Vision Paper: Computing behind Transparent Screen

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ABSTRACT

Mobile devices are playing increasingly significant roles in our daily lives through innovative mobile computing applications. Meanwhile, we observed the rise of *transparent screens* and their novel applications in advanced full-screen devices, whose front-facing optical sensors, such as ambient light sensors and cameras, are now placed under the transparent screen to capture ambient light and visual information. This design eliminates the on-screen area occupied by optical sensors, maximizing devices' screen-to-body ratio for the best use experience and device aesthetics. Motivated by this trend, we propose **Through-Screen Computing**, a new concept that we define as: *the computing of light signals for various purposes such as communication, sensing, and imaging, where the light comes from the physical world and passes through a special medium –the transparent screen– before reaching the under-screen optical sensors.* In this paper, we present the main challenges brought by transparent screens with respect to the proposed computing behind transparent screens. We describe how to overcome these challenges to retain the full functionality of under-screen sensors in terms of imaging and connectivity. Besides, we discuss some applications that could be enabled/enhanced by through-screen computing.

CCS CONCEPTS

• **Human-centered computing → Ubiquitous and mobile computing theory, concepts and paradigms**; • **Computer systems organization → Embedded systems**.

KEYWORDS

Through-screen computing, transparent screen, under-screen sensors, full-screen devices

1 INTRODUCTION

Mobile devices, such as smartphones, tablets, laptops, smartwatches, e-readers, and handheld gaming consoles, have become ubiquitous worldwide. Now, it is hard to imagine a world without these mobile devices. By 2022, there were more smartphones than people worldwide, and the number of mobile devices continues to grow at nearly five times the rate of the global human population [25]. The academic and industrial communities envision an exciting mobile computing future where mobile devices play an increasingly significant role in daily life. The rapid evolution in mobile devices leads to the fact that a flagship device from just a few years ago now seems outdated. Take the smartphone screens for an example. The screen has become the 'only' interactive interface between users and their smartphones since the launch of the first iPhone in 2007, which revolutionized the industry by eliminating most of the physical buttons. In the past decade, various innovative smartphone screen designs have been further realized to minimize the bezels and the notch area taken up by front cameras and other optical sensors to increase the screen-to-body ratio. These designs include the notch screen, teardrop notch screen, and through-hole screen of Android phones, as illustrated in Figure 1, and the "dynamic island" of iPhones. The ultimate goal is to achieve a borderless *"full-screen device"*, unifying user interaction functions and aesthetic design with the potential wide adoption of *transparent screens*.

Figure 1: Evolution of mobile devices and the efforts made on the screens to eliminate notch and bezel.

1.1 The Rise of Transparent Screen

Transparent screen technology utilizes transparent electrode materials to maintain display functionality while being visually transparent. Nowadays, transparent screens have revolutionized mobile devices, leading to the development of full-screen devices such as laptops (e.g., Thunderobot T-BOOK and Samsung Blade Bezel) and smartphones (e.g., ZTE AXON20/30/40, Xiaomi MIX4, and Samsung Galaxy Z Fold3/4/5/6) [20]. These full-screen devices, with their larger screen-to-body ratios, provide a better user experience by offering a more immersive and intelligent interface [3].

To achieve this goal, the screen of full-screen devices comprises a *Transparent Screen Region* and a *Normal Screen Region*, as illustrated in Figure 2(a-b). The transparent screen region is built with transparent electrode materials, serving two purposes: 1) displaying various contents, similar to the normal screen, and 2) allowing light to pass through the screen to reach under-screen optical sensors. The transparent screen's pixel layout is therefore optimized to balance the display functionality and the light transmittance to meet these two purposes [27], as shown in Figure 2(c). This innovative design allows placing optical sensors under the transparent screen without sacrificing their functionality, leading to the so-called *Under-Screen Sensors* [24], such as the Under-Screen Ambient Light Sensors (ALS) [3] and Under-Screen Cameras (USC)[1].

1.2 Our Vision: Through-Screen Computing

Transparent screens are revolutionizing our visual experience of mobile devices. However, they also change the traditional mobile

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[1] It is also referred as Under-Display Camera (UDC) or Under-Panel Camera (UPC) in the literature [6, 27, 30, 35].

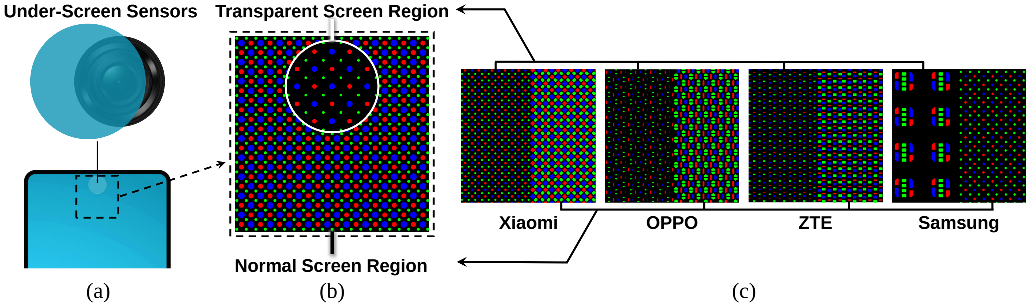

Figure 2: Illustrations: (a) full-screen smartphone with under-screen sensors; (b) magnified micrograph of the transparent screen region and the normal screen region; (c) screen diversity: the comparison of transparent screen regions and normal screen regions designed by different smartphone manufacturers.

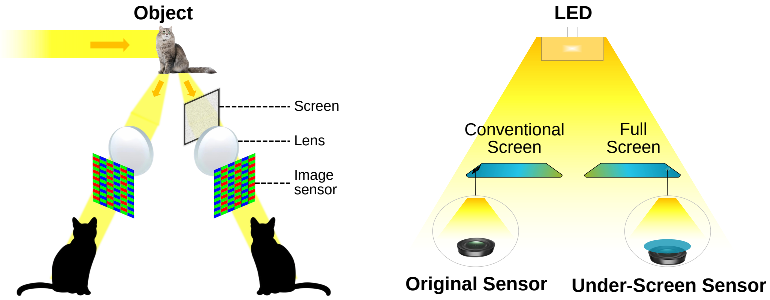

Figure 3: The concept of Through-Screen Computing: (left) Passive source; (right) Active source.

computing of light-based signals since optical sensors now must be placed *under* the transparent screen instead of traditionally *on* the screen. Motivated by this paradigm shift, in this paper, we propose the concept of **Through-Screen Computing**, which we define as: *the computing of light signals for various purposes such as communication, sensing, and imaging, where the light comes from the physical world and passes through a special medium –the transparent screen– before reaching the under-screen optical sensors.* We will explore several key themes with long-term potential for research and innovation: (i) How to overcome screen barriers for existing important directions in mobile computing, such as imaging and communication; (ii) How to leverage the screen to drive innovation in mobile computing, such as interaction, sensing, privacy, security, energy harvesting, and in fields like Augmented/Mixed Reality (AR/MR) and spatial intelligence. Below, we first present the essential components of the envisioned through-screen computing.

Light Source: Through-screen computing uses light signals as the computing input. We mainly consider two types of light sources: (1) *Passive sources:* referring to the objects that reflect light when illuminated, containing spatial information about the object and its environment. (2) *Active sources:* referring to the LED luminaires present in the lighting infrastructure, which are not only beneficial for illumination but also can be modulated in light intensity or colors at a high frequency to transmit information.

Transparent Screen: In through-screen computing, the transparent screen significantly affects light propagation. It influences the visual imaging of light reflected by passive objects (e.g., cats, see Figure 3(left)) or the intensity and color of light emitted by active sources (e.g., LEDs, see Figure 3(right)). Additionally, the transparent screen can act as an active source, featuring an array of RGB pixels in various layouts, shapes, and sizes. This array displays dynamic contents on mobile devices and brings challenges to through-screen computing, such as attenuation, color shift, and interference with other passive and active light.

Under-Screen Sensors: We consider two types of under-screen sensors in this paper: (1) *Single-pixel under-screen sensors*, such as an under-screen photodiode and an under-screen ambient light sensor. Both are semiconductor devices that convert the detected light into electrical information. While an under-screen photodiode only measures light intensity, an under-screen ambient light sensor, which combines a photodiode and a color filter, can measure both the intensity and the color of through-screen light signals; and (2) *Multi-pixel under-screen sensors*, such as an under-screen camera, which can also detect through-screen light signals but in an intuitive and understandable multi-pixel image output.

In this vision paper, we will focus on the computing behind the transparent screens of full-screen devices, addressing several critical challenges to advancing through-screen computing.

2 CHALLENGES

Although the screen considered is "transparent", it still introduces new challenges to under-screen sensors. The transparent screen is not merely a passive medium like glass; it is also a dynamic, active light source that changes unpredictably based on the displayed content. Thus, adopting conventional mobile system designs for through-screen computing is impractical. Designing, implementing, and deploying through-screen computing brings new challenges. Next, we discuss several primary challenges of realizing through-screen computing on full-screen devices, as shown in Figure 4. We focus on the transparent screen's different states (OFF and ON),

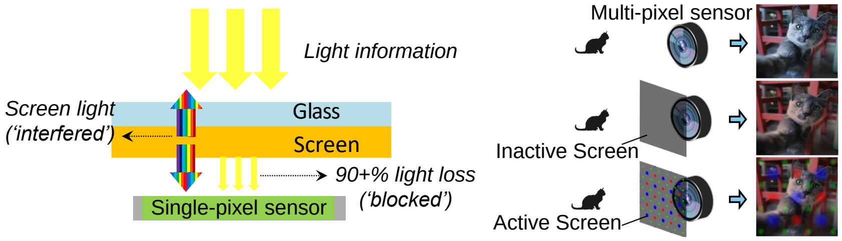

Figure 4: Challenges in realizing Through-Screen Computing: Perspectives of *communication signals* (left) and *vision* (right).

design (pixel layout), and the characteristics of different types of under-screen sensors (single-pixel and multi-pixel sensors).

2.1 Screen as a Passive 'Blocker'

Although the screen may appear transparent to the naked eyes, it is actually not completely transparent. The light transmittance of the transparent screen used on current mobile devices is merely 2.9% [35]. This strong attenuation of light significantly reduces the Signal-to-Noise Ratio (SNR) of light 'signals' at the under-screen optical sensors, severely degrading the system performance. Furthermore, the basic principle of camera imaging is the "pinhole camera", which has a small aperture to allow a narrow beam of light rays to pass through and reach the camera. The optimal imaging distance of a pinhole camera is its focal length. However, in through-screen computing, the aperture of the under-screen camera can be regarded as a combination of the finite screen openings in the transparent screen and the under-screen camera aperture. This combined small aperture changes the focal length and the amount of light reaching the under-screen camera, and it is comparable in size to the wavelength of visible light, resulting in light scattering, diffraction, and absorption [35]. These optical impacts caused by the screen lead to lower SNR, blurred visuals, and color shifts in the image captured by under-screen cameras [33, 35].

2.2 Screen as an Active 'Interferer'

The activated transparent screen region of a full-screen device significantly impacts the captured signal in the intensity and color domains. In the intensity domain, the detected screen light often far exceeds the input light signal, as shown in Figure 4, since the under-screen sensor is much closer to the screen than to the light source. This proximity poses a challenge in removing dynamic screen light interference from the detected light signals. In the color domain, single-pixel photodiodes as sensors can have differential sensitivity to light of varying frequencies, and thus the interference induced by different screen colors is not uniform [7]. The strong and inconsistent interference from the screen (depending on the displayed content) is superimposed on the attenuated input signal, resulting in a low Signal-to-Interference-plus-Noise Ratio (SINR) at the under-screen sensors. Furthermore, the pinhole camera alone is not sufficient to fully capture a clear image. Modern cameras use convex (converging) lenses at small apertures to collect light, refracting light rays from a reflecting object or an emitting active source to form an image. The presence of lenses allows the object being photographed to maintain its original shape while enlarging its size on the camera's sensor. However, this enlargement causes the object in the image to lose sharp boundaries, resulting in a diffuse rendering effect with blurred edges. Hence, when the screen is lit up, different tiny R/G/B screen pixels lead to *optical perturbations [31]: magnified and inverted speckled color blocks and color shifts of the R/G/B screen pixels on the captured image.*

2.3 Screen Diversity

Variations in the design of transparent screens across different full-screen devices affect the performance of through-screen computing in multiple ways. Firstly, differences in the intrinsic material and manufacturing properties of device screens lead to varying light transmittance. Secondly, different manufacturers customize screen parameters, such as maximum screen brightness and screen color gamut, introducing different interference detected by the under-screen sensor. Furthermore, both academia and industry have invested effort in designing diverse screen pixel shapes and layouts to optimize the screen resolution and enhance the screen's light transmittance [27]. As a result, manufacturers have developed distinctive pixel configurations within their screen designs (cf. Figure 2(c)). As mentioned in Section 2.2, camera optics indicate that even tiny illuminated screen pixels can result in optical perturbations on the captured image. These specialized designs introduce unique optical perturbations on the images captured by the under-screen camera. So far, manufacturers can only deactivate the screen display to eliminate this interference when using the under-screen cameras for imaging. However, achieving reliable through-screen computing at all times, regardless of whether the screen is activated or deactivated, remains a significant challenge.

3 OVERCOMING SCREEN BARRIERS

As screens become a new obstacle, we must revisit existing necessary applications in the new context of through-screen computing. For example, imaging and communication are the critical functions of current optical sensors. However, the imaging of passive objects becomes blurrier when viewed through the under-screen camera compared to the original camera, and the detection of input light emitted by active sources may not be as accurate with under-screen sensors as with the original 'on-screen' optical sensors. Under-screen sensors now need to overcome the screen's interference to detect and recover input light signals.

3.1 Under-Screen Imaging

Maintaining the full functionality of a camera after placing it under a transparent screen is challenging. The imaging quality of a camera will be severely degraded due to the low light transmittance and diffraction effects. As a result, the captured images are noisy and blurry. While improving the user experience by providing a full screen, an under-screen camera sacrifices the quality of photography, face recognition, and other vision tasks. Restoring and enhancing the images captured by under-screen cameras are essential. Methods to mitigate these effects include techniques to restore diminished spatial frequencies in the captured images [6], redesign pixel layouts [30], and conventional deep neural networks for correcting the significantly blurred images and enhancing the SNR in the images [35]. This is an important research direction of through-screen computing. Further work could continue to restore the quality of images captured by under-screen cameras through advanced *computational imaging* system design driven by large vision foundation models in the Generative AI era.

3.2 Through-Screen Communication

Visible Light Communication (VLC) is considered a key enabler for future wireless networks such as 6G [1]. Several leading VLC companies, such as pureLiFi and Signify, have developed VLC products for mobile devices, including smartphones and laptops. pureLiFi launched the world's first certified USB VLC receiver, LiFi-XC. The VLC receivers are integrated into mobile devices: smartphones and laptops, facilitating the first LiFi phone call at MWC 2018 [21]. Here, where to place VLC receivers on smartphones is of paramount importance. Hence, pureLiFi launched the IEEE 802.11bb-compliant Light Antenna ONE at MWC 2023, a VLC module ready for integration into billions of mobile devices [22]. However, full-screen devices introduce new challenges new challenges for the deployment of VLC receivers on COTS devices, because there is *no space on the device screen* to place VLC receivers. The strong attenuation of light significantly reduces the received signal strength at the under-screen receiver, negatively impacting the performance of VLC. Additionally, the activated screen could introduce strong and dynamic screen light interference, leading to a low SINR of the received modulated light signal. We recently proposed advanced signal processing methods based on color-shift keying to remove screen interference and correctly demodulate VLC information [32, 33]. Still, these methods cannot completely overcome the interference introduced by the screen when displaying complex dynamic content, such as watching videos and playing games. Further studies on advanced signal processing methods to accurately estimate and preemptively eliminate pixel-level interference from dynamic and complex screen contents to improve the SNR in the received signal could be a promising direction for enhancing *through-screen VLC*.

4 HARNESSING SCREEN BENEFITS

The screen itself could also act as a unique transmission medium in the optical path of under-screen sensors. This offers numerous advantages and opportunities to enhance and extend existing mobile computing functions, such as more natural interaction, sensing with reflective screen light, screen-based perturbation protection, and other novel applications.

4.1 More Natural Interaction When Facing the Screen

Positioning the camera behind the screen eliminates the constraints imposed by the device's bezel, notch, or hole, thereby enhancing gaze awareness during video calls and conferencing–key functions of a front-facing camera. In conventional setups, cameras are often positioned at the top or bottom of the screen, causing an offset from the natural interaction where the user's eyes focus on the screen's center. These offset camera positions disrupt natural eye contact, as participants must choose between looking directly at the camera or at the screen, resulting in a loss of subtle non-verbal cues [12]. This misalignment between the camera's perspective and the on-screen image of the remote participant persists in modern video conferencing systems. We could optimize camera placement behind the screen based on the UI design of traditional video apps. For example, by positioning both the camera and the speaker's face at the center of the screen, the offset between the user's viewpoint and the displayed face of the speaker can be minimized, enabling a more natural eye contact experience. We envision that this new through-screen computing paradigm could refine the user's on-screen appearance and perspective by optimizing the positions of under-screen sensors and applying gaze correction technology, creating a more natural and immersive interaction experience.

4.2 Through-Screen Sensing with Reflected Screen Light

Since the light spectrum is license-free and fine-grained optical sensors such as cameras are widely deployed on mobile devices, pervasive sensing with light has received significant interest. Existing sensing systems with light rely on identifying the shadow caused by a moving object blocking the light source [10] or the reflected light [11, 17]. For instance, SMART [11] introduced an in-air gesture recognition system that uses the screen and ALS located in the notch of the screen. In this system, users perform hand gestures above the screen, and the light emitted by the screen is reflected by the hand back to the ALS to interpret the gesture. In our proposed through-screen computing, however, the ALS is placed under the screen, which presents additional challenges. For example, since the under-screen sensor is placed much closer to the screen than to the users' hand, removing interference from dynamic screen light reflected during hand gestures becomes a more difficult task compared to traditional setups [13]. Future work could explore leveraging the screen as the light source and the under-screen sensors as the receiver to enable *through-screen sensing with reflected screen light*: the under-screen sensors would capture information from the light emitted by the screen and reflected by surrounding objects. This approach offers the advantage of eliminating the need for an additional light source or modifications to the screen's display content, integrating both display and sensing functions seamlessly. Below we discuss some directions on this topic.

Gesture recognition. One direction is to sense people's movements (motions, postures, positions, etc.) in a two-dimensional (2D) or three-dimensional (3D) plane, utilizing the light emitted by smartphone screens or TVs. The users can perform the gestures in front of a device and the gestures can be perceived and recognized by under-screen sensors, enabling convenient and non-invasive control of future mobile devices. This can also be combined with popular motion-sensing games to achieve higher recognition accuracy and finer resolution in 3D human body modeling.

Novel authentication scheme. One existing novel under-screen authentication scheme is under-screen fingerprint sensors. We can design similar authentication schemes, for instance, facial liveness detection using an under-screen camera. The screen can emit light with carefully designed brightness or color; our faces with unique shapes and flatness can reflect screen light differently to the under-screen sensors, enabling novel face authentication. Moreover, in more challenging scenarios, under-screen sensors could leverage existing screen content to perform real-time user authentication without altering the display. Another important biometric measure is cardiac patterns, uniquely defined by the heart, lung, and vein structures of individuals. These cardiac patterns can be obtained with a photoplethysmogram (PPG), which measures changes in blood volume via light absorption. Traditionally, PPG is obtained using a pulse oximeter on a finger, consisting of a small LED that emits light and an optical sensor that captures how much light is absorbed through the body. With through-screen sensing with reflected light, the screen could utilize its RGB pixels to emit the light, without using an additional LED.

Integrated sensing and communication behind screen. In future through-screen communication, sensing will still be needed. It is essential to design new protocols in through-screen computing to integrate communication and sensing. At the communication level, overcoming the dynamic interference of the screen and designing a scheme to address signal interruptions caused by real-world actions that need to be sensed is necessary. At the sensing level, overcoming the influence of dynamic modulated signals and screen interference to complete sensing is essential. Hence, new communication signal processing and intelligent sensing recognition schemes must be designed. We could develop a hierarchical system to accomplish various sensing tasks alongside communication functions.

4.3 Screen Perturbation Protection

Front-facing cameras are bringing privacy issues in the advanced AI era. In today's digital world, the front-facing cameras on mobile devices have become our windows to connect, work, and share moments. However, this incredible convenience has pitfalls. Privacy concerns have appeared as hackers can find ways to turn the cameras into instruments of intrusion. Cybercriminals, equipped with sophisticated AI like deep neural networks, can now mine images for valuable information. The risks are real, as demonstrated when an unintentional selfie exposed sensitive password from post-it note, leading to a breach at the TV network TV5Monde, disrupting broadcasts across 11 channels [4]. This highlights the pressing need for innovative privacy solutions that not only protect us but also maintain the aesthetic integrity of our devices. The vision is to use the transparent screen to generate screen perturbation from tampering. We could utilize the transparent screen's features to inconspicuously modify its pixels, imperceptible to human eyes but inducing screen perturbations on captured images. These screen perturbations effectively ensuring visual privacy in full-screen devices without affecting normal screen use. While there is a need to improve security system design at different scales for computing community, the list below provides a glimpse into the near future:

Side information leakage. Side-channel attacks exploit unintended leakage information from mobile devices to launch unexpected attacks and violate user privacy. In through-screen computing, the advent of transparent screens not only provides opportunities to implement new side-channel attacks but also brings new possibilities for preventing potential side-channel attacks and protecting user privacy. Below, we outline potential side information leakage in through-screen computing:

- *Side App activity leakage.* Wireless data transmission patterns could reveal the activities of common mobile apps (e.g., YouTube, Facebook, and WhatsApp) across different categories: video, music, social media, communication, and gaming [26]. The screen, as a crucial interface, can also be used to reveal the activity of mobile devices. UI design is prioritized for each app upon launch, and under-screen sensors can track screen light emissions during app usage to infer user activities on mobile devices, thereby compromising user privacy. The primary reasons for this include: 1) Each app has a distinct design style and color scheme. For example, YouTube predominantly uses red, Facebook uses blue, and WhatsApp uses green. By detecting the main color of the screen display, under-screen sensors can infer the app in use. 2) Apps exhibit different interactive behaviors. Social media apps, for instance, do not update displays as frequently as gaming or video apps and often display static content. The content presentation and user interaction logic of these apps can further expose app activity on the screen. Additionally, distinctive startup animations of different apps can help hackers infer app activity history solely by analyzing the reflected screen light.
- *Side visual leakage.* Side visual leakage refers to sensors whose main function is not visual imaging, such as ALS and Time-of-Flight (ToF) sensors, which can recover visual information from their readings after applying signal processing algorithms. Recent studies [16] show that ALS could present imaging privacy threats. Also, ToF measurements not only display depth information, such as the three-dimensional structure of a face used in Face-ID, but can also be manipulated to expose visual information, including key facial details of users [29]. To address these leakage concerns, the screen can slightly and infrequently change its brightness, color, and displayed contents, modifying the under-screen sensor's single-pixel readings in through-screen computing. This slight modification will not trigger the entire screen brightness or alter the measured Face-ID but will prevent the optical sensor's low-resolution and even single-pixel readings from being restored to a high-resolution visual image through generative AI models.

Under-screen hidden spy camera detection. Hidden spy cameras monitoring people in private spaces have increasingly become a worldwide problem. The rise of these spy crimes not only negatively impacts general trust in the protection of people's privacy but also significantly affects the health and lives of the victims. Further, hackers can customize devices to hide spy cameras behind transparent screens, such as TVs and monitors. The transparent screens allow light to reach the under-screen spy camera while displaying content, making the camera unnoticeable to the human eye, especially when content like videos is being displayed. This makes the under-screen camera a new attack vector in the field of spy camera crimes. Detecting hidden under-screen spy cameras is a challenging task and needs to be addressed. There are research opportunities to detect under-screen spy cameras using network traffic [15], thermal emissions [34], or interesting optical reflections [23] due to the limited field of view for combined screen and under-screen spy cameras.

4.4 Charging behind/on Transparent Screen

Energy harvesting could replace traditional batteries in low-end mobile devices [2]. Transparent screen can enable energy harvesting behind/on the screen, promoting battery-free through-screen computing. Specifically, the transparent screen can absorb and harvest energy from infrared and ultraviolet light, as well as portions of visible light, while allowing the remaining light to pass through [14, 17, 19]. Meanwhile, the transparent screen can maintain their electrochemical properties under wearable conditions and thus have great potential in acting as batteries [28]. With these features, a transparent screen can be fitted to the entire mobile device body, including on top of the device, to simultaneously display information, harvest energy, and store energy to enable battery-free through-screen computing. Besides, transparent screen can be seamlessly integrated into various parts of the human body or accessories like arms and necks without affecting the wearer's vision. This battery-free through-screen computing on the human body can empower applications such as motion detection and health monitoring.

4.5 Spatial Intelligence over Screen

Depth information is critical to understanding the 3D world, significantly influencing people's interaction with objects in space. The KinectFusion project used a depth camera to reconstruct 3D objects in real scenes [9, 18]. As for MR applications, the representation of information (text, 2D graphics, and 3D images) is superimposed on the real-world environment by the transparent screen with high resolution, like smart holographic glasses [8]. However, sunlight in the real world can have more luminance than transparent screen can produce. The contrast of light and shadow also affects depth perception [5], which is an important factor when an MR user is moving through a real-world environment. In this complex and dynamic situation, future research directions may involve exploring how to leverage the advanced AI capabilities of large vision and language models to mimic human spatial perception, such as complex visual reasoning and action planning, with through-screen light signals. This would enable the spatial perception capabilities of the depth camera located behind the screen, thereby realizing the integration of spatial intelligence and MR applications.

5 CONCLUSION

In this paper, we traced new horizons for innovations in full-screen devices. We presented our vision on several innovations expected in *through-screen computing* in the coming years, harnessing the developments in full-screen devices and even any future transparent screen product, such as AR glasses. We described how to overcome screen barriers to retain the full functionality of under-screen sensors, including imaging and connectivity. Additionally, we discussed several innovative applications that can be enabled/enhanced by the unique features of transparent screens: more natural interactions when facing the screens, sensing with reflected screen light, privacy and security with screen perturbation, energy harvesting behind/on transparent screens, and spatial intelligence over screens, showcasing our visions for the future of through-screen computing. While not all potential research directions are presented here, we hope some of the discussed examples will achieve breakthroughs in the near future and become integral to our future daily lives.

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