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CRoCs-XR: A Cross-Reality Collaborative Experience for Fashion X-Commerce via Virtual and Augmented Reality

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Figure 1: CroCs-XR enables users in Virtual Reality to try on 3D dresses on their avatars, while Users in the physical realm can synchronously visualize, in Augmented Reality, what the user is doing and communicate with her/him through video and audio streaming.

Abstract

Recent advances in eXtended Reality (XR) technologies, particularly Virtual Reality (VR) and Augmented Reality (AR), are redefining the landscape of online shopping. This paper introduces CRoCs-XR, a novel Cross-Reality (CR) system designed to enhance fashion x-commerce through a collaborative virtual and augmented environment. By enabling real-time interaction between a VR user immersed in a virtual dressing room and remote AR users on mobile devices, CRoCs-XR fosters a social, inclusive, and immersive shopping experience. The architecture integrates VR immersion, AR accessibility, and synchronized communication mechanisms, offering a proof-of-concept that bridges physical and digital fashion experiences. We describe the system's design, implementation, and demo functionalities, concluding with discussions on future enhancements and research directions.

Index Terms: Extended Reality, Cross-Reality, Augmented Shopping, Virtual Try-On.

1 Introduction

Extended Reality (XR) — the umbrella term encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) [18] — is increasingly leveraged across the fashion industry to deliver innovative services and reshape traditional paradigms. Virtual fashion weeks and 3D runway shows allow designers to host immersive and interactive experiences accessed globally, breaking free from physical venue constraints [9]. AR-enhanced cataloguing, digital wardrobes, and virtual try-on tools enable customers to preview garments, experiment with size and color, and reduce returns without physical contact [11, 24, 2].

Within this broader XR landscape, immersive shopping has emerged as a flagship application [19]. Research in VR shopping includes virtual showrooms, simulated fashion stores, and VR-based try-on experiences. For instance, eye-tracking studies in immersive VR environments reveal how consumer visual behavior correlates with fashion involvement and overall satisfaction [14], while systematic reviews have identified key challenges and opportunities in VR-based retail experiences [24, 10]. On the AR side, systems such as AR mirrors and mobile-based virtual try-on have demonstrably improved customer engagement, boost conversion rates, and decrease product returns [2, 3, 15]. Further, metaverse platforms and spatial computing devices (e.g. Apple Vision Pro, SharePlay-enabled virtual closets) are merging social interaction and virtual commerce into cohesive brand experiences [5, 4].

Despite these advances, most immersive shopping systems remain siloed: VR users are isolated in fully virtual environments, while AR users operate through device overlays in physical contexts. Indeed, there is a noticeable lack of systems able to synchronously merge these two worlds: cross-reality (CR) experiences that connect users in the virtual domain (e.g.

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VR avatar try-on) with agents in the physical world using AR — enabling both parties to see and interact with each other in real time [1]. Although cross-reality metaverse frameworks have been considered, there is a lack of implementations that support real-time VR–AR collaboration specifically tailored to fashion retail and immersive shopping [25].

In this paper, we address this underexplored intersection by presenting CRoCs-XR (Cross-Reality Collaborative eXperience for fashion via virtual and augmented Reality), a cross-reality virtual and augmented system designed for fashion x-commerce. CRoCs-XR allows a user in VR, embodied via a base avatar, to try on garments in a virtual dressing room, while remote AR users (using a mobile device) can view the live avatar, suggest outfit combinations, vote on styles, and communicate with the VR participant in real time. This design fosters a social, inclusive, and immersive shopping experience: VR wearers benefit from peer feedback, AR users actively participate from physical realms (with cheap devices), and both realms converge in synchronized interaction.

By enabling simultaneous VR immersion and AR accessibility, CRoCs-XR bridges physical and digital worlds in fashion shopping, democratizing access, enhancing social engagement, and enabling richer consumer decision making.

2 Related Works

In this Section, we review the most recent related works where domains fall under the key methodologies adopted for this work: XR for Fashion commerce and Cross-Reality.

2.1 XR for Fashion Commerce

XR technologies bring substantial advantages to both consumers and brands in the fashion realm, with different kinds of interactions and applications [19, 3]. As an example, XR enables customers to virtually try clothing items before purchase. AR systems let users overlay garments on their body via smartphones or tablets, facilitating informed purchase decisions and reducing return rates [7, 6]. On the other side, VR-based try-ons deepen realism by immersing users in simulated dressing rooms or virtual stores [14]. This often comes with product customization in real time—letting users adjust colors, fabrics, fit, and style through interactive interfaces in VR or AR. This active design involvement fosters higher user satisfaction and loyalty. Moreover, XR allows users to curate and manage personalized virtual wardrobes, combining garments and accessories to test different looks and synchronize styles [16]. This supports outfit planning, enhances shopping excitement, and can serve as a digital record of owned items. Finally, XR facilitates remote participation in virtual runway events, enabling consumers to attend fashion shows with immersive and realistic presence—regardless of location [3, 17]. This, in principle, enables immersive virtual showroom spaces where users interact with garments in a digital setting. This reduces physical event costs and expands brand reach globally, allowing themed environments beyond spatial constraints.

2.2 Collaborative Cross Reality System

Collaborative XR environments allow geographically distributed users to engage in shared virtual spaces for communication, ideation, design, or simulation through immersive technologies such as virtual, augmented, or mixed reality [25]. These systems emphasize co-presence, real-time interaction, and spatial awareness across physical boundaries. Different works have demonstrated that such platforms can enhance teamwork, design collaboration, and even education through immersive shared spaces that replicate face-to-face engagement [13].

On this line, CoVAR [20] integrates AR and VR to allow users to perceive and manipulate shared content from different perspectives, showing how multi-modal awareness enhances coordination.

Cross-reality (CR) takes this further by focusing not only on collaboration within a shared XR space, but on bridging users across different points of the reality-virtuality continuum [25]. Transitional interfaces and cross-device systems like [21] illustrate how seamless transitions between realities can be achieved and studied: it demonstrated hybrid AR interaction by combining HMDs and smartphones to explore usability across multiple display paradigms. On a similar line, [12] enabled both in-situ (VR) and ex-situ (desktop) analysis of mixed reality data, bridging interaction modalities for richer user evaluation. Furthermore, analytical studies such as [22] provide valuable frameworks to understand how dyads interact across reality boundaries, identifying design considerations for temporal and spatial transitions.

Despite these relevant contributions, most collaborative XR and CR systems remain centered on general-purpose collaboration (e.g., education, design, analytics) and do not target domain-specific experiences such as retail or fashion. Additionally, they often focus on enabling transitions across devices or modalities rather than supporting simultaneous multi-user experiences across devices in real time. Our system advances this field by not only connecting AR and VR users in real-time but also doing so within a fashion retail context, combining practical garment interaction, visual feedback, and interpersonal communication into a cohesive collaborative shopping experience. Moreover, our system put together different features and needs which are required in order to implement a complete fashion commerce scenario (e.g., virtual try-on and customization).

3 Methodology

The system revolves around the concept of Collaborative Cross-Reality applied to the fashion x-commerce field, by enabling users to experience clothing in a realistic virtual space prior to making a purchase. The application comprises two primary components: a VR-based wardrobe and an AR mobile application.

At the core is a virtual wardrobe accessed via VR headset, where users browse and try on clothes using personalized avatars. They can move freely and view themselves in a virtual mirror for a realistic sense of fit and appearance.

To enhance accessibility, CRoCs-XR includes a mobile AR app that lets users join the virtual wardrobe via a shared code. Using their smartphones, they can view the VR avatar and interact with the environment, enabling remote participation and feedback.

The VR and mobile experiences are connected through real-time interaction and communication. VR users see the mobile user's camera feed on a virtual wall, while voice chat enables sharing feedback on outfits. AR users can view the VR activity and suggest clothing changes or new combinations.

This CR approach provides several benefits: (i) Only one VR headset is required, while multiple mobile AR devices can join, broadening access and reducing equipment barriers typical of XR collaborative environments. (ii) Fashion advice and feedback can be shared from anywhere, at any time, enhancing the practicality and engagement of the virtual wardrobe. (iii) The system promotes social interaction, allowing users to share experiences with friends and family through real-time video and voice, fostering a realistic sense of presence.

3.1 System Architecture

The design of CRoCs-XR is grounded in a thorough analysis of the underlying system architecture, which aims to bridge the gap between the physical and digital realms. The system architecture is illustrated in Figure 2 and is briefly described here. As outlined in the previous Section, CRoCs-XR provides two XR applications developed using Unity Editor and Game Engine (version 2022.3.3f1 - LTS). Indeed, CRoCs-XR follows a client-server architecture where the VR system acts as the server (host) and AR users function as clients.

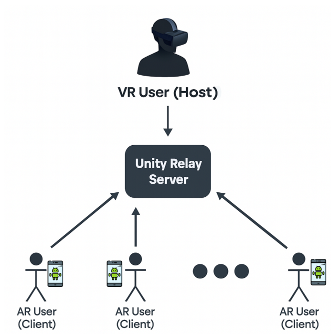


Figure 2: System architecture of a cross-reality CRoCs-XR session.

The VR application was developed using the XR Interaction Toolkit to implement all the interactions, targeting the HTC-Vive Pro Device. The VR application supports any OpenXR-compatible device and is implemented using the XR Interaction Toolkit to ensure a fully immersive experience. The AR application is developed for Android mobile devices using AR Foundation and Google ARCore, offering a lightweight and intuitive interface that allows users to view and comment on virtual outfits.

The collaborative CR communication between VR and AR systems is facilitated by a Relay Server, enabling multiplayer-like XR experiences without a custom backend. To implement real-time data exchange and state synchronization, we use Netcode for GameObjects (Netcode) [23], a networking library built for Unity that simplifies the implementation of network logic. Netcode provides a high-level abstraction that allows GameObject states to be synchronized across multiple players during a networked session, thereby facilitating the creation of collaborative XR environments. In our case, the host transmits the state of the VR avatar—controlled via an HMD and controllers—to all connected AR clients in real time. However, in scenarios where the host and clients are not on the same local network, direct peer-to-peer connections may fail. To address this, we integrate the Unity Relay Service (UniRS) [8], which provides connectivity through a public relay server acting as a universal proxy. Both host and clients connect to this publicly accessible server, which mediates communication between them. Once the host requests a relay allocation, the server reserves capacity and generates an access code, a randomly generated string that clients must enter to join the correct session. This approach eliminates the need for third-party networking solutions or the maintenance of dedicated game servers, while also abstracting away the complexities of peer-to-peer networking. It provides a scalable and robust infrastructure for delivering real-time, cross-reality collaborative experiences.

3.2 Virtual Reality Wardrobe experience

The VR side of CRoCs-XR places users in a virtual walk-in closet to try on garments with a VR headset, emphasizing immersion through realistic body motion and rich environmental interaction. The VR application includes the following core functionalities:

The VR application provides several key functionalities: (a) real-time synchronization of the avatar's motion and clothing changes across all connected clients; (b) movement within the virtual wardrobe space enabled by Inverse Kinematics; (c) the ability to virtually try on garments displayed inside the closet environment; (d) the capability to view connected users on a dedicated wall and communicate with them through voice chat; and (e) access to an interactive mirror.

The interactive mirror is the main interaction component of the experience, indeed it allow users to: (1) launch the server and retrieve the access code, (2) browse a categorized garment catalog with options to try on, add to cart, or view additional information, (3) view a list of recommended outfits with corresponding recommendation percentages based on connected users' input, (4) add currently worn items directly to the shopping cart, and (5) review and re-try cart items before proceeding with a virtual purchase. Figure 3 depicts a user exploiting the main system functionalities.

In the following, a brief description of the main VR functionalities is provided.

Real-time Synchronization of Movement and Outfit Changes

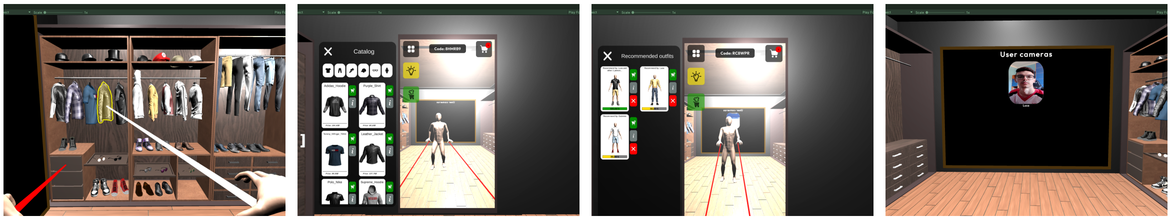
The CRoCs-XR system ensures that both the avatar's movements and clothing changes are synchronized in real time across all connected clients. Although the purpose is the same—disseminating changes from the server to every client—the implementation involves two distinct mechanisms. Movements are synchronized using Unity's `NetworkObject` and `NetworkTransform` components. These enable the avatar's position and rotation data to be continuously shared and updated across clients. To function properly, the object must also be registered within the `NetworkManager`. For clothing changes, a Client RPC is triggered from the server, executing the same function across all clients. Since the VR and AR applications share the same scene structure, this allows for seamless synchronization of outfit states across platforms.

Avatar Movement via Inverse Kinematics

To achieve realistic limb animations, we employed Inverse Kinematics (IK) to compute the positions of elbows and knees based on the tracked positions of hands and feet. This is crucial in creating a fully articulated avatar, a feature not commonly implemented in many VR applications which often only animate the upper body or hands. The IK system was implemented using Unity's `Animation Rigging` package, assigning a two-bone IK constraint to each limb. The constraints use target and hint objects to guide joint positioning. For example, the elbow's direction is influenced by a backward-placed hint object. This results in natural bending of joints, enhancing the immersive realism of the VR experience. As outlined in Section 3.2, head, hand, and foot movements are shared with all connected AR clients via `NetworkTransform`.

Virtual Garment Interaction

The virtual wardrobe experience in CRoCs-XR replicates real-life interactions. Using



(a) Virtual Closet. (b) Dress Catalogue. (c) Outfit suggested by AR users. (d) Communication with AR users.

Figure 3: Key functionalities of the VR interface in CRoCs-XR. (a) The virtual closet allows users to explore and try on garments in an immersive environment using inverse kinematics and avatar synchronization. (b) The interactive mirror enables browsing of a categorized dress catalogue, launching the XR session, and managing the shopping cart. (c) Outfit suggestions provided by connected AR users are displayed in real time, with options to try or reject recommended combinations. (d) The communication wall displays front-camera feeds from connected AR users and enables voice interaction, fostering a socially inclusive XR shopping experience.

VR controllers, users can point to garments hanging in the virtual closet to select and try them on. A visual outline appears when an item is selected, and with the press of a button, the outfit is instantly worn by the avatar. This action is synchronized with all connected AR clients, allowing them to observe changes in real time. The outline effect was implemented using a package specifically compatible with Skinned Mesh Renderers and VR setups. Synchronization is handled via Client RPCs, broadcasting clothing changes from the VR server to all AR clients.

Communication with Connected Users A dedicated wall within the virtual closet displays the front-facing camera feeds of connected AR users. This enables the VR user to see their friends' facial expressions in real time, enhancing emotional engagement and social presence. Voice communication is unidirectional: AR users hear the VR user's voice but cannot respond verbally. This video chat functionality is powered by the Agora Video SDK for Unity[1], which supports cross-platform compatibility and real-time audio/video streaming. The addition of real-time facial expressions and audio cues greatly enriches the social dimension of the virtual shopping experience.

Interactive Mirror Interface The interactive mirror is the main interface through which users manage the session. It includes multiple modules:

- Session Initialization: At the top of the mirror interface is a button that creates a unique access code for the virtual session. This code, generated via Unity Relay's library, is used by AR users to join the VR-hosted room.
- Garment Catalogue: The mirror provides access to a categorized catalog of clothing items. Users can browse categories such as upper body, lower body, shoes, hats, glasses, and watches. Each catalog card includes the item name, image, price, and buttons to try, add to cart, or view additional information.
- Recommended Outfits: AR users can recommend complete outfits, which are displayed to the VR user with recommendation percentages based on voting. Colors indicate popularity, from red (low agreement) to green (high agreement). Selecting an outfit card causes the VR avatar to immediately wear the suggested combination.
- Add Worn Clothes to Cart: A quick-action button allows users to add all currently worn items to the virtual cart. The backend retrieves item prices and updates the cart accordingly.
- Shopping Cart Management: The cart icon on the mirror indicates the total number of added items. Users can view, re-try, or remove garments and see the total cost. This final module provides a complete overview before proceeding to virtual checkout.

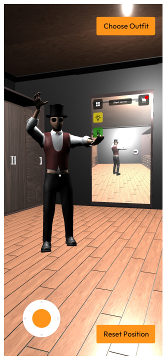
[1]https://github.com/AgoraIO/video-sdk-samples-unity

3.3 Augmented Reality Streaming application

The AR interface of CRoCs-XR is designed to complement the VR experience by enabling remote collaboration through a smartphone-based application. This setup enhances accessibility, allowing a broader audience to participate in the XR fashion experience without the need for specialized VR hardware. The AR application empowers users to visualize the VR avatar in real-time, provide style feedback, and co-create outfit selections dynamically and engagingly.

The AR application supports the following core functionalities: (a) connecting to the virtual room using an access code and username; (b) visualizing the shared XR scene and observing the VR avatar in real time; (c) navigating the environment using a screen-based joystick; (d) resetting position to the default spawn point; and (e) interacting with a dedicated outfit selection menu to preview, compose, recommend, and apply clothing combinations. Figure 4 illustrates the main interaction stages within the AR interface.

Connection to the Virtual Room Upon launching the application, users are prompted to enter their name and the access code associated with the target virtual room. This login process ensures identity assignment and proper session connection. The user name is utilized to display identity within the VR environment (e.g., below the avatar's camera) and to label clothing suggestions. The access code is critical for correctly joining the intended session. The login mechanism integrates error handling to prevent incomplete form submission, enhancing usability and connection robustness. Furthermore, the application implements an initialization process upon joining: the client sends a Server RPC to fetch and synchronize the current outfit worn by the VR avatar, ensuring a coherent shared state even for late joiners.



(a) Mobile view in AR where the Virtual Closet is overlayed.

(b) Outfit Menu to suggest outfits.

(c) Single product view.

Figure 4: Main interaction stages of the CRoCs-XR AR interface. The AR application complements the VR experience by enabling real-time remote collaboration through a mobile device. (a) Users can observe the VR avatar within a shared augmented scene and interact using a virtual joystick. (b) The outfit selection menu allows users to preview clothing items and suggest outfit combinations. (c) Detailed product views support more informed clothing decisions.

AR Scene and Avatar Visualization After login, the user is immersed into the AR scene, where the virtual room and avatar are overlaid in real-time through the smartphone camera. The AR interface allows users to observe the VR avatar's actions, movements, and outfit changes in a synchronized and low-latency manner. Voice chat functionality enables remote verbal interaction with the VR user, enhancing social presence. The AR view serves as the primary environment for collaboration and interaction.

Virtual Joystick for Navigation To support exploration within the virtual room, a screen-based virtual joystick enables movement through the AR scene. This feature allows users to dynamically change perspective, approach the VR avatar, and interact more closely with the environment, thus reinforcing immersion and spatial agency.

Reset Position Mechanism The application includes a button for resetting the user's position to the default spawn point. This feature improves the user experience by offering a quick way to reorient within the scene, particularly useful in collaborative or repeated usage scenarios.

Outfit Selection Menu The AR interface provides a dedicated outfit selection menu that allows users to browse, compose, recommend, and test clothing combinations. This module includes multiple interaction components. The clothing catalog is organized by category and browsed via horizontal sliders. Each item shows an image, name, and interaction options. AR users can view the selected outfit on a virtual mannequin matching the VR avatar, which can be rotated with touch gestures. A detailed viewer also allows 360-degree inspection of individual garments. Selected combinations can be suggested to the VR user via a simple RPC call. These recommendations are rendered both as visual indicators above garments and as entries in the VR mirror's recommendation list, complete with recommendation scores.

Users can remotely apply an outfit directly to the VR avatar by triggering a Server RPC. This action updates the outfit for all connected clients, maintaining consistency across the session.

Through this suite of features, the AR application not only enables participation from users outside of the VR context but also enriches the collaborative dimension of the XR fashion experience, making it more inclusive and interactive.

3.4 Future Developments: Photorealistic Avatars

An important avenue for future development of CRoCs-XR is integrating photorealistic 3D avatars to enhance realism and user embodiment in immersive shopping. Creating these avatars involves a multi-stage computer vision and graphics pipeline focused on geometric accuracy and visual fidelity.

The process starts with multiview capture using calibrated cameras to ensure full-body coverage. Depth maps are estimated per view, generating partial point clouds that are aligned and merged through robust registration techniques. Surface reconstruction methods like Poisson reconstruction then create a continuous mesh, followed by localized refinement to enhance detail and reduce artifacts. High-resolution texture mapping uses original RGB images and camera parameters to tightly align textures with geometry, producing lifelike avatars. These avatars improve virtual try-on realism, enabling better garment visualization and user identification (see Figure 5). Their inclusion supports telepresence, personalized shopping, and extended identity expression, paving the way for CRoCs-XR in metaverse commerce, gaming, and remote social interaction.

4 Discussions and Conclusion

In this work, we introduced CRoCs-XR, a cross-reality platform that bridges VR and AR to support collaborative and immersive fashion shopping experiences. This system allows a VR user to interact with a digital wardrobe and try on garments using a virtual avatar, while simultaneously enabling AR users on mobile devices to view the avatar in real time, suggest outfit combinations, and communicate through audio-video streaming. This design allows to remove of isolation with a hybrid architecture that merges both modalities, fostering a shared environment that enhances social inclusion, accessibility, and user engagement in virtual shopping. This dual-modality and multi-user system demonstrates several advantages: (i) it democratizes access to immersive fashion experiences, and (ii) supports practical x-commerce scenarios, laying the groundwork for further research on retail-focused cross-reality systems. While CRoCs-XR offers a complete and

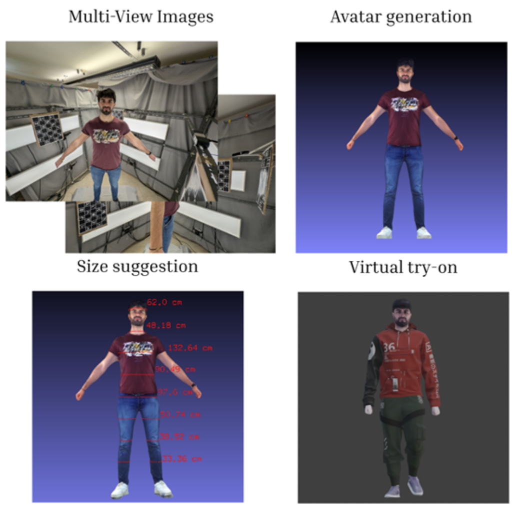


Figure 5: Pipeline for photorealistic avatar generation and virtual try-on: from multiview image acquisition to avatar reconstruction, body measurements for size recommendation, and realistic garment simulation.

functioning prototype, multiple avenues for enhancement remain. First, greater personalization of the VR avatar, along with more expressive facial animations and smoother inverse kinematics, would allow users to adjust fine-grained facial and body features, creating stronger identification with the virtual self. Moreover, simulating realistic cloth physics remains a challenging but promising direction, offering more accurate visualization of garment fit and movement. For these reasons, we planned to include all of these development in our future works, to place CRoCs-XR at the forefront of next-generation x-commerce systems.

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