Council on Tall Buildings and Urban Habitat

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Title: **Mixed Reality for AECO**

Author: Aviad Almagor, Director, Mixed Reality Program, Trimble Solutions Corporation

Subjects: Architectural/Design
IT/Computer Science/Software

Keywords: BIM
Virtual Reality

Publication Date: 2016

Original Publication: Cities to Megacities: Shaping Dense Vertical Urbanism

Paper Type:
1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

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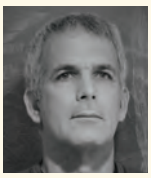
Mixed Reality for AECO

混合现实技术在建筑、工程、施工与运营（AECO）行业的运用



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Aviad Almagor 是天宝混合现实计划总监，主要负责公司的混合现实技术、愿景、战略、以及执行。Aviad 在 Vico Software 被天宝收购之后加入天宝，此前曾在Vico担任产品设计总监。在加入Vico之前，Aviad在领先建筑、工程与施工（AEC）软件公司担任了多个职务。Aviad是一名执业建筑师，持有苏格兰赫瑞瓦特大学工商管理硕士学位和以色列理工学院建筑学士学位。

Abstract | 摘要

This paper investigates the use of mixed reality for AECO. The far-reaching impact of construction projects on the urban fabric and the economic impact of such projects require efficient design review and analysis tools. Moreover, the global nature of such projects and the involvement of public and government organizations imply the need for effective communication and collaboration solutions. The last few years' transition from 2-D to 3-D models and the implementation of BIM have improved communication, but still, interacting with volumetric data behind a 2-D screen is extremely limited. Mixed reality brings the content out of the screen and provides users the ability to interact with design data more intuitively. Unleashing the 3-D models democratizes the data by offering a natural way for everyone to experience the design and associated information overlaid onto the world. This rich, hyper-reality environment supports design decisions, enables efficient collaboration, and introduces new design opportunities.

Keywords: Augmented Reality, BIM, Mixed Reality, Virtual Reality

本文对混合现实技术在建筑、工程、施工与运营（AECO）行业的运用进行了调查。考虑到施工项目对城市结构的深远影响以及这些项目的经济影响，有效的设计审查和分析工具就显得十分必要。此外，这些项目的全球性以及公共部门和政府机构的参与表明，这方面需要一些高效的沟通与协作解决方案。过去几年，2D到3D模型的转变以及建筑信息模型（BIM）的实施改善了沟通水平，但通过2D屏幕与体积数据进行交互依然极具局限性。混合现实让内容从屏幕中走了出来，让用户能够以更加直观的方式与设计数据进行交互。通过释放3D模型，这提供了一种对设计和叠加到现实世界上的相关信息进行体验的自然方式，实现了数据的民主化。这种丰富的超现实环境能够为设计决策提供支持，实现高效协作并创造新的设计机会。

关键词：增强现实、建筑信息模型(BIM)、混合现实、虚拟现实

Prologue

Just one human lifetime ago, the digital universe began. At the start, it was a kind of digital, primordial soup. A few people worked like puppeteers at a great distance from the digital world – they manipulated bits and switches to get work done with digital information: abstractions were rapidly created, techniques were compounded, and users began leveraging agents to manipulate larger digital structures, compilers, operating systems, and data sets. It was the age of big machines in data centers – the age of monolithic giants.

When the desktop revolution came along, user populations grew significantly and the distance between the operator (user) and the digital world shrank. Office work was automated, and users brought this digital universe into their homes, where computing got personal. Then, the mobile device revolution came along. User populations grew to include all age groups, and the digital world became richer, more diverse, and social.

序言

仅仅一代人之前，数字世界便开始初露端倪。起初，这只是一种数字混沌。极少数人像木偶师一样远远地隔着数字世界忙碌着——通过操纵比特和开关，他们用数字信息来完成工作。抽象化很快形成，技术得以整合，用户则开始利用代理来操纵更大的数字结构、编译程序、操作系统以及数据集。这是数据中心中的大机器时代，是单体庞然大物的时代。

随着桌面革命的到来，用户数大幅提升，操作者（用户）和数字世界之间的距离也缩短了。办公室工作实现了自动化，用户将这种数字生活方式带入了他们的家中，计算实现了个性化。接着出现了移动设备革命。用户涵盖了各个年龄阶层，数字世界变得更加丰富、多元、更具社交性。

用户透过数字窗户透视数字世界。系统转到了后台，成为了计算能力。用户希望穿过这扇数字窗户，完全沉浸到数字世界之中，进入一个现实世界之外100%合成的虚拟环境。虚拟现实让用户实现了这一愿望。不过这是孤立脱节的。但这种情形很

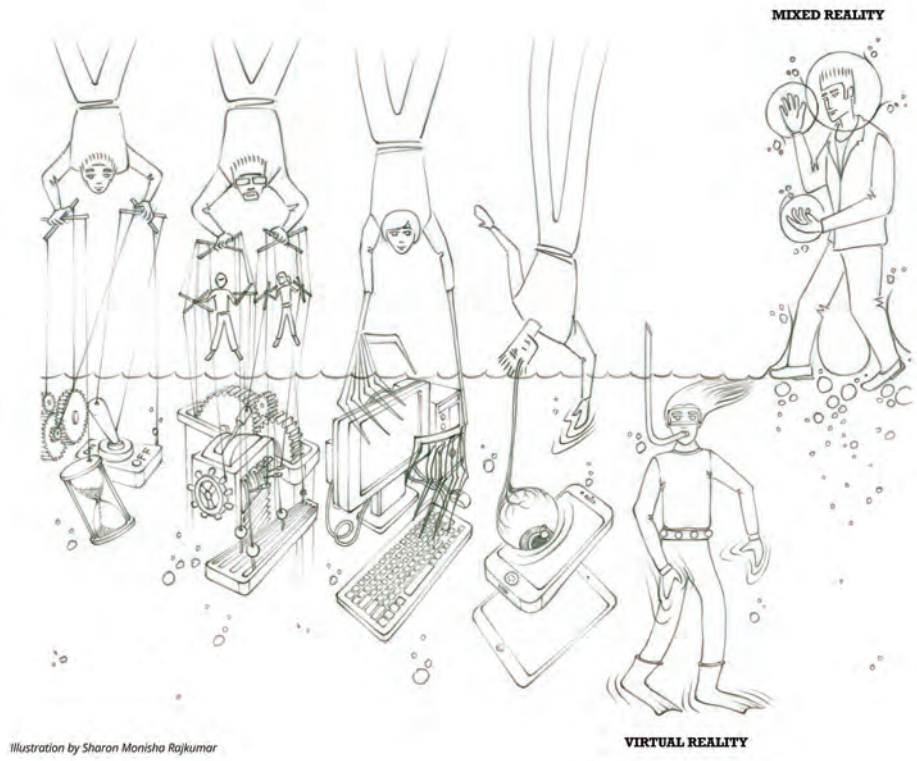

Figure 1. From a digital primordial soup to a mixed reality: the path and interaction between people and data along the short history of the digital era (Source: Trimble)
图1. 从数字混沌到混合现实：人类与数据在数字时代简短历史中的发展与交互。（来源：天宝）

Entire populations of users now press their faces against the window into the digital world, with systems swarmed into the background, becoming a cloud of computing capability. Users yearn to dive through this digital window and completely immerse themselves in a digital world – a 100 percent synthetic virtual environment, located outside of the real world. Virtual reality enabled them to cross this threshold and dive, isolated and disconnected; but not for long. The need to socialize and to be engaged in reality, brought the user back to the surface.

This time, the digital world crosses the threshold in another direction. Digital content floods over the barrier and mixes with our reality, coating the senses without masking them out. Unlike the virtual space, one can still see and interact with the real world; it is this mixed reality space that can leverage a new way of interacting with data, in context, moving out of computer screens and into the real world. It is not a trend but a true revolution, capable of impacting almost every aspect of life, and especially the way people consume, interact, create, and communicate data (Figure 1).

About Mixed Reality

Mixed reality technology blends real world objects with digital content, interactively and in real time. In 1994, Paul Milgram and Fumio Kishino defined mixed reality as "... anywhere between the extrema of the virtuality continuum" (Milgram & Kishino, 1994), spanning the purely virtual and purely real environments (Figure 2). Four main technologies co-exist along this Virtuality Continuum: virtual reality, augmented virtuality, augmented reality, and mixed reality.

Virtual reality (VR) presents a world that is completely modeled. The virtual experience becomes your reality, filling your vision in a full immersion mode. A key factor in VR is a sense of presence (Mantovani & Castelnuovo, 2013) as a mechanism to trick the user into believing that he or she is in a "real environment."

Augmented virtuality (AV) adds real-life notions to the virtual world. A gyroscope with real-time orientation data or a video feed from the physical environment are typical examples of AV environments.

快便发生了改变。对社交的需求和对现实的需要将用户拉回了现实世界。这一次，数字世界朝着另外一个方向发展。数字内容冲破障碍，与现实世界混合在一起。数字内容模糊了我们的感官，但并没有将我们的感官完全遮蔽。与虚拟空间不同的是，用户依旧可以看到并与现实世界进行交互。这种混合现实空间在情境之中实现了全新的数据交互方式。从电脑屏幕中走出来，走进现实世界，这不是一种趋势，而是真正的革命，将影响我们生活的方方面面，尤其是影响人们进行数据消费、交互、创造与沟通的方式方法（图1）。

关于混合现实

混合现实技术能够以实时交互的方式将现实世界对象与数字内容融合在一起。1994年， Paul Milgram和Fumio Kishino将混合现实定义为“……虚拟连续统极值的任意位置”(Milgram & Kishino, 1994)，涵盖完全虚拟和完全真实的环境（图2）。虚拟连续统中同时存在着四大技术：虚拟现实、增强虚拟、增强现实、混合现实。

虚拟现实呈现的是完全模型化的世界。虚拟体验成为了用户所体现到的现实，以完全沉浸的方式覆盖用户的视野。虚拟现实的一个关键因素就是存在感(Mantovani & Castelnuovo, 2013)，这种机制能够让用户认为自己处于一个“真实环境”中。增强虚拟为虚拟世界增添了现实生活概念。虚拟环境增强的典型例子包括包含实时定位数据的陀螺仪或来自物理环境的视频流。增强现实是以物理环境为主，以数字内容为辅。增强现实让用户处于周围环境之中，在现实世界的基础上叠加一层数字内容。叠加的数据可以是简单的文本注释，也可以是一栋建筑复杂的3D模型。第四大技术就是混合现实。混合现实让数字内容从电脑屏幕中走出来，走进物理世界，打造一个物理和数字对象共存的集成环境。混合现实的一个关键特点就是数字内容和现实世界内容能够实时交互。混合现实提供的灵活性让人们能够在虚拟连续统中从完全沉浸体验无缝切换至现实世界情景。由此一来，混合现实便能够让人们

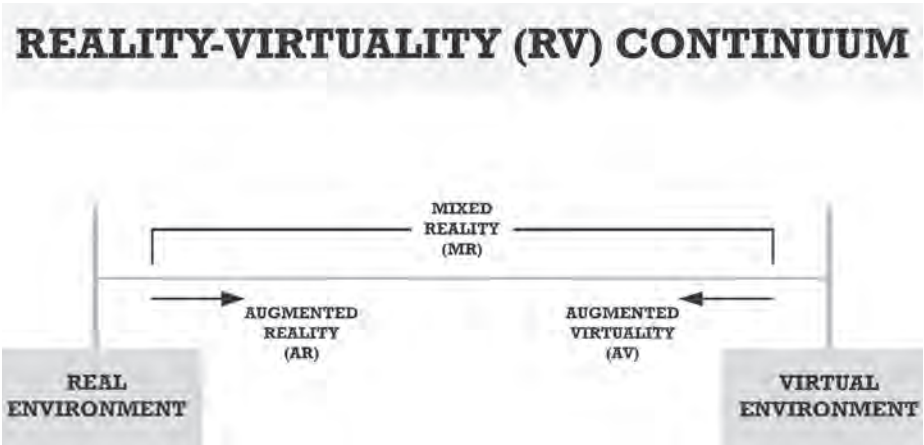

Figure 2. The Reality-Virtuality Continuum: a continuous scale ranging between the completely virtual to the completely real (Source: Paul Milgram)
图2. 现实–虚拟连续统：一个从完全虚拟到完全真实的连续统。（来源：Paul Milgram）

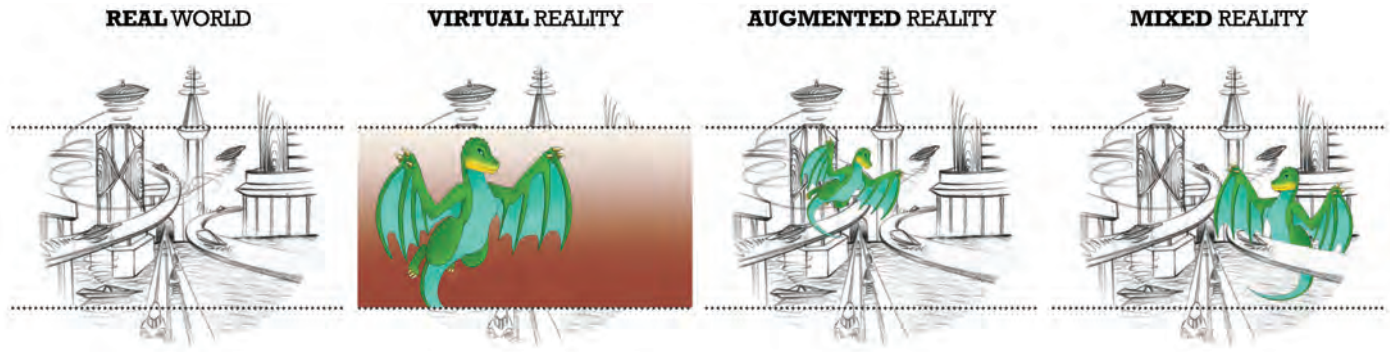

Figure 3. VR, AR, and MR: from a completely modeled world through a physical world overlaid with digital content to an integrated mixed reality environment (Source: Trimble)
图3. 虚拟现实、增强现实、混合现实：从完全模型化的世界到叠加了数字内容的物理世界到集成混合现实环境。（来源：天宝）

Augmented reality, or AR technology, is a predominantly physical environment enriched with digital content. AR keeps the user within the context of the environment around him and overlays the natural world with a layer of digital content. The overlaid data can be as simple as textual notes or as complex as a 3-D model of a building.

Mixed Reality (MR) is the fourth technology in which digital content is brought out of the computer screen and into the physical world, creating an integrated environment where physical and digital objects coexist. A key characteristic of MR is that the digital content and the real-world content are able to react to each other in real time. MR provides the flexibility to move seamlessly along the Virtuality Continuum, from a fully immersive experience to a real-world view; as such, it enables a multi-level exploration of a designed environment and spatial relations between the virtual content and the physical world (Figure 3).

Mixed Reality Taxonomy

Unlike the common saying, seeing is not always believing; mixed reality challenges our perception of what is real and what is virtual. To gain an authentic perceptual experience from this hybrid environment, mixed reality technology should accurately stimulate multiple senses. An array of tuned input and output sensors provide the necessary infrastructure required to deliver a trustful experience. The most common ones are visual and audio sensors, which track light, shape, relative distance, and audio sources on the input side, and generate spatially aligned audiovisual digital content as an output. Haptic feedback is another critical component in the mix, and is essential to fool our brain into believing that virtual objects really exist. "The main benefits of providing haptic information in physically remote or virtual scenes are manifold. Firstly, there is a natural interaction with the environment, similar to real-world experiences; this also allows for a higher degree of immersion and an improved sense of (tele)presence" (Weber & Eichberger, 2015). Our hands can feel, and differentiate various levels of pressure, weight, temperature, and texture. Anatomically, the ten fingers configuration is a natural and effective way to interact with objects around us. It is currently the stone age of haptic technology, but improvements in motion tracking, technologies such as electro-tactile systems, and midair tactile feedback are expected to enrich the immersion experience and present a natural way to interact with 3-D content. Of the five senses, smell and taste-enhanced mixed reality are still in the very early stages of research, but the realization of mixed reality technology that can stimulate all five senses is closer than ever (Figure 4).

对设计环境以及虚拟内容和物理世界之间的空间关系进行多层探索（图3）。

混合现实分类学

与俗语不同的是，眼见并不一定为实。混合现实向我们的真实和虚拟感知发起了挑战。要想在这种混合环境中获得真正的感知体验，混合现实技术就必须对多种感官进行准确模拟。一排调谐输入和输出传感器为提供这种值得信赖的体验提供了所需的基础设施。最常见的就是视觉和音频传感器，在输入端对光照、形状、相对距离以及音频源进行跟踪，然后在输出端生成空间相对的视听数字内容。在这方面，触觉反馈至关重要，能够让我们的大脑误以为虚拟对象真的存在。“通过在物理远程或虚拟情景中提供触觉信息，这能够实现多重好处。首先就是与环境的自然交互，与现实世界体验相似。此外，这还能够实现更高的沉浸度和更好的（远程）存在感”（Weber & Eichberger，2015）。我们的双手能够感知并区分不同的压力、重量、温度以及质感。从解剖学的角度来说，我们双手的十指结构是与周围对象进行交互的自然有效方式。目前的触觉反馈技术尚处于初始阶段，不过动作跟踪方面的改进、电子触觉系统等技术以及空中触觉反馈有望丰富沉浸体验，提供一种自然的3D内容交互方式。在五种感官中，嗅觉和味觉增强型混合现实依旧处于早期研究阶段，但能够模拟五种感官的混合现实技术已经不再遥远（图4）。

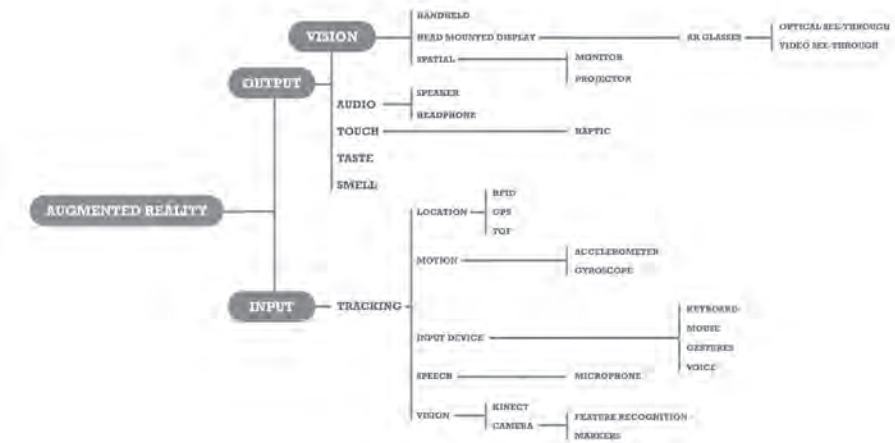

Figure 4. Five senses input and output taxonomy for augmented reality (Source: Bart Gereard)
图4. 增强现实的五种感官输入和输出分类学。（来源：Bart Gereard）

混合现实和建筑、工程、施工与运营（AECO）

在建筑、工程、施工与运营（AECO）行业，混合现实能够在物理和数字环境之间牵线搭桥。它根植于数字和真实内容共存的各个阶段。在这些阶段，建筑设计与现实情形相碰撞，施工团队将数字内容转化为物理对象，设施管理工程师开展日常巡检。本章节对混合现实在建筑生命周期中所提供的机遇进行了探索。

设计阶段

建筑与城市设计是定义上的空间过程。过去几年从2D文件到3D模型的转变是一种

Mixed Reality and AECO

In the context of the AECO industry, mixed reality bridges the gap between physical and digital environments: it is embedded in phases where digital and real content co-exist, where architectural design collides with reality, where construction teams transform digital content into physical objects, and where facility management engineers perform their daily routines. The following section explores the opportunities of mixed reality along the lifecycle of a building.

Design Phase

Architecture and urban design are, by definition, spatial processes. The last few years' transition from 2-D documents to 3-D models was a natural evolution, which improved team communication and coordination. Today, 3-D models are common, but the interaction with volumetric data remains within the constraints of a 2-D screen. The following paragraph covers the potential impact of mixed reality during the design phase.

Given that decisions made during early design stages have a significant impact on later design stages, the building cost, and its lifecycle (Paulson, 1976), it is important to fully understand the implications of such decisions. In his article, "Design for Micro-Utopias: Making the Unthinkable Possible," Wood suggested that designers need to "become the facilitators of flow, rather than the originators of maintainable things such as discrete products or images" (Wood, 2007). Adding mixed reality to the designer toolset as a decision support technology can help with this transition. In this context, the ability to quickly communicate the impact of design changes and seamlessly move along the virtuality continuum are major benefits to any project. On one end of the continuum is a tabletop visualization mode, which provides spatial understanding, context, and urban scale, and on the other end is an immersive mode, with its intimate interaction with the design, allowing for an understanding of the design environment just by being in it (Figures 5 & 6).

Moreover, while the physical world is finite, mixed reality presents an infinite environment. Seamlessly coupling established design analysis and communication tools, such as drawing and physical models, with digital data provides the opportunity to overlay context related info like specs, cost, schedule, design alternatives, environmental impact, and dynamic simulations, on top of the physical model in real-time, creating a hyper-reality environment.

自然演变，改善了团队沟通与协作水平。现如今，3D模型十分常见，但与体积数据的交互依旧受制于2D屏幕。下面一段内容介绍了混合现实在设计阶段所能产生的影响。

考虑到早期设计阶段所做的决定将对后期设计阶段、建筑成本以及建筑生命周期产生重大影响(Paulson，1976)，全面理解这些决定的潜在影响就显得非常重要。在文章“微型乌托邦设计：将不可思议变成可能”中，Wood表示，设计师需要“成为过程的推动者，而不是离散产品或图像等可维持‘事物’的创作者”（Wood，2007）。混合现实这种决策支持技术能够为设计师的这种转变提供帮助。在这种情境下，快速沟通设计变更所带来的影响并在虚拟连续统中无缝移动就成为了一大优势。连续统的一端是一个桌面可视化模式，提供了空间理解、情境和城市规模。连续统的另一端是一个沉浸模式，能够与设计进行亲密交互，通过融入其中来理解设计环境 （图5、6）。

此外，虽然物理世界是有限的，混合现实所呈现的环境却是无限的。通过将绘图和物理模型等现有设计分析和沟通工具与数字数据进行无缝匹配，这就提供了机会，能够将规格、成本、进度、替代设计、环境冲击、动态模拟等情境相关信息实时叠加到物理模型之上，从而打造一个超现实环境。从沟通方面来说，通过释放3D模型，这提供了一种对设计进行体验和理解的自然方式，实现了数据的民主化。虽然多年的教育和实践让建筑师能够以3D方式设想他们的设计，但其他利益相关者将很难对此进行理解。凭借混合现实，现场和非现场的利益相关者将能够以协作的方式分享虚拟空间，实现设计叙事的可视化，以真

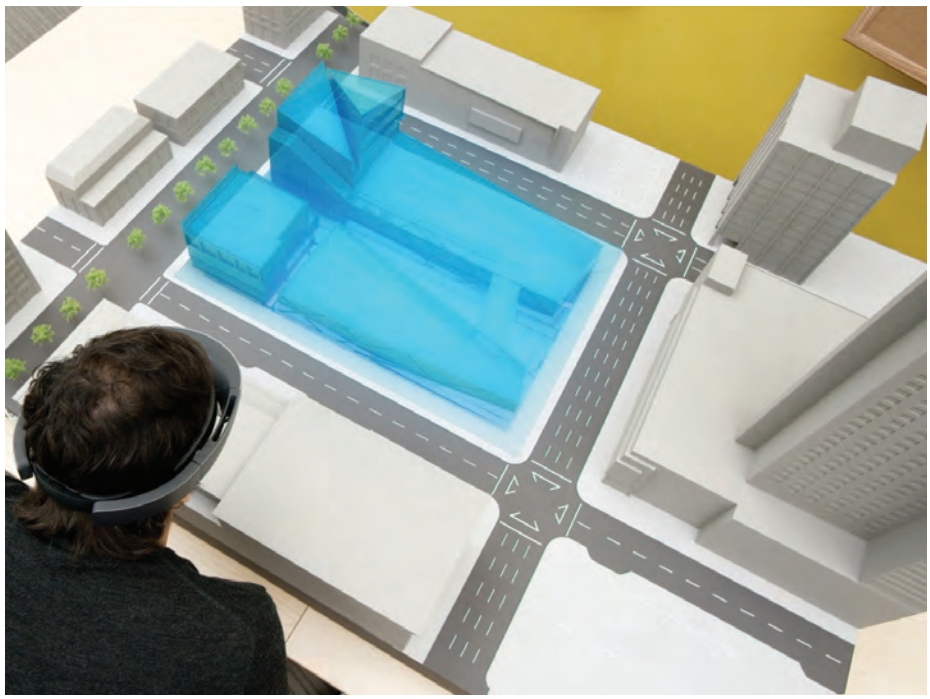

Figure 5. Moving along the Reality-Virtuality Continuum: a table-top view to best experience spatial relations, context, and urban scale (Source: Trimble & Microsoft)
图5. 在现实——虚拟连续统中移动（1）：空间关系、情境和城市规模的桌面视图。（来源：天宝和微软）

Figure 6. Moving along the Reality-Virtuality Continuum: immersive mode is the understanding of the design environment just by being in it (Source: Trimble & Microsoft)
图6. 在现实——虚拟连续统中移动（2）：沉浸模式——通过融入其中来理解设计环境。（来源：天宝和微软）

From a communication aspect, unleashing a 3-D model democratizes the data by offering a natural way to experience and understand the design. While years of education and practice might train architects to visualize their designs in 3-D, other stakeholders have a hard time deciphering them. Using mixed reality, stakeholders – both co-located and remotely located – can share the virtual space collaboratively, visualize the design narrative, and explore the design in real 3-D without the need for an expert to guide them and dictate their point of view (Figure 7).

The impact of mixed reality is expected to go beyond consumption of data and to influence the core design process as well. Technologies such as gesture recognition, highly accurate real-time motion tracking, and haptic input will enable designers to model and formalize their ideas by sculpturing in 3-D space. Basic AR modeling toolkits are already available and mixed reality-based CAD systems are in development. The ability to design in context of the target space can potentially support design decisions, improve communication, and accelerate the design process.

Finally, the author expects that mixed reality will also impact the way buildings and urban spaces will be designed and used. With mass adoption, miniaturization of the technology, and growing virtual social environments, mixed reality will become an integral part of our life. The line between virtuality and reality will be blurred, and the world around us will become a mix of physical and virtual artifacts. This new environment invites new design paradigms and methodologies. Physicality might be limited to necessities such as a structural frame wrapped with dynamic, customizable virtual environment. What is the meaning of a space, a partition, a corner room, or a view to the ocean in this new environment? What form will the future urban space take, and what will be the balance between virtual and real in this environment? The road ahead is long and there are technological and social challenges to be solved, but the foundations of this new environment have already been laid.

Construction Phase

In every construction project there is a decisive process in which design transforms into reality, and abstract ideas translate into physical objects. As almost every project is unique, site-specific, and labor-based, an intensive and accurate "translation" of the design information is required. The current translation process of turning design documents into reality is a constant struggle; it is a complex cognitive process in which wrong interpretations of data often lead to costly errors, quality issues, and/or rework. Digital 3-D models can reduce the level of abstraction and help clarify the design intent, but still, at the execution stage, there is a clear boundary between documentation and the real world (Almagor, 2015).

Converging geospatial, BIM, and mixed reality technology is a disruptive change for the construction industry. The potential ability to project a geo-referenced 3-D BIM model on site with sub centimeter alignment between real and virtual will eventually transform the error prone workflow of "interpret-measure-mark–build" into a more reliable WYSIWYG-like workflow. With this approach, information is superimposed on the physical environment; this minimizes the need for translation and reduces subjective interpretation. The user visualizes the design in context, and can better understand, interact, and execute the required actions in real time. The immediate visual feedback also supports a more effective QA and production control process. Overlaying design on as-build structures reveals any deviation and provides immediate feedback.

Construction trade training and safety are two additional and critical aspects in which mixed reality can play a significant role.

Figure 7. Remote Collaboration: Remote team members experience the "spatial presence" of the design model, sharing views, positions, and gaze (Source: Trimble & Microsoft)
图7. 远程协作：远程团队成员体验设计模型的"空间存在"，分享观点、立场和关注重点。（来源：天宝和微软）

正的3D方式对设计进行探索，并且不需要专家对他们进行指导和讲解（图7）。

混合现实不仅能够影响数据消费，还能够影响核心设计过程。手势识别、高精度实时运动跟踪、触觉输入等技术让设计师能够在3D空间建模，从而呈现出他们的理念。市面上已经推出了基础的混合现实建模工具，基于混合现实的CAD系统也正在开发之中。通过在考虑目标空间的情况下进行设计，这有望为设计决策提供支持，改善沟通水平，加速设计过程。

最后，本文作者预计，混合现实将影响建筑与城市空间的设计和使用方式。随着这项技术的大规模采用和小型化，随着虚拟社交环境的不断增多，混合现实将成为我们生活中不可或缺的一部分。虚拟和真实之间的界限将变得模糊，我们周围的世界将成为由物理和虚拟物体组成的混合体。这种新环境势必催生新的设计范式和方法。物理可能仅限于结构框架等必需品，周围则是动态定制化的虚拟环境。在这种新环境中，空间、分区、拐角客房、海景又意味着什么呢？未来的城市空间将以何种形式存在？这种环境中虚拟和真实将是怎样的一种平衡？前路漫漫，相关技术和社会挑战有待解决，但这种新环境的基础已经奠定了。

施工阶段

每个施工项目都要经历一个决定性过程，将设计变成现实，将抽象概念变成物理对象。由于几乎每个项目都是独特的，地点不同，施工人员各异，这就需要对设计信息进行密集且准确的"转译"。当前将设计文件变成现实的转译过程充满了挑战。这是一个复杂的认知过程，对数据的错误解释往往会导致成本高昂的误差、质量问题以及返工。数字3D模型降低了抽象化水平，有助于阐明设计意图。尽管如此，在执行阶段，文件记录和现实世界之间还是存在着清晰的边界(Almagor，2015)。通过将地理空间、建筑信息模型（BIM）以及混合现实技术融合在一起，这将为施工行业带来颠覆性变革。未来，我们或许能够以真实和虚拟之间亚厘米级的误差实现地理参考3D BIM模型的现场投影，最终改变容易出错的"解释–测量–标记–建造"工作流，打造类似WYSIWYG的更加可靠工作流。这种方法能够将信息叠加到物理环境之上，将转译的需求降到最低，减少主观解释。用户可以在情境中对设计进行可视化查看，对所需采取的行动进行更好的实时理解、交互以及执行。此外，这种即时的视觉反馈还能够实现更加高效的质量保证和生产控制过程。通过将设计叠加到竣工结构之上，这能够突显偏差，提供即时反馈。在施工行业培训和施工行业安全这两个关键方面，混合现实同样可以发挥重要作用。混合现实技术有助于增强培训体验，改进培训标准，消除或降低健康安全风险，从而提升施工项目的绩效表现(Bosche，Abdel – Wahab，& Carozza,

Figure 8. Visualizing location-based and asset-based data in context (Source: Trimble)
图8. 在情境中可视化查看基于位置和基于资产的数据。（来源：天宝）

Mixed reality technology can help enhance the training experience, improve training standards, eliminate or reduce health and safety risks and, in turn, induce performance improvements on construction projects (Bosche, Abdel - Wahab, & Carozza, 2016). In 2014, falls accounted for more than one-third (39.9 percent) of fatal injuries in construction (OSHA, 2014). In a recent experiment by Bosche, Abdel-Wahab, & Carozza (2016), researchers used VR technology to enable construction trainees to experience work-at-height situations: standing and moving on a scaffold at 10 meters in height and sitting on a structural steel beam at 100 meters in height. Researchers concluded that this exposure enables trainees to experience such heights and assess their comfort in standing, and eventually working, in such conditions. Ultimately, it will enable them to accustom themselves to such conditions.

Facility Management Phase

The 2006 study, "Re-examining the Costs and Value Ratios of Owning and Occupying Buildings" (Ive, 2006), found the cost of operation and maintenance of office buildings to be about one and a half times the cost of the initial construction. Other estimates put the cost of operation and maintenance even higher. Potential saving is the primary motivation for the adoption of disruptive technologies in facility management.

Organizations with large asset portfolios struggle to make the connection between these real-world elements and the data sources used to manage them. While management teams in these organizations constantly find themselves wrestling with the task of integrating disparate data sources, it is the workforce in the field, charged with the tasks of managing and maintaining the built environment, that suffer from insufficient access to the information they need. The availability of comprehensive inventories and quantitative data provide organizations with opportunities to more effectively manage their facilities and optimize the tasks needed to maintain them. Making this data readily accessible to those in the field tasked with maintaining assets reduces the time and effort required to perform the work and increases reliability. A key aspect of this solution is the ability to present context-related information. Using mixed reality technology, location- and asset-based data can be visualized by on-site engineers while performing their tasks in a more responsive, digitally manipulated, and interactive environment (Figure 8).

Maintaining a digital twin – an identical and comprehensive 3-D BIM model of the facility – that embeds the required information of all assets, including their geometry, adds an additional value to the solution. The digital twin will enable a mixed reality-based training of maintenance tasks – a critical capability, especially with remote or mission critical assets. When used within the context of its physical twin, the digital version can be utilized to visualize hidden components, structural deformations, and proposed changes, improving operation efficiency and saving critical maintenance time.

Summary and Outlook

Mixed reality will have a significant impact on the AECO industry over the next few years. The technology addresses some of the industry's major inefficiencies during the design, construction, and operation stages of a project. The sense of presence and the integration of digital and physical content provide a higher quality experience when

2016)。2014年，跌落占到了施工过程中致命伤亡事故的三分之一以上（39.9%）（OSHA，2014）。在Bosche，Abdel - Wahab，& Carozza（2016)近期开展的一项实验中，研究人员利用虚拟现实技术让施工受训人员体验高处作业情形：站在离地10米高的脚手架上来回移动，坐在离地100米高的结构钢梁上。研究人员发现，这能够让受训人员体验在高处作业的情形并评估他们能否在这种情形下站立并作业。最终，这将帮助他们适应这种作业情形。

设施管理阶段

2006年开展的一项名为“重新审视拥有和占用建筑的成本和价值比”的研究(Ive，2006)发现，写字楼的运营和维护成本是最初建造成本的1.5倍左右。其他的一些估计认为运营和维护的成本更高。为了实现成本节约，设施管理方面开始采用颠覆性技术。

持有大规模资产组合的组织机构很难将这些现实世界元素与用来对其进行管理的数据源联系起来。尽管这些组织机构的管理团队一直都在努力整合这些各不相同的数据源，真正遭殃的却是负责对建成环境进行管理维护的一线员工，因为他们无法获取所需的足够信息。综合库存和定量数据让组织机构有机会对他们的设施进行更加高效的管理，对设施维护所需的工作进行优化。通过让负责资产维护的一线员工能够随时获取这些数据，这能够减少所需的工作时间和强度并增加可靠性。这种解决方案的一个关键方面就是提供与情境相关的信息。凭借混合现实技术，现场工程师在更具响应性、数字操纵性的交互环境中执行任务时将能够可视化查看基于位置和基于资产的数据（图8）。

通过维持一个包括几何形状等所需资产信息的数字孪生模型（一个完全相同的综合设施3D BIM模型），这能够为解决方案增添更多价值。这种数字孪生模型有助于对维护任务进行基于混合现实的培训，这对于远程或任务关键资产来说尤为重要。通过与物理孪生模型结合使用，数字模型可以用来查看隐藏的组件、结构变形以及所提议的变更，从而提升运营效率，节省重要的维护时间。

总结与展望

未来几年，混合现实将对建筑、工程与施工（AEC）行业产生重大影响。这项技术解决了建筑、工程与施工（AEC）行业在设计、施工以及运营阶段主要面临的一些效率低下问题。与2D屏幕相比，存在感以及数字和物理内容的集成能够提供更高质量的体验，推动三大轴线方面从信息沟通到体验沟通的转变：

compared to a 2-D screen, and shift from information communication to experience communication in three main axes:

The Project Stage Axis (Design to Build / and Operate): Moving along this axis, MR brings 3-D data to life and puts information in the user's hands without the need to change or adjust the data format. A sign-off BIM model can be projected in context to guide construction teams on-site, and later by facility management teams while evaluating required changes or maintenance work.

The Digital to Physical Axis: Holographic display is not limited to 3-D models; in fact, with mixed reality, multi-layered datasets can be overlaid with the real world. A partial list includes 2-D documents, energy analysis, light simulation, acoustics, layout data, and equipment metadata. The abilities to integrate digital and physical content and present data in context can improve communication and leverage confidence in decision-making.

Office to Field Axis (Build to Design—Design to Build; and Sharing Design Data): Using mixed reality technology, construction teams benefit from access to geo-located, context-based data, which can be projected and anchored to the physical environment around them. The ability to map the as-built physical environment supports communication from the field to the office and completes the "Build to Design—Design to Build" loop.

While it is possible to describe the benefits of mixed reality in words, one must experience it first hand in order to really appreciate its power and realize how it can transform the AECO industry.

项目阶段轴线：设计到建造（及运营）：在这一轴线上，混合现实能够对3D数据进行鲜活展现，无需改变或调整数据格式便可以将信息交到用户手中。一个签核的BIM模型可以在情境中投影，为现场施工团队提供指导，并在后期评估需做出变更或进行维护工作时为设施管理团队所用。

数字到物理轴线：全息显示并不仅限于3D模型。事实上，凭借混合现实，多层数据集都可以叠加到现实世界之上，其中包括2D文件、能源分析、照明模拟、声学、布局数据、设备元数据等等。通过将数字和物理内容进行集成并在情境中对数据进行呈现，这能够改善沟通水平，增加决策信心。

办公室到现场轴线：在设计到建造、建造到设计阶段与现场团队分享最新的设计数据，这对于动态施工环境来说至关重要。凭借混合现实技术，施工团队将能够获取基于地理位置和情境的数据，锁定并投射到周围物理环境中。通过绘制竣工物理环境，这能够推动现场到办公室的良好沟通，完成整个建造到设计——设计到建造环路。

虽然我们可以描述出混合现实所能带来的好处，但要想真正领略其实力，真正体会这将如何改变建筑、工程与施工（AEC）行业，就需要对其进行亲身的体验。

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