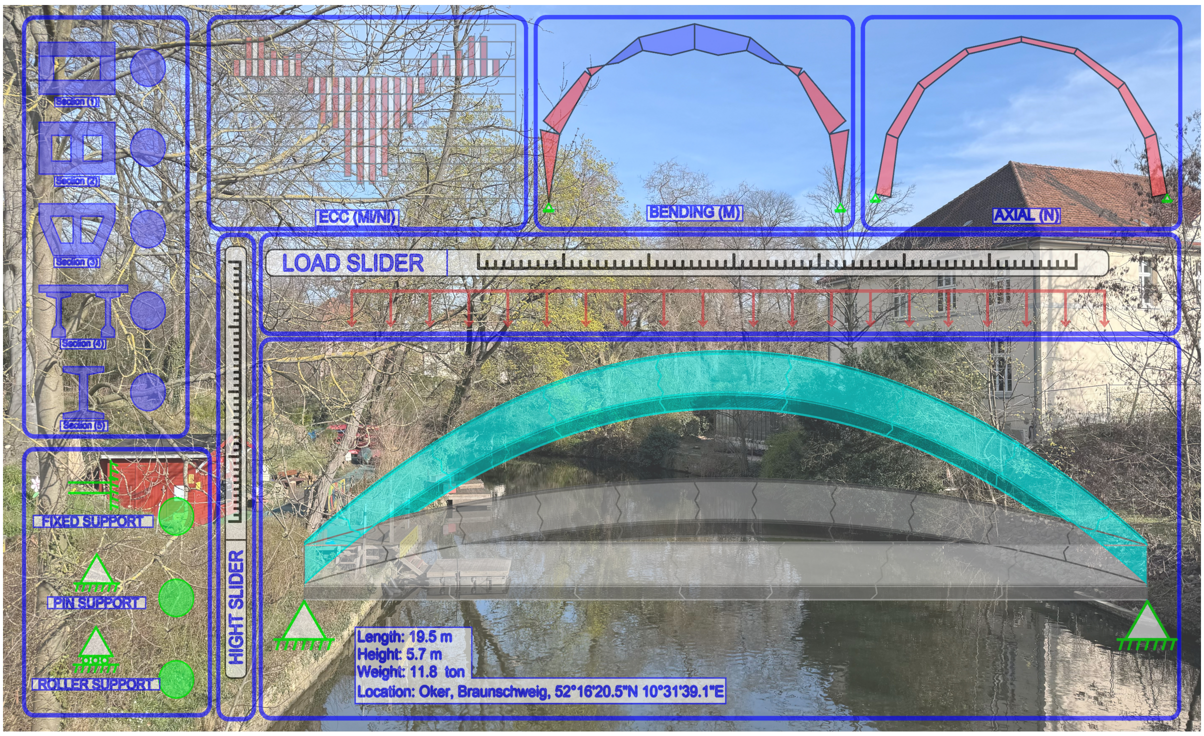

Figure 4: Application of the HoloLens in Live Analyses of the Bridge-Arch

seamlessly transition into CAD models for direct transmission to a concrete precast company.

This example as a prototype was addressed to describe the process, as well as simple geometry and a quick calculation process for the analysis of the arch selected, to be run by the HoloLens.

3. Conclusion

This study demonstrates the significant potential of Augmented Reality (AR) in structural and architectural evaluation by developing a live analysis tool for real-world construction sites. Utilizing HoloLens technology, the approach outlined in this study offers a dynamic means to guide operators toward structurally and architecturally optimal construction practices. Illustrated through the example of an adjustable arch bridge spanning the Oker River Valley in Braunschweig, Germany, this method enables the selection of critical variables such as height, span, arch radius, and segment cross-section to inform design decisions. By integrating statistical force calculations and leveraging HoloLens capabilities, the study showcases how AR can bridge the gap between conceptual design and physical construction. This iterative AR-based approach revolutionizes traditional boundaries, allowing for real-time exploration, adjustment, and optimization of bridge designs directly within the construction environment. The methodology presented here not only highlights the transformative potential of AR in bridge engineering but also suggests broader applications in complex structures and diverse construction scenarios. Additionally, the scalability of this approach holds promise for enhancing efficiency, accuracy, and adaptability in bridge construction practices, ushering in a new era of innovation and advancement in the field.

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