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Microsoft HoloLens: A Review of Architecture, Applications and Challenges in Untethered Mixed Reality

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Abstract — Microsoft HoloLens is one of the first commercially available, fully untethered optical see-through head-mounted displays (HMDs) for mixed reality (MR). Since the release of the first generation in 2016 and HoloLens 2 in 2019, the device has been adopted in healthcare, manufacturing, education, defense and remote collaboration. This paper reviews the hardware and software architecture of both generations, including the waveguide display, depth sensing, spatial mapping, the Holographic Processing Unit and the interaction model. It then surveys the main application domains and summarizes reported strengths and limitations, such as field of view, tracking accuracy, ergonomics, battery life and cost. Finally, it discusses open research problems and the future of head-worn MR following the discontinuation of HoloLens 2 hardware production. The review aims to help researchers and practitioners choose, evaluate and design MR systems for real-world use.

Keywords— HoloLens, mixed reality, augmented reality, head-mounted display, spatial computing, human-computer interaction

I. INTRODUCTION

Mixed reality (MR) merges real and virtual worlds so that physical and digital objects coexist and interact in real time. Milgram and Kishino described this as a continuum between the purely real and the purely virtual environment. Augmented reality (AR), a closely related concept, was characterized by Azuma as a system that combines real and virtual content, is interactive in real time, and registers virtual objects in three dimensions.

For many years, AR/MR research relied on tethered prototypes or handheld devices such as smartphones. Microsoft HoloLens, announced in 2015 and shipped in 2016, changed this by offering a self-contained computer, sensors and transparent display in a single headset. HoloLens 2, released in late 2019, improved the field of view, comfort and interaction, and became a common research platform in computer vision and human-computer interaction.

This paper makes three contributions: (i) it summarizes the architecture of HoloLens 1 and 2; (ii) it reviews application areas and the evidence for their benefits; and (iii) it identifies technical and human-factors limitations and future directions.

1. Motivation

Head-worn displays have long promised hands-free access to digital information anchored in the physical world. Early systems were expensive, bulky and confined to laboratories. HoloLens was among the first devices to package inside-out tracking, a depth sensor, a transparent display and an onboard computer in a single wearable unit, so that a researcher or a frontline worker could use mixed reality without cables, base stations or markers placed in the room. Because of this, it quickly became a reference platform: a large share of published MR studies in medicine, engineering and education report results obtained on HoloLens hardware.

The growing body of work makes it difficult for newcomers to see what the device can and cannot do. Reports come from different disciplines, use different measures and sometimes draw opposite conclusions about the same capability, for example hologram accuracy or user comfort. A structured synthesis is therefore useful for three audiences: researchers who must decide whether HoloLens suits an experiment, developers who must design for its constraints, and organizations that must judge whether the technology is mature enough for deployment.

2. Research Questions

This review is organized around four questions:

- RQ1: What hardware and software components make up HoloLens 1 and HoloLens 2, and how do they differ?
- RQ2: In which application domains has HoloLens been used, and what benefits have been reported?
- RQ3: What technical and human-factors limitations recur in the literature, and how are they measured?
- RQ4: What are the open research problems and the likely path forward after the end of HoloLens 2 hardware production?

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3. Scope and Review Method

This is a narrative review. Technical descriptions are drawn from manufacturer documentation and from peer-reviewed work on the display, sensing and research capabilities of the device. Application evidence is drawn from published studies and systematic reviews in healthcare, industrial maintenance and education. Studies were considered relevant if they used a HoloLens device as a primary platform, reported a technical measurement or a user-based evaluation, and were published in English. Purely conceptual proposals without implementation were treated as context only. [Author to insert: databases searched, search strings, date range and number of records screened

4. Organization of the Paper

Section 2 gives the conceptual and technical background. Section 3 describes the hardware of both generations. Section 4 covers the software platform and interaction model. Section 5 surveys application domains. Section 6 discusses how HoloLens has been evaluated and what limitations were found. Section 7 compares HoloLens with other platforms, raises ethical issues and proposes directions for future work, and Section 8 concludes.

II. BACKGROUND: MIXED REALITY AND HEAD-MOUNTED DISPLAYS

HMDs for AR/MR are generally divided into two groups. Video see-through devices capture the environment with cameras and show it on opaque displays together with virtual content. Optical see-through devices, such as HoloLens, let the user see the real world directly through transparent
optics onto which virtual imagery is projected. Optical see-through designs preserve natural vision and

have low latency for the real world, but they struggle with bright environments, occlusion of real objects by virtual ones, and limited field of view.

The key technologies in an MR headset are a display and optics that combine light from the world and from a projector tracking of the head and, ideally, hands and eyes; a spatial understanding of the environment; and a natural interaction model. The following sections describe how HoloLens addresses each.

1. A Short History of Head-Worn Displays

The first head-mounted three-dimensional display was demonstrated by Ivan Sutherland in 1968. It was so heavy that it hung from a ceiling mount, which earned it the nickname "Sword of Damocles" For the following decades, AR research advanced through military, aviation and laboratory systems, and by the late 1990s the field had matured enough for Azuma to survey its definitions, applications and open problems. A later survey by Azuma and colleagues documented advances in tracking, display and interaction, and Billinghurst and colleagues reviewed the rapid growth of AR from the 1960s to the 2010s, including handheld and wearable approaches [7]. Kress and Starner reviewed head-mounted display technologies for consumer electronics and highlighted the optical and ergonomic barriers to mass adoption.

Against this background, HoloLens represents a shift from research prototypes to a commercially supported product with a development ecosystem, enterprise management tools and a global user base.

2. Optical See-Through Principles

An optical see-through HMD must solve several problems at once. It needs a combiner, an optical element that lets light from the real scene reach the eye while also directing light from a micro-display toward the same eye. It must produce an image that appears at a comfortable focal distance, provide an eyebox large enough to tolerate different head shapes and small headset movements, and do so with low weight and good power efficiency. Waveguide combiners, which guide light inside a thin transparent plate and couple it out toward the eye through diffractive or reflective structures, allow a slim form factor but impose limits on field of view, color uniformity and efficiency Because the display adds light to the real scene rather than replacing it, virtual content cannot be darker than the background, and bright surroundings reduce contrast. These physical properties explain many of the user experience issues discussed in Section 6.

3. Spatial Computing Concepts

Several concepts recur throughout HoloLens documentation and literature:

- Six degrees of freedom (6DoF) tracking: estimation of the headset's position and orientation as the user moves.
- Simultaneous localization and mapping (SLAM): building a map of the unknown environment while tracking the device within it.
- Registration: the alignment of a virtual object with its intended real-world counterpart; errors in registration are visible as misplaced or drifting holograms.
- Occlusion: correct hiding of virtual content behind real objects, which depends on a reasonably accurate depth model.

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- Hologram stability: the perception that a virtual object stays fixed in space as the user moves, which depends on tracking accuracy and low rendering latency.

In Microsoft's terminology, a hologram is any virtual object rendered in the user's environment. It is an image on a stereoscopic display and should not be confused with an optical hologram recorded on film.

III. HOLOLENS HARDWARE AND SYSTEM ARCHITECTURE

1. HoloLens (1st generation)

The first HoloLens was announced in January 2015 and shipped as a Development Edition in March 2016. It ran Windows 10 on an Intel 32-bit architecture system-on-chip and included a custom Holographic Processing Unit (HPU) that processes data from the sensors, including head tracking, spatial mapping and gesture recognition. Its display used see-through waveguide optics with a relatively narrow field of view of roughly 30° by 17.5°, which is the most frequently cited limitation of the device [3, 5].

2. HoloLens 2

HoloLens 2 was announced in 2019 and began shipping in late 2019. It is built on a Qualcomm Snapdragon 850 platform with an updated HPU. Its display uses MEMS laser scanning with waveguides and offers a field of view of about 52° diagonal at a 3:2 aspect ratio, about twice the area of its predecessor. Key additions include articulated hand tracking, eye tracking (used for iris-based sign-in and gaze interaction), a time-of-flight depth sensor, an inertial measurement unit, and improved weight distribution for comfort.

3. Sensing and Research Mode

HoloLens contains several visible-light tracking cameras for head tracking, a depth camera and an RGB camera for photo/video capture. Ungureanu et al. describe the Research Mode of HoloLens 2, which gives researchers access to raw sensor streams, such as depth, infrared reflectivity, grayscale cameras and IMU data, enabling use as a platform for computer vision and robotics research. This capability is a major reason for the device's popularity in academic work.

4. Display Optics

Kress and Cummings discuss the optical design choices behind the HoloLens display architecture, including the trade-offs among field of view, eyebox, resolution and efficiency of waveguide combiners These trade-offs explain why a wider field of view, higher brightness and lighter weight are difficult to achieve simultaneously in an optical see-through HMD.

5. Side-by-Side Comparison of the Two Generations

Table 1 summarizes the main differences. Values are approximate and are taken from manufacturer documentation and the literature; authors should confirm them against the sources before submission.

Table 1. Comparison of HoloLens 1 and HoloLens 2 (approximate values)

Feature	HoloLens (1st gen)	HoloLens 2
Announced / shipped	Jan 2015 / Mar 2016	Feb 2019 / Nov 2019
Processor	Intel Atom (Cherry Trail) + HPU 1.0	Qualcomm Snapdragon 850 + HPU 2.0
Memory / storage	2 GB RAM, 64 GB	4 GB RAM, 64 GB
Display technology	Waveguide, projector-based light engine	Waveguide, MEMS laser scanning
Field of view	about 30° × 17.5° (about 35° diagonal)	about 52° diagonal, 3:2
Weight	about 580 g	about 566 g, balanced rear
Hand input	Gaze, air-tap, bloom	Articulated hand tracking, direct touch and grab
Eye tracking	No	Yes (gaze, iris sign-in)
Depth sensing	Time-of-flight depth camera	Improved time-of-flight depth sensor
Typical active use	about 2-3 hours	about 2-3 hours
Operating system	Windows 10 (Windows Holographic)	Windows Holographic (Windows 10-based)

The most important change for users is the larger field of view combined with direct hand interaction, which removed the need for the "air-tap" gesture that many first-generation users found unnatural.

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6. Head Tracking, Spatial Mapping and Scene Understanding

HoloLens estimates its pose using visible-light tracking cameras and an inertial measurement unit, a technique known as inside-out tracking. Camera images and inertial data are fused to give a pose estimate at high frequency, while the depth sensor supports the reconstruction of surface meshes of the surrounding environment. This spatial mapping mesh can be used for collision, occlusion and hologram placement. Higher-level scene understanding functions classify surfaces such as floors, walls, ceilings and tables so that applications can place content sensibly.

Tracking quality depends on the environment. Feature-rich, well-lit indoor spaces work best; large featureless rooms, strongly reflective or moving surfaces and very dark or very bright conditions can degrade tracking. Researchers who need high-fidelity data, for example for reconstruction or localization experiments, use Research Mode to obtain raw sensor streams and run their own algorithms.

7. Hand and Eye Tracking

HoloLens 2 tracks the articulated pose of both hands, giving the application the position and orientation of the joints of each hand, which enables grasping, pinching, pushing and two-handed manipulation of holograms. Eye-tracking cameras estimate where the user is looking. Gaze can be used as a pointer, to adapt interfaces, to measure attention in user studies and, in combination with iris recognition, for sign-in. For researchers, built-in gaze and hand data reduce the need for external motion-capture or eye-tracking equipment, although the accuracy of these streams should be validated before they are used as measurement instruments.

8. Compute, Power, Thermal and Ergonomic Design

To be untethered, HoloLens has to fit its compute, sensors, optics and battery into a package worn on the head. This imposes a strict power and thermal budget. Complex scenes, intensive computer vision and continuous Wi-Fi streaming can shorten battery life and cause the device to throttle. HoloLens 2 moved the battery and main compute to the rear of the headband so that the center of mass sits closer to the head, and added a flip-up visor and adjustable fit to improve comfort over longer sessions. Even so, weight and heat remain frequent complaints in field studies, especially in surgical and industrial use.

9. Hologram Stability and Registration Accuracy

Measured hologram stability is central to professional use. Vassallo and colleagues evaluated the stability of holograms on the first-generation HoloLens and reported that they can drift or jitter depending on conditions such as the motion of the user and the lighting of the environment. In a surgical context, Qian and colleagues compared optical see-through HMDs for interventions and highlighted issues of calibration and alignment that affect perceived and actual accuracy. In practice, the achievable accuracy depends on how the hologram is aligned with the physical target. Manual alignment, marker-based tracking and external tracking systems give different results, and tasks that need sub-millimetre accuracy normally require an additional tracking system or specialized calibration.

IV. SOFTWARE ECOSYSTEM AND INTERACTION MODEL

Applications for HoloLens are typically developed with Unity or Unreal Engine and the Mixed Reality Toolkit (MRTK), and increasingly through the open OpenXR standard. Core platform services include:

- Spatial mapping and scene understanding: a triangle-mesh representation of the surroundings used for occlusion, physics and placement of holograms.
- Spatial anchors: persistent anchors that keep holograms fixed to physical locations across sessions; cloud-based anchors enable shared experiences between multiple devices.
- Input modalities: gaze, air-tap and hand gestures on HoloLens 1; direct hand manipulation, hand rays, eye gaze and voice commands on HoloLens 2.
- Enterprise tools: remote assistance and guided-work applications that overlay instructions on real equipment.
- This design supports an interaction model in which users can touch, grab and move holograms directly, which lowers the learning curve compared with abstract input devices.

1. Development Workflow

A typical HoloLens project is built in Unity or Unreal Engine, uses MRTK for interface components and input handling, and targets OpenXR so that the application logic is less tied to one vendor. The developer can test in an editor-based simulator, deploy over USB or Wi-Fi, and use the device portal to inspect performance and logs. Native C++ development with DirectX and the Windows Mixed Reality APIs is also possible for applications that need maximum control over rendering.

Because the device is an ARM-based or low-power platform, developers must deploy appropriate builds, and many desktop libraries are not available. A common pattern in research is

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therefore split rendering or remote processing: heavy computation such as deep-learning inference or high-resolution rendering runs on a PC or a cloud server, while the headset streams sensor data and displays the result.

2. Rendering Performance and Design Guidelines

Performance is critical in MR. Low frame rates or inconsistent frame times make holograms appear to swim and can cause discomfort. Platform guidance recommends keeping a steady target frame rate and limiting scene complexity, polygon counts and expensive shader effects. The system applies reprojection to the final image using the latest head pose to reduce the perceived latency of holograms. Design guidelines also recommend placing content at a comfortable viewing distance (roughly 1-5 m for most interfaces), avoiding rapid camera-like motion of content, using large, high-contrast text and keeping the user's central field of view free for the real task.

3. Persistent and Shared Experiences

Persistent spatial anchors let an application save the position of a hologram relative to the physical world and restore it in a later session. Cloud-based anchor services allowed several users, possibly with different device types, to see content in the same physical place. Microsoft has announced the retirement of its Azure Spatial Anchors service, so authors of long-running projects should check the current status of the service and consider alternative anchoring strategies, such as marker-based alignment or vendor-neutral approaches.

4. Security, Privacy and Enterprise Management

HoloLens 2 supports iris-based sign-in, device encryption and enterprise management through mobile device management systems, which are important for use in hospitals, factories and public-sector settings. At the same time, a device with continuously operating cameras and eye tracking raises privacy concerns for bystanders and for the wearer; these are discussed in Section 7. Applications that capture video or spatial maps of private spaces should obtain informed consent, store data securely and keep only what is needed.

5. Interaction Design Considerations

The interaction model of HoloLens 2 favors direct manipulation when the object is within arm's reach and far interaction using a ray cast from the hand when the object is distant. Gaze and voice can be combined with gestures, which makes multimodal input possible. Designers need to consider arm fatigue during long sessions (sometimes called "gorilla arm"), the lack of haptic feedback when touching a hologram, and the need for clear visual and audio cues such as highlights, hover states and sound effects that confirm that an interaction has registered.

Application Domains

Healthcare and Surgery

Healthcare is among the most studied areas. Reported uses include visualizing patient-specific 3D anatomy from CT/MRI data during surgical planning, intra-operative navigation overlays, medical education with 3D anatomical models, and tele-mentoring where a remote expert sees the wearer's view and annotates it. Benefits cited include improved spatial understanding and hands-free access to information. Challenges include registration accuracy between holograms and patient anatomy, sterility and regulatory approval.

Early clinical papers presented HoloLens as a way to bring three-dimensional patient data into the operating room. Tepper and colleagues described a plastic-surgery workflow in which CT-derived 3D reconstructions were viewed as holograms to help plan and perform surgery. Comparison studies of optical see-through HMDs for interventions suggest that while holographic guidance can improve spatial understanding, accuracy depends on calibration and on how the hologram is registered to the patient. Typical workflow steps in the surgical literature are: segmentation of medical images into 3D models; export to a format usable by the headset; registration of the model to the patient or phantom, using fiducial markers, surface matching or manual alignment; and display of the model in the surgeon's view during planning or the procedure.

Beyond surgery, HoloLens has been explored in radiology review, ultrasound and catheter guidance, dental and orthopaedic planning, anatomy teaching, rehabilitation and patient education. The common selling points are improved visualization, reduced need to look away to a monitor and the possibility of remote consultation. Common concerns include the narrow field of view, the need for sterile handling of the device, regulatory clearance of software as a medical device, and the lack of large randomized trials showing improvements in patient outcomes.

Industry and Manufacturing

In industrial settings, HoloLens is used for assembly guidance, maintenance and inspection, design review of 3D models at full scale, and training. Overlaying step-by-step instructions on real machinery can reduce errors and training time. Remote assistance allows a specialist to guide a field technician without travel.

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Palmarini and colleagues reviewed augmented reality in maintenance and found that most applications target assembly and inspection, that tracking in industrial environments remains a technical challenge and that many studies are laboratory-based, with few long-term field deployments [12]. For HoloLens in particular, enterprise use is supported by purpose-built tools for guided procedures and remote assistance, in which instructions, arrows and annotations are anchored on the machine while a remote expert sees the technician's view.

Typical benefits claimed in this literature include shorter task completion time, fewer errors, faster onboarding of new staff, reduced travel and better documentation of work. Typical obstacles include creating and maintaining the 3D content, aligning holograms with machines to the accuracy needed, poor Wi-Fi coverage on factory floors, safety rules about wearing devices in hazardous areas and the need to integrate with existing enterprise systems.

Education and Training

Educational use includes interactive 3D models for science, engineering and anatomy, and simulation-based vocational training. MR can make abstract or hazardous content tangible and enables collaborative learning in a shared physical space. Evidence of learning gains exists but is often from small, short-term studies.

Akçayır and Akçayır reviewed advantages and challenges of AR in education and reported benefits such as increased motivation, improved learning achievement and better spatial understanding, alongside challenges such as technical difficulties, usability problems and increased cognitive load.

These themes also apply to HoloLens-based teaching. The device's strengths in this domain are the ability to walk around a 3D model, to share it with a group of students in the same room and to combine it with real objects such as a skeleton, an engine or a lab bench. Limitations include the cost of one headset per student, the time needed to set up and calibrate devices in a classroom, and the lack of standard curricula built around MR content.

Good practice for educational studies includes comparing MR to a strong non-MR control (for example a 3D model on a screen or a physical model), measuring learning with validated tests before and after the intervention, including delayed retention tests and reporting usability and workload alongside learning outcomes.

Defense and Public Safety

A modified HoloLens-based system was selected under the U.S. Army's Integrated Visual Augmentation System (IVAS) program, intended to provide soldiers with navigation, situational awareness and training capabilities. The program has been subject to technical and organizational changes since its announcement, illustrating the difficulty of adapting consumer-grade optical MR to harsh operational conditions.

The IVAS case is useful in a review because it shows how consumer or enterprise MR meets extreme requirements: ruggedness, low-light and night operation, thermal management, weight on the head over many hours, and tolerance of motion. Reports on the program have noted user-feedback and technical issues, and responsibility for the program has since moved. For researchers, this illustrates that a headset that works well in a hospital or a classroom is not automatically suitable for field conditions, and that requirements engineering should precede technology selection.

Public-safety applications such as firefighting and emergency response have been proposed, using overlays for navigation and hazard information, but few have been validated in realistic conditions.

Architecture, Design and Collaboration

Architects, engineers and designers use MR to review building models in situ and collaborate around a shared hologram. Multi-user sessions with shared spatial anchors allow distributed teams to discuss the same virtual object in different locations.

Remote Collaboration and Telepresence

Remote collaboration is one of the most mature uses of HoloLens. In a typical scenario, a local user shares a first-person video stream while a remote expert draws annotations or places arrows that appear anchored in the local user's space. More advanced systems share a 3D scan of the environment so that the remote participant can navigate it independently, or show a volumetric avatar of the remote partner (holoportation-style telepresence). Studies in this area compare MR with phone calls, video calls and screen-based sharing, and commonly measure task time, error rate, mutual understanding and social presence. Bandwidth, latency and the quality of the shared spatial map are the main technical limiting factors.

Robotics, Computer Vision and HCI Research

Because Research Mode exposes raw sensor streams, HoloLens has been used as a mobile sensor platform for computer vision, simultaneous localization and mapping, activity recognition and egocentric perception research. In robotics, researchers use the headset to visualize a robot's plan,

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sensor data or workspace limits in the operator's view, to teleoperate robots with hand and gaze input, and to teach robots by demonstration. In human-computer interaction research, the device is used to study gesture design, text entry in the air, menu layouts in 3D, gaze-based interaction and the effects of virtual content on attention.

Accessibility, Rehabilitation and Well-Being

Some work explores HoloLens for people with disabilities and for therapeutic purposes, including navigation aids for people with low vision, motor rehabilitation games in which patients follow holographic targets, and exposure or relaxation exercises in mental-health research. Evidence is preliminary: studies often have small samples and short follow-ups, and comfort, weight and cost limit routine use. The same properties that make MR attractive, such as the overlay on a real environment and the ability to manipulate real objects while seeing virtual guidance, may be particularly valuable in rehabilitation, where transfer to real-world tasks is the goal.

Summary of Application Domains

Table 2. Summary of application domains and the main findings reported for them.

Domain	Typical use	Reported benefits	Main barriers
Healthcare	Surgical planning, 3D anatomy, tele-mentoring	Better spatial understanding, hands-free information	Registration accuracy, sterility, regulation, little outcome evidence
Industry	Assembly, maintenance, inspection, remote assistance	Fewer errors, faster training, less travel	Content creation, tracking in harsh environments, network coverage
Education	3D models, shared lessons, simulation	Motivation, spatial understanding	Cost per student, set-up time, cognitive load
Defense / public safety	Navigation, situational awareness, training	Hands-free overlays	Ruggedness, weight, low-light operation
Design / architecture	On-site model review, shared design sessions	Scale-accurate visualization, collaboration	Model preparation, field of view
Domain	Typical use	Reported benefits	Main barriers
Research	Sensor streams, HCI and robotics experiments	Mobile, calibrated multi-sensor platform	Validation of sensor accuracy, vendor dependence

Evaluation, Strengths and Limitations

Technical evaluations of HoloLens examine tracking stability, spatial-mapping quality, hologram registration and latency. Liu et al. offer an early technical evaluation of the first-generation device for multimedia applications. Across the literature, several recurring themes appear.

Strengths

- Untethered, self-contained operation with no external tracking infrastructure.
- Robust inside-out tracking and environment mapping.
- Natural interaction through hands, gaze and voice (HoloLens 2).
- Open access to sensor data via Research Mode for research use.

Limitations

- Field of view: still narrow compared with human vision, causing holograms to be clipped at the edges.
- Brightness and contrast: virtual content can appear faint in bright environments, and dark colors cannot be rendered because the display only adds light.
- Registration accuracy: tracking drift and calibration errors limit use in high-precision tasks without additional markers or external tracking.
- Ergonomics and battery life: weight, heat and a typical runtime of only a few hours restrict long sessions.
- Cost and scalability: enterprise-level pricing limits adoption in schools and small organizations.
- Human factors: visual fatigue, vergence-accommodation conflict and cognitive load require further study.

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How HoloLens Is Evaluated: Measurement Instruments
Studies of HoloLens use a mix of objective and subjective measures. Objective measures include task completion time, error rate, positional error of a hologram relative to a physical target, tracking drift over time, frame rate and latency, and physiological or eye-tracking data. Subjective measures are collected mostly with standard questionnaires:

- System Usability Scale (SUS): a ten-item scale that gives a single usability score and allows comparison with benchmarks.
- NASA Task Load Index (NASA-TLX): a multidimensional rating of mental, physical and temporal demand, effort, performance and frustration.
- Simulator Sickness Questionnaire (SSQ): a symptom checklist developed for simulators and widely used to quantify nausea, oculomotor strain and disorientation in immersive systems.

Using validated instruments, reporting means and variances, and following a pre-registered protocol where possible make results more comparable across papers. Studies that evaluate an MR system should report which software version, operating system build and device generation were used, because behavior can change between updates.

Accuracy, Stability and Latency Findings
Accuracy studies are the most technical part of the HoloLens literature. They typically place a physical target (a marker, a phantom or a calibration object) in a known position and measure the difference between the real target and the hologram as seen by the user or as captured by an external tracker. Reported errors are strongly dependent on the method: errors for manually aligned holograms are different from those for marker-registered holograms, and results measured with a camera in place of the eye are different from those perceived by a real user. Vassallo and colleagues observed measurable drift and jitter in the first-generation device , and Qian and colleagues discussed calibration and perceptual effects when using optical see-through displays in interventional settings . A general conclusion is that HoloLens is accurate enough for visualization, guidance and training in many cases, but that safety-critical tasks should use independent verification and should not rely on holograms alone.

Perceptual and Human-Factors Issues
Several perceptual effects are specific to head-mounted MR:

- Vergence-accommodation conflict: the eyes converge to the apparent distance of a hologram, but the focus stays at the fixed focal plane of the display, which can cause fatigue and reduced visual performance, especially at close range
- Depth perception errors: misperception of distance, caused by limited field of view, cue conflicts and differences between real and virtual lighting, may affect tasks that require precise reaching.
- Limited field of view: clipping of holograms at the display edges breaks the illusion of presence and forces more head movement.
- Brightness and contrast: under strong ambient light, holograms appear washed out, and dark objects cannot be displayed.
- Physical load: neck strain, pressure points and heat have been reported in studies with long sessions.
- Cognitive load and attention: rich overlays can distract users or draw attention away from the real task, an important concern in surgery and industry.

For long-term use, studies should follow users over several sessions and weeks, because short laboratory sessions may understate fatigue and overstate novelty effects.

Adoption and Organizational Factors
Even when the technology works, adoption depends on factors beyond the device. These include the cost of devices and content creation, integration with existing information systems, training of staff, hygiene and cleaning procedures, data governance, and the readiness of workers to accept wearable cameras and sensors in the workplace. Many reported pilots do not move to full deployment because of these factors, so a technology evaluation should include a return-on-investment analysis and a change-management plan in addition to usability testing.

Discussion and Future Directions
Microsoft ended production of HoloLens 2 in 2024, and the company has indicated continued support for existing devices for a limited period. This leaves open questions for projects built on the platform. Research and development is likely to shift toward the open OpenXR ecosystem, which reduces dependence on a single vendor, and toward other optical and video see-through headsets.

Several research directions remain important:

- Wider field of view and lighter optics using new waveguide and holographic technologies.
- Accurate, drift-free registration through sensor fusion and learning-based tracking.
- Adaptive and context-aware interfaces that use gaze and hand data to reduce cognitive load.
- Rigorous human-factors and clinical studies with larger sample sizes and long-term follow-up.

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- Privacy and ethics, because always-on cameras and eye tracking capture sensitive personal and environmental data.
- Integration of AI, such as scene understanding and natural-language assistants, with MR displays.

HoloLens in the Wider Landscape of MR Devices

The end of HoloLens 2 production does not mean the end of head-worn MR. Table 3 places HoloLens 2 among other current headsets. The principal design choice is optical see-through (a direct view of the world with added light) versus video see-through (camera-based passthrough shown on opaque displays).

Table 3. HoloLens 2 compared with other mixed reality headsets (approximate and non-exhaustive).

Device	Approx. release	See-throug h type	Notable characteristics
HoloLens 2	2019	Optical (waveguide)	Untethered, hand and eye tracking, enterprise focus, production ended 2024
Magic Leap 2	2022	Optical (waveguide)	Wider field of view, dimming feature for bright scenes, enterprise focus
Meta Quest 3	2023	Video (color passthrough)	Consumer price range, standalone, large app ecosystem
Apple Vision Pro	2024	Video (high-resolution passthrough)	Eye, hand and voice input, high-end display, premium price

Optical see-through devices keep a natural, unmediated view of the world and low real-world latency, which is attractive for safety-critical and face-to-face tasks. Video see-through devices can render fully opaque virtual content, support better occlusion and wider fields of view, but add camera-to-display latency and alter the user's view of the world. Researchers should choose the type that fits the task rather than the one that is newest.

Ethical, Legal and Safety Considerations

MR headsets collect a rich stream of data: video of the user's surroundings, spatial maps of rooms, eye gaze, hand motion and sometimes iris templates. These data can reveal personal characteristics, attention, health and the presence of other people. Studies and deployments should therefore address: informed consent of wearers and, where relevant, bystanders; data minimization and secure storage; transparency about what is recorded and for what purpose; fairness and accessibility for people with different vision, body sizes or physical abilities; and safety rules for use while walking or operating machinery, given that holograms can distract users and block the view. In medical applications, regulatory approval, liability and clinical validation are additional requirements.

Recommendations for Researchers and Practitioners

- Define requirements first. Specify the accuracy, field of view, environment and duration of use before selecting a device.
- Validate the sensors you rely on. Do not assume that built-in hand, gaze or depth data are accurate enough for measurement without checking against a reference system.
- Use validated instruments and report details. Use SUS, NASA-TLX and SSQ where relevant, and report device, software and build versions
- Compare against strong baselines. Compare MR with conventional screens, paper or physical models, not only with no support.
- Plan for platform change. Use open standards such as OpenXR and keep content and logic separate from device-specific code to ease migration
- Study the long term. Include multi-session studies to capture fatigue, learning and novelty effects.
- Address privacy and ethics early. Involve ethics boards and stakeholders before collecting data from real workplaces or patients.

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Limitations of This Review

This review is narrative rather than systematic, so the selection of studies may reflect the author's judgment and the availability of sources. Rapid change in the field means that product details, support dates and service availability may have changed since writing, and manufacturer documentation was used for specifications that have not always been independently verified. The review focuses on HoloLens and mentions other devices only for context. Future work could carry out a formal systematic review following the PRISMA guidelines, with a meta-analysis of accuracy and usability outcomes where the data permit.

V. CONCLUSION

Microsoft HoloLens has played a central role in making mixed reality practical outside the laboratory. Its combination of untethered operation, spatial mapping and hand-based interaction has enabled meaningful applications in medicine, industry and education, while its limitations in field of view, brightness, ergonomics and cost show the remaining gap to ubiquitous MR. Although HoloLens 2 hardware production has ended, the body of research built around it provides a foundation for the next generation of head-worn spatial computing devices.

Declarations

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