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Human digital twin for long-distance relationships: a scoping review

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ABSTRACT

Human Digital Twins (HDTs), building upon the concept of Digital Twins (DTs), offer transformative potential for seamless human interaction across physical and virtual worlds. This review aims to establish the groundwork for utilising HDTs in Long-Distance Relationships (LDRs) to enrich the quality of human connections over geographical separations. Searching from four academic databases, this paper examines current DT research in Human-Computer Interaction (HCI) and synthesises existing LDR solutions across commercial and research realms, including communication technologies, social media platforms, wearable and tangible interfaces, Extended Reality (XR) and immersive telepresence, and Artificial Intelligence (AI)-based companions. The findings reveal significant gaps in the research of broad DTs in HCI communities and highlight the limitations of current LDR solutions. To address these challenges, this study envisions HDTs encompassing both microscopic (individual) and macroscopic (dyadic) dimensions, offering a novel approach to enhancing emotional and experiential closeness despite geographical separation. Several potential scenarios for HDT integration in LDRs are presented, demonstrating its capability to enhance LDR interactions.

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Review; digital twin; human; long-distance relationship; geographically separated

1. Introduction

A Digital Twin (DT) refers to a dynamic, real-time virtual representation that mirrors physical entities, processes, or systems, enabling predictive analysis, optimisation, and interaction (Grieves and Vickers 2017; Liu et al. 2021). Specifically, there exists a consensus that DTs are commonly characterised by several key features: i) acting as a mirror of the physical twin, ii) enabling the virtual simulation of physical twin behaviour, iii) providing real-time response capabilities, and iv) maintaining a dynamic and bidirectional relationship where changes in either twin affect the other (Liu et al. 2021; Vainionpaa et al. 2022). From its initial use in manufacturing, such as cyber-physical systems (Lazaroiu et al. 2024) and engineering (Fuller et al. 2020) to its current widespread use in healthcare, product development and performance improvement (Tao et al. 2018), DTs have demonstrated significant potential for bridging the physical and digital realms. Beyond industrial and infrastructural applications, the interaction between humans and DTs is evolving, with Human Digital Twins (HDTs) utilising a range of technologies such as Internet of Things (Kliestik et al. 2024), multisensory modelling (Kliestik et al. 2024b, computational intelligence, and visualisation tools to create precise virtual human representations, extending the concept of DTs from manufacturing to human-centric applications (Naudet, Baudet, and Risse 2021; Pascual et al. 2023). The dynamic and multifaceted nature of the human body and behaviour make HDTs significantly more complex than traditional DTs (Okegbile et al. 2022). Although HDTs can simulate all aspects of human beings, including physical, behavioural, social and cognitive dimensions (Lin et al. 2024), the potential of HDTs remains largely untapped, especially in addressing interpersonal and relational challenges like Long-Distance Relationships (LDRs). More specifically, current studies on DTs primarily focus on enabling remote connectivity across three interaction paradigms: system-to-system interaction (e.g. executing intelligent operations between physical objects in DTs during production (Tao and Zhang 2017)), human-to-system interaction (e.g. operators remotely controlling machines using robotic arms (Tsokalo et al. 2019)) and human-to-self interaction (e.g. using a DT of the human body for monitoring patient health (Liu et al. 2019), which is the predominant form for HDTs. However, there is a notable gap in exploring human-to-human interactions mediated through DTs. Expanding the scope of HDT studies to encompass remote human-to-human

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interactions could address current limitations in supporting more engaging and immersive remote experiences. Such advancements hold the potential to bridge physical distances in LDRs, offering transformative possibilities for interpersonal connectivity that remain largely underexplored.

LDRs, a form of interpersonal relationship (e.g. romantic relationships, family relationships and even professional or mentorship relationships), are characterised by geographic constraints that limit face-to – face communication opportunities (Stafford 2004). These LDRs are increasingly common, with millions of people reporting being in LDRs annually (Aylor 2003), necessitating novel approaches to bridge the physical divide between people geographically separated. Individuals in LDRs used a variety of strategies to bridge the physical gap. These include adaptive self-disclosure, where partners intentionally share personal thoughts and feelings to build trust and intimacy, and idealised cognition, which involves focusing on positive or idealised aspects of the relationship or partner to strengthen emotional bonds (Pistole, Roberts, and Mosko 2010). Additionally, they rely on imagination to create emotional, daily, and embodied intimacy (Center n.d.). Technology plays a crucial role in maintaining LDRs, with video chat enabling individuals to share presence and engage in prolonged activities together (Kasahara and Rekimoto 2014). Hybrid approaches, such as telepresence robots, combined video chats, remote interaction, and even immersive technologies, promote physical and emotional intimacy (Fischedick et al. 2023). Despite these innovations and provide basic channels for interaction, people in LDRs continue to face contextual, technological, and personal challenges (e.g. dimensions of emotional presence, shared experiences, and the tangible aspects of intimacy). As a result, there remains a critical need for innovative approaches to enhance relational quality in LDRs.

Existing evidence highlights the immense capacity of DT and HDT technologies to connect individuals across distances. Yet, their application in fostering meaningful interactions in LDRs has not been thoroughly investigated. This gap underscores the need for research aimed at leveraging HDTs to create immersive, impactful interactive experiences for geographically separated individuals. As a result, incorporating LDRs into the scope of HDT applications presents an opportunity to broaden their utility and redefine their purpose. By facilitating interactions between individuals in LDRs, HDTs could effectively bridge the geographic divide, offering new ways for LDR people to remain connected, share meaningful moments, and nurture intimacy. Exploring the integration of HDTs in this context could not only expand the reach of this technology but also significantly enhance the quality of life for individuals in LDRs.

The next section reviews existing backgrounds on DTs and HDTs for connecting people across distances, providing foundational evidence for their potential application in the context of LDRs. Section 3 outlines the methods employed for the scoping review, detailing the search database for data selection, search criteria, and the strategies used to identify relevant studies on using DTs in Human-Computer Interaction (HCI) and its application to LDRs. Section 4 presents the results of the review, revealing a growing body of DT-related research but highlighting the limited attention given to DT within the HCI field and the absence of studies on DT applications for LDRs. Furthermore, section 5 categorises and reviews existing solutions for LDRs from both market and research perspectives. It also discusses the findings, emphasising the limitations of current DT research in HCI and the inadequacies of existing LDR solutions. Section 6 envisions an HDT from initial to stable LDR statuses, exploring potential future scenarios for HDTs as a solution. Finally, section 6 concludes the paper, summarising key insights and implications.

2. Background

DTs have been widely applied connecting people across distances in various domains, including industry and manufacturing (Calandra et al. 2022, 2023), remote education and virtual laboratories (Dashkina et al. 2020), cultural heritage (Gabellone 2020), remote care (Hu et al. 2022), and healthcare (Rufai et al. 2024). These technologies are leveraged to enhance connectivity and collaboration, particularly in remote contexts. Within this context, Extended Reality (XR) enhances the creation of immersive and interactive environments that facilitate remote collaboration. XR encompasses a spectrum of combined real and virtual environments, including Virtual Reality (VR), Mixed Reality (MR), and Augmented Reality (AR) (Fast-Berglund, Gong, and Li 2018).

Through XR platforms, remote users can exchange and visualise real-time data while collaborating on tasks such as programming collaborative robots (cobots) using AR and VR, achieving improved efficiency and accuracy in complex workflows (Calandra et al. 2022, 2023; Kaarlela et al. 2022). MR further enables participants to share and manipulate DTs of physical environments, such as architectural spaces or industrial facilities, improving decision-making and design processes tasks like interior design and urban planning

(Kim et al. 2021). The integration of haptic feedback and tactile interaction into XR systems further boosts effectiveness in teleoperation and telepresence. For instance, haptic gloves and DTs facilitate realistic virtual handshakes and seamless collaboration, fostering multi-sensory immersive experiences that bridge physical and virtual realms with greater fidelity and engagement (Huang et al. 2024). Additionally, telepresence technologies enhance the synchronisation between virtual and physical environments, ensuring accurate human posture estimation, object tracking, and training tasks, thereby streamlining workflows and improving task outcomes (Wang et al. 2021).

In education and training, DT platforms provide remote access to robotic devices, enabling users to programme, monitor, and interact with systems as if physically present (Geng et al. 2022; Kaarlela et al. 2022). One study explored virtual laboratories where students interacted with virtual replicas of real – world objects and processes. This allowed them to conduct experiments and participate in professional development tasks remotely as if they were in the same physical laboratory (Dashkina et al. 2020). Neural networks were also integrated into DTs to improve simulation accuracy and efficiency, supporting simultaneous participation by multiple users without the need for costly physical setups (Mihai et al. 2022).

In the cultural heritage and remote care sectors, DTs have been utilised to create virtual tours of otherwise inaccessible heritage sites, enabling shared experiences in virtual settings (Gabellone 2020). Similarly, Hu et al. (2022) demonstrated how DTs can bridge emotional and practical gaps in caregiving by engaging remote family members in household management tasks, offering virtual companionship, and improving the mental health of older adults.

In healthcare, DTs have been explored as a transformative tool for remote patient care. For instance, Rufai et al. (2024) investigated the application of 3D holoportation in telemedicine, integrating holographic imaging technology with DT frameworks. This approach enables three-dimensional telepresence of patients, providing clinicians with an immersive, real-time visualisation of a patient's condition during teleconsultations. Moreover, by incorporating real-time patient data into DTs, the accuracy of remote diagnosis and continuous monitoring is significantly enhanced (Fuller et al. 2020).

Despite their wide range of applications, current DTs are primarily task-oriented, focusing on technical and operational goals. Its traditional paradigm is limited to embodying non-living entities (Chen et al. 2023). These systems excel in improving productivity, safety, and educational outcomes but fall short in connecting and addressing dynamic interpersonal relationships and human experience. For example, while DTs can simulate the physical environment of professional collaboration, they lack the ability to replicate the subtle emotional aspects of human interaction, such as those required in interpersonal relationships.

Although HDTs hold potential applications across industry and daily life domains (Lin et al. 2024), the primary focus of HDTs currently lies in healthcare, where they are applied in personalised medicine and proactive diagnosis (Okegbile et al. 2022). They are also used in education and professional development, such as sports, to evaluate training programmes, optimise nutrition and hydration, and enhance performance (Pascual et al. 2023). These applications highlight the potential of HDTs in improving individual outcomes (e.g. tailored individual needs and more accurate performance optimisation) (Okegbile, Cai, and Yi 2024). Despite these advancements, HDTs are predominantly designed with utilitarian and predictive functions, prioritising data collection, prediction, and decision-making over interactive capabilities. Evidence of HDTs (as a category of DTs) being utilised in daily life for addressing complex interpersonal dynamics, especially in domestic settings like LDRs, remains scarce, revealing a critical gap in the existing body of research.

In this review, we aimed to gather evidence on the extent to which DTs have been studied in the field of HCI and LDR-related research, with the aim of comprehensively mapping the current landscape of technological solutions and exploring the potential applications of HDTs in supporting LDR connections.

3. Method

In this section, we conducted a scoping review to detail our process for database selection, inclusion criteria and search strategy, focusing on the current research of the DT applications in the context of LDRs. Instead of addressing a specific question, this review explores broad questions and provides an overview of the available research evidence (Munn et al. 2018). Specifically, during the initial evidence collection phase, we were unable to identify any studies that directly addressed DT applications to LDRs. This lack of direct evidence led us to broaden our scope and map this field by independently examining research on DTs, DTs in the context of HCI, and studies on LDRs from academic and commercial perspectives. This method enabled us to synthesise evidence regarding the emerging concept of DTs and the human-centric applications of DTs (HDTs), emphasising their potential to address the unique challenges to LDRs.

3.1. Database selection

We selected four major academic databases: the *ACM Digital Library, SpringerLink, Scopus, and IEEE Xplore*. These databases were chosen because of their broad coverage of HCI, digital technology, computer science and engineering research, which are highly relevant to exploring DTs and potential applications in LDRs. Specifically, the *ACM Digital Library* emphasises HCI and computer science, offering key insights into user-centered digital systems. *SpringerLink* provides interdisciplinary content across computing, psychology, and social sciences. *Scopus* offers broad cross-disciplinary indexing, supporting comprehensive searches and tracking across both technical and behavioural domains. *IEEE Xplore* focuses on engineering and applied computing, making it particularly relevant for identifying technical innovations in digital communication tools.

3.2. Search strings and inclusion criteria

We conducted multiple search strategies and separated search strings tailored to capture relevant research. For the search strings, 1) '*Digital Twin' AND 'Long-Distance Relationship'*, 2) '*Digital Twin' AND ('Geographically Separated' OR 'Geographically Distant' OR 'Personal Relationship' OR 'Remote Relationship' OR 'Virtual Relationship' OR 'Online Relationship')*, the criteria are that studies (January 2014–November 2024) should explore the application of DTs in the context of LDRs, and to address challenges specific to maintaining personal relationships over distance.

For the search strings, '*Long-Distance Relationship' OR 'Geographically Separated' OR 'Geographically Distant' OR 'Personal Relationship' OR 'Remote Relationship' OR 'Virtual Relationship' OR 'Online Relationship'*, publications (January 2014-November 2024) should examine technological solutions aimed at supporting LDRs, or discuss specific technologies (e.g. VR, AR, wearable devices) focusing on interpersonal relationships, experiential dimensions of remote interaction, mitigating physical separation, or enhancing a sense of presence.

3.3. Search strategy

Our preliminary search used the combination of search terms 'Digital Twin' AND 'Long-Distance Relationship' to directly address our research focus. The search process was not limited to specific fields such as titles or abstracts and covered all searchable content in the databases from January 2014 to November 2024. However, we found no studies that met our inclusion criteria. To broaden the scope, we expanded the search terms to include synonyms for LDRs, using 'Long-Distance Relationship' OR 'Geographically Separated' OR 'Geographically Distant' OR 'Personal Relationship' OR 'Remote Relationship' OR 'Virtual Relationship' OR 'Online Relationship' across the four selected databases. Despite this expanded search, we did not identify any relevant studies aligned with our criteria. This outcome highlights a significant gap in the existing literature and underscores the need for further research in this area.

Consequently, we divided our search strategy into two distinct phases. The first phase focused on gathering a general understanding of DTs through the search terms 'Digital Twin', exploring its broader concepts and applications, including intersections with HCI. In the second phase, we shifted focus to investigate the current landscape of technologies and solutions used in LDRs. For this, we used the search terms 'Long-Distance Relationship' OR 'Geographically Separated' OR 'Geographically Distant' OR 'Personal Relationship' OR 'Remote Relationship' OR 'Virtual Relationship' OR 'Online Relationship'. This approach allowed us to comprehensively review existing technological interventions and identify potential areas where DTs could be applied to enhance LDR experiences.

Unlike academic studies, which are well-documented and indexed in scholarly databases, commercial solutions to LDRs remain fragmented and less systematically catalogued. Information on commercial solutions is dispersed across various online platforms, including company websites, application marketplaces, press announcements, and market analyses. These sources are not indexed in academic databases, requiring the use of conventional web search using the Google search engine and snowballing. This manual process involved carefully examining communication platforms, social media tools, and applications widely utilised by individuals in LDRs. The results from both commercial and academic perspectives are summarised in the following section.

3.4. Screening and data extraction

In the first phase, using the search term ('*Digital Twin*'), we calculated the number of publications retrieved from the four databases. After removing duplicates (i.e. publications indexed in multiple databases), we summarised the publication trends between broader DT research in the subsequent section.

In the second phase, we employed the search terms ('*Long-Distance Relationship' OR 'Geographically Separated' OR 'Geographically Distant' OR 'Personal Relationship' OR 'Remote Relationship' OR 'Virtual Relationship'*

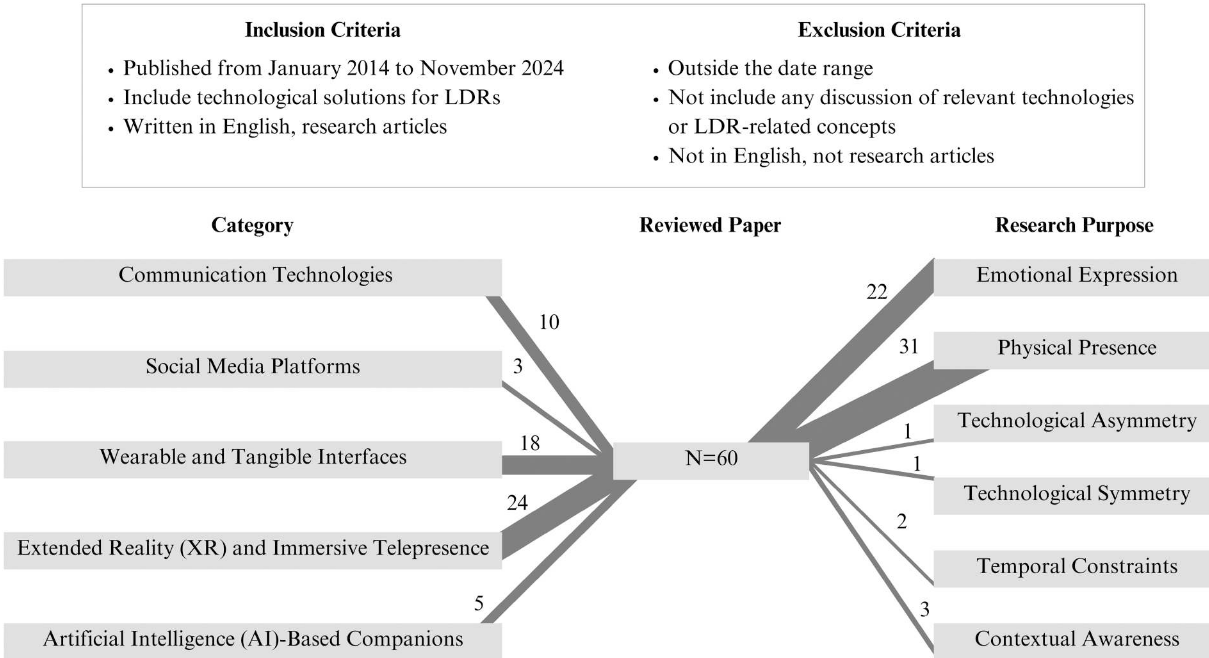

Figure 1. Category and Research Purpose of the 60 Reviewed Papers.

OR 'Online Relationship'). Initially, we screened the titles and abstracts of retrieved papers based on pre-defined inclusion criteria, followed by a full-text review. This process yielded 60 papers for our analysis. Based on their solutions, we categorised them into five categorises and further identified key research purposes related to LDRs. The details are provided in the subsequent section and Figure 1.

4. Result

This section summarises publication trends, highlighting a growing yet underexplored interest in HCI-focused research on DTs. It also points to the emergence of diverse technological approaches across both commercial and academic domains to LDRs. As illustrated in Figure 1, these include communication technologies, social media platforms, wearable and tangible interfaces, XR and immersive telepresence, and AI-based companions, all of which aim to address the complex challenges of LDRs, including emotional expression, physical presence, technological asymmetry and asymmetry, temporal constraints, and contextual awareness.

4.1. Publication trend on DTs for HCI

The number of publications on DT has seen exponential growth, particularly from 2017 onwards, as shown in Figure 2. The early years (2014-2016) had minimal research activity, but starting in 2017, the publications increased significantly, reaching over 13,750 in 2023. This surge is driven by the broader adoption of DT technology across various industries, including manufacturing and healthcare. However, our review and analysis revealed that research specifically focused on HCI in the context of DT remains significantly limited compared to the broader DT research landscape, highlighting a clear research gap.

4.2. Key technologies in LDRs

Based on the analysis of reviewed publications (60 papers), including both conventional and unconventional approaches to maintaining LDRs, 22 reviewed academic studies emphasise using telepresence and video communication technologies. These solutions enable people in LDRs to maintain a sense of presence through real-time video calls and immersive telepresence devices. Telepresence enhances human interaction in two key ways: through telepresence robots and XR technologies (Fischedick et al. 2023; Yazaki et al. 2023).

Telepresence robots serve as physical proxies, are controlled remotely, and can be involved in shared activities, providing a sense of physical presence and interaction. For example, Boudouraki et al. (2022) revealed how mobile telepresence robots with autonomous capabilities enhance mediated visits in domestic environments. Fitter et al. (2020) identified interpersonal closeness as the primary predictor of telepresence quality rather than robot customisation, highlighting

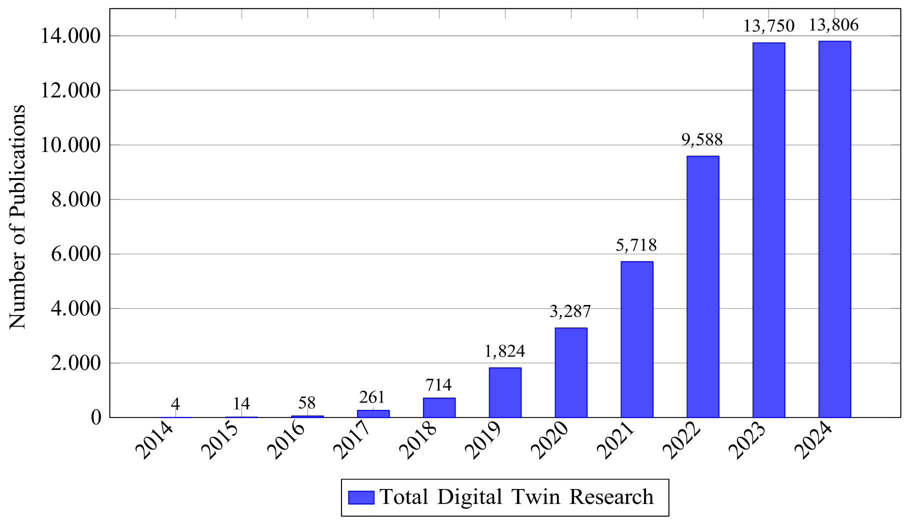

Figure 2. Digital Twin Research (2014 – November 2024).

relationship significance. Seo et al. (2024) showed how telepresence robots foster dynamic, natural family communication by restoring shared routines across generations. XR technologies create immersive environments where users can interact with each other through their environments in shared virtual spaces (Freeman and Acena 2021; Zhang et al. 2021). Also, wearables and sensor-based technologies play a critical role in LDR solutions by collecting real-time data about users' physiological states (e.g. heart rate) (Jarusriboonchai et al. 2020). Haptic and tactile technologies are incorporated into wearable devices to simulate sensations such as a virtual touch, hug, or handshake, which is a critical component in enhancing emotional connection in LDRs (Dziabiola et al. 2022; Tanaka and Fujimoto 2020). Furthermore, Artificial Intelligence (AI)-driven conversational agents that utilise natural language technology to engage users in text-based information search and task-oriented conversations (Lester, Branting, and Mott 2004), like chatbots (Lee et al. 2020), provide asynchronous communication options (interactions not requiring real-time engagement), offering real-time emotional support and sentiment analysis (Zheng et al. 2021). AI algorithms can analyze user communication patterns, tone of voice, and physiological data, helping to interpret emotional states and facilitate deeper emotional connections between people separated geographically (Zimmerman, Janhonen, and Beer 2023).

4.3. Market solutions for LDRs

Based on our academic research and manual exploration of existing solutions on markets, there are a wide variety of technologies and products on markets today designed to address the challenges of LDRs (Table 1). Academic research on LDRs typically emphasises innovative and emerging technologies such as XR (Orts-Escolano et al. 2016; Wang et al. 2023), AI-based companions (Armony and Hazzan 2024; Assuncao et al. 2022), and tangible interfaces that emphasise the physical body and environment in embodied interaction (Marshall 2007), while the commercial marketplace focuses primarily on solutions that are more readily available and widely adopted in communication technologies, social media, and sharing platforms. For example, voice call platforms such as FaceTime ('FaceTime' 2024), Zoom ('Zoom' 2024) and WhatsApp ('WhatsApp' 2024), as well as messaging tools such as Telegram ('Telegram' 2024) and iMessage ('iMessage' 2024), have become staples of LDR because of their immediacy and simplicity. Social media like Facebook ('Facebook' 2024) and Instagram ('Instagram' 2024) have become an integral part of the LDR by providing a space for couples to share their daily lives in an interactive way. Also, advances in AI have fuelled the development of emotional AI tools, such as Grammarly Tone Detector ('Grammarly' 2024) and SwiftKey ('Microsoft SwiftKey' 2024), that adjust communication to better reflect the emotional state of the user. Conversational agents, including chatbots (e.g. Replika ('Replika' 2024)) and virtual assistants (e.g. Alexa ('Amazon Alexa' 2024) and Siri ('Siri' 2024)), can provide companionship and interactive conversations that offer emotional support to individuals in LDRs.

4.4. Academic studies for LDRs

The reviewed studies, as previously shown in Figure 1, predominantly focus on physical presence and the

Table 1. Market Solutions for Long-Distance Relationships with Real-Life Scenarios.

Category	Subcategory	Solution	Real-Life Scenario
Communication Technologies	Smartphones and Video Calls	FaceTime ('FaceTime', 2024), Zoom ('Zoom', 2024), Skype ('Skype', 2024), WhatsApp ('WhatsApp', 2024)	Used for regular video Calls to maintain visual interaction
	Messaging Platforms	Telegram ('Telegram', 2024), iMessage ('iMessage', 2024)	Enables instant updates and photo sharing
	Email Communication	Gmail ('Gmail', 2024), Outlook ('Microsoft Outlook', 2024)	Used for detailed or formal updates with attachments
Social Media and Media-Sharing Platforms	Social Media	Facebook ('Facebook', 2024), Instagram ('Instagram', 2024), X ('X (formerly Twitter)', 2024), LinkedIn ('LinkedIn', 2024), TikTok ('TikTok', 2024)	Helps share updates and interact publicly
	Media Sharing Applications	Snapchat ('Snapchat', 2024), Cupla ('Cupla', 2024)	Facilitates sharing of multimedia and voice messages
Wearable and Tangible Interfaces	Wearable Devices	Apple Watch ('Apple Watch', 2024)	Tracks and shares activity or health updates Sends tactile signals like vibrations for connection
	Tangible Interfaces	Bond Touch ('Bond Touch', 2024), Touch Ring ('TheTouch X', 2024)	
Extended Reality (XR) and Immersive Telepresence	XR	VRChat ('VRChat', 2024), Rec Room ('Rec Room', 2024), Microsoft Mesh ('Microsoft Mesh', 2024), Meta Horizon ('Meta Horizon Worlds', 2024)	Creates virtual spaces for interactive activities
	Telepresence Robots	Double Robotics, OhmniLabs (physical presence simulation) ('OhmniLabs', 2024)	Provides a physical presence through remote robotics
Artificial Intelligence (AI)-Based Companions	Emotional AI Generators	SwiftKey ('Microsoft SwiftKey', 2024), Grammarly Tone Detector (emotionally adaptive responses) ('Grammarly', 2024)	Supports drafting adaptive and emotionally resonant messages
	Conversational Agents	Chatbots: Replika ('Replika', 2024) Virtual Assistants: Alexa ('Amazon Alexa', 2024), Siri ('Siri', 2024), Google Assistant	Offers conversational interaction during offline, and simplifies shared tasks and reminders

explicit and implicit emotional expressions in LDRs, utilising a range of technologies such as smartphones (Kasahara and Rekimoto 2014), video calls (Massimi and Neustaedter 2014), XR systems (Maddali and Lazar 2023), and telepresence robots (Seo et al. 2024). These technologies prioritise replicating physical closeness, fostering a shared sense of 'being there,' and facilitating shared daily activities. In addition to addressing basic barriers, some research has shifted toward improving the quality of connections through contextual information in remote communication, such as augmenting shared experiences with live maps and secondary video streams (Kim, Junuzovic, and Inkpen 2014), embedding social and emotional context in XR reconstructions (Maddali and Lazar 2023), enabling real-time, context-aware AR interactions between remote users (Surale et al. 2022), and studying temporal constraints caused by different time zones (Heshmat et al. 2017, 2020). For example, AR system was designed to provide contextually relevant and personalised content, thereby interpreting the receiver's environment and projecting meaningful AR elements to enhance the feeling of togetherness and shared experience in LDRs (Surale et al. 2022). Regarding temporal constraints, asynchronous systems allow users to send and receive messages without requiring simultaneous availability, addressing the common challenge of mismatched schedules in different time zones (Heshmat et al. 2020). Two studies specifically investigated technological asymmetry (Nanda, Maddali, and Lazar 2022) and symmetry (Yazaki et al. 2023). For instance, for asymmetric experiences where multiple users use different computational devices to interact (Grandi, Debarba, and Maciel 2019), different users, such as older adults and younger participants, utilise varying degrees of immersion and sensory engagement during shared gardening activities in intergenerational interactions (Nanda, Maddali, and Lazar 2022). Conversely, in symmetric experiences (all users have equal roles and capabilities in sharing their environments and experiences), a wearable telepresence system enables multiple users to explore their own environments while simultaneously sharing and interacting with others' environments (Yazaki et al. 2023).

4.4.1. Communication technologies

Traditional solutions primarily centred on *smartphones and video calls* have dominated the landscape of academic research. Traditional video-mediated communication was explored for LDRs (Massimi and Neustaedter 2014; Neustaedter et al. 2015), particularly during significant life events and daily interactions, such as weddings and family gatherings (Massimi and Neustaedter 2014), contributes significantly to emotional closeness and ambient awareness between partners. However, past studies suggested that while current technologies offer valuable means of connection, there remains a notable gap between virtual and physical co-presence, highlighting the need for more sophisticated technological solutions to better approximate the richness of in-person experiences.

In response to these challenges, recent studies have investigated enhancements to traditional video call experiences using first-person (Pan et al. 2017) and 360-degree perspectives (Tang et al. 2017) for long-distance people, allowing them to share real-time experiences from their own perspectives. Besides using 360-degree video communication, comprehensive spatial awareness and environmental context were underscored through shared geographic and physical activities to create a strong sense of shared experience during video streaming (Baishya and Neustaedter 2017; Gan, Greiffenhagen, and Reeves 2020; Procyk et al. 2014).

Beyond traditional camera-based video call solutions, LDR solutions integrated additional modalities, such as projector-combined mixed-reality environments (Kim, Junuzovic, and Inkpen 2014) and third-party involvement (Gan, Greiffenhagen, and Reeves 2020), significantly enhancing connectedness and the sense of presence during shared mobile experiences. Robot-mediated haptic feedback, including finger movements and temperature consistency during video calls, effectively strengthened spatial sharing and emotional bonding (Tanaka et al. 2021). Similarly, transparent head-mounted displays and head-mounted cameras enhanced spatial context understanding and enabled detailed interaction, particularly in tasks requiring shared spatial awareness, such as guidance and collaborative activities (Kasahara and Rekimoto 2014).

Overall, communication solutions for LDRs have evolved from basic smartphone and video call technologies to more sophisticated approaches, including first-person and 360-degree video experiences (Table 2). These advancements have further progressed to incorporate mixed-reality environments, robot-mediated haptic feedback, and transparent head-mounted displays, collectively striving to bridge the gap between virtual and physical co-presence.

4.4.2. Social media and media-sharing platforms

While commercial platforms such as *social media apps* (e.g. Facebook ('Facebook' 2024), Instagram ('Instagram' 2024)) and *media-sharing platforms* (e.g. WhatsApp ('WhatsApp' 2024)) have seen widespread use in facilitating communication for LDRs in markets, academic research in this domain remains relatively sparse. A key theme emerging from recent research is the emphasis on creating shared experiences, including lasting shared emotional experiences and engaging users in shared activities rather than simply information exchange (Wei et al. 2019; Xu et al. 2024).

Another key solution shifts away from the constraints of synchronous communication (real-time interaction) to asynchronous sharing. In recent studies, by allowing partners to engage in parallel activities and then share their experiences through media artifacts like audio recordings or photos, asynchronous audio sharing offered a personalised, flexible alternative to synchronous communication methods like video calls, which may not always be feasible due to conflicting schedules due to geographical distance (Heshmat et al. 2017; Wei et al. 2019).

Overall, compared to the other types of LDR research, studies focusing on social media and media-sharing platforms are relatively sparse, as shown in Table 3, likely reflecting the maturity and widespread adoption of commercial applications in this domain. Academic research has primarily focused on asynchronous communication, emphasising their flexibility and ability to support diverse content sharing, such as audio recordings and photos. These ways cater to the

Table 2. Communication Technologies for Long-Distance Relationships.

Category	Subcategory	Reference	Solution Approach	Research Purpose
Communication Technologies	Smartphones and Video Calls	(Kasahara and Rekimoto 2014)	First-Person and Out-of-Body View Systems	PP
		(Kim, Junuzovic, and Inkpen 2014)	Contextual Mobile Shared Experiences During Outdoor Activities	CA
		(Massimi and Neustaedter 2014)	Video Chat for Life Events	PP
		(Procyk et al. 2014)	Shared Geocaching Over a Distance Using Mobile Video Chat	PP
		(Neustaedter et al. 2015)	The Long-Term Video Connection Systems	PP
		(Baishya and Neustaedter 2017)	Always-On Video and Audio Streaming Technologies	PP
		(Pan et al. 2017)	First-Person View Video Streaming 360° Video Chat	PP
		(Tang et al. 2017)		PP
		(Gan, Greiffenhagen, and Reeves 2020)	Three-Party Mobile Video Calls	PP
		(Tanaka et al. 2021)	Robot-Mediated Handholding with Video	PP

Abbreviations: Emotional Expression (EE); Physical Presence (PP); Technological Asymmetry (TA); Technological Symmetry (TS); Temporal Constraints (TC); Contextual Awareness (CA).

Table 3. Social Media and Media-Sharing Platforms for Long-Distance Relationships.

Category	Subcategory	Reference	Solution Approach	Research Purpose
Social Media and Sharing Platforms	Social Media and Sharing Platforms	(Heshmat et al. 2017)	Asynchronous Media Sharing	TC
		(Wei et al. 2019)	App Tangibly Interactive Desktop	EE
		(Xu et al. 2024)	Device Collaborative Planting System (Hardware and App)	PP

Abbreviations: Emotional Expression (EE); Physical Presence (PP); Technological Asymmetry (TA); Technological Symmetry (TS); Temporal Constraints (TC); Contextual Awareness (CA).

challenges of conflicting schedules and geographical distances, providing a personalised alternative to synchronous communication.

4.4.3. Wearable and tangible interfaces

Current wearable and tangible solutions are designed to serve as intimate, lightweight communication channels, leveraging these items' symbolic and emotional significance. Such implicit solutions aimed to increase mutual awareness of a person's presence or activities (Ambe et al. 2022; Brereton et al. 2015) through symmetric interactions where both people experience the same type of feedback or interaction. Compared to tangible interface solutions, the results show that fewer studies have focused on *wearable devices*. The most commonly explored wearable devices are accessories like rings and bracelets (Jarusriboonchai et al. 2020; Li et al. 2020; Pradana et al. 2014; Tanaka and Fujimoto 2020). In addition, one research developed Flexi Card Game (FCG) (Li et al. 2021), a card- based design toolkit to bridge the gap in conventional communication tools that often lack emotional expressiveness and user participation in design focused on unconventional communication systems.

Tangible interfaces rely heavily on movable or semi-fixed objects. These devices are typically integrated into everyday items such as cups (Tanaka and Fujimoto 2024), kettles (Ambe et al. 2022; Brereton et al. 2015), lights (Gaver and Gaver 2023; Li 2018; Yu, Inakage, and Ueki 2021), picture frames (Li, Muller, and Hakkila 2020), portable audio storytelling devices (Heshmat et al. 2020; Wallbaum et al. 2018) and even with robots (Chien, Hassenzahl, and Welge 2016; Nakanishi, Tanaka, and Wada 2014), allowing flexibility and ease of use within domestic environments.

Various input and output modalities were used for these devices, which were designed to support symmetric interactions, allowing different users to use the same computational devices (Grandi, Debarba, and Maciel 2019). For input, touch-based methods are widely used and encompass several forms of tactile interaction to emphasise subtle, implicit and aesthetic emotional expressions in LDRs. Actions like squeezing (Pradana et al. 2014) and tapping (Dziabiola et al. 2022) were commonly implemented due to their intuitive nature and ease of execution to support natural and easy-to-execute gestures, resulting in heightened emotional engagement, improved communication, and greater intimacy, particularly when verbal channels fall short (Cheok 2020; Yu, Inakage, and Ueki 2021). Beyond touch, non-contact methods have also been employed (Gaver and Gaver 2023), often utilising gesture recognition and mid-air interactions to provide more versatile input options. Object manipulation and movement (Brereton et al. 2015) and speech (Heshmat et al. 2020) are other important input types that offer a natural and convenient way for remote users to interact, further facilitating seamless communication.

On the output side, vibrotactile sensations are a common output modality used to simulate physical touch and convey emotional cues (Dziabiola et al. 2022; Pradana et al. 2014). Other output modalities, including visual displays (Gaver and Gaver 2023; Li, Muller, and Hakkila 2020), haptic feedback (Cheok 2020), sound (Heshmat et al. 2020), and shape-changing and object movement (Yu, Inakage, and Ueki 2021; Zhang et al. 2024) often provide immediate visual feedback and information to help users (e.g. parents and their adult children) better interpret and respond to remote communication.

Overall, wearable and tangible interfaces for LDR studies (Table 4) serve as lightweight, context- aware, and emotionally meaningful communication tools designed to enhance mutual awareness and interaction. Wearable devices, often designed as accessories, enable seamless and symmetric interactions. Meanwhile, tangible interfaces embed technology into everyday objects, such as picture frames, kettles, and storytelling devices, prioritising flexibility and ease of use, particularly in domestic settings.

4.4.4. XR and immersive telepresence

For *XR*, high-fidelity 3D reconstructions of avatars and meaningful environments that integrate 3D scanning technologies and telepresence, haptic feedback can facilitate meaningful remote interactions such as hugs

Table 4. Wearable and Tangible Interfaces for Long-Distance Relationships.

Category	Subcategory	Reference	Solution Approach	Research Purpose
Wearable and Tangible Interfaces	Wearable Devices	(Pradana et al. 2014)	Ring-Shaped Wearable Devices	EE
		(Jarusriboonchai et al. 2020)	Wearable Ambient Displays	EE
		(Li et al. 2020)	Vocabulary Wearable Displays	EE
		(Tanaka and Fujimoto 2020)	Heartbeat-Transmitting App	EE
		(Li et al. 2021)	Flexi Card Game (Participatory	EE
		(Dziabiola et al. 2022)	Toolkit) Vibro-Tactile Wearable + App	EE
	Tangible Interfaces	(Nakanishi, Tanaka, and Wada 2014)	Haptic-Enhanced Videoconferencing	PP
		(Brereton et al. 2015)	Messaging Kettle	EE
		(Chien, Hassenzahl, and Welge 2016)	Robotic Pet	EE
		(Wallbaum et al. 2018)	Tangible Storytelling System	EE
		(Li 2018)	Connected Candles	EE
		(Heshmat et al. 2020)	Asynchronous Audio Storytelling System	TC
		(Cheok 2020)	Haptic Communication Device for Smartphones (Kissenger)	EE
		(Li et al. 2020)	Electrochromic Ambient Display (Interactive Picture Frame)	EE
		(Yu, Inakage, and Ueki 2021)	Nostalgia-Based Designs	EE
		(Ambe et al. 2022)	Messaging Kettle	EE
		(Gaver and Gaver 2023)	Light Touch	EE
		(Zhang et al. 2024)	Augmented Everyday Object (WhisperCup)	EE

Abbreviations: Emotional Expression (EE); Physical Presence (PP); Technological Asymmetry (TA); Technological Symmetry (TS); Temporal Constraints (TC); Contextual Awareness (CA).

over a distance, family caregiving and shared family events (Cohen et al. 2017; Yazaki et al. 2023). Real-time 3D telepresence system (Holoportation) captured high-quality 3D models of people and their environments, enabling immersive interactions through AR/VR displays (Orts-Escolano et al. 2016). Through XR system settings, asymmetry experiences (Nanda, Maddali, and Lazar 2022), and cross-platform and multi-agency spaces (Zhang et al. 2021) cater to different user (e.g. intergenerational interactions) preferences and comfort levels, enhancing spatial cognition (Keil et al. 2020) and ensuring a balanced experience. Such settings like ARcall even allowed users to share an immersive experience by projecting AR content directly into the wearer's field of view (Surale et al. 2022).

In contrast to the other XR solutions on high visual fidelity, *social VR* prioritises enhancing social and emotional interaction experiences through embodied physical interactions, sense of co-presence and replication of real-life activities (Zamanifard and Freeman 2019). First, it enables embodied physical interactions through advanced features like full-body tracking and precise avatar control, allowing users to engage in natural gestures such as holding hands and embracing (Freeman and Acena 2021). Second, the integration of spatial mapping (Sra, Mottelson, and Maes 2018) and synchronised interactions (Wang et al. 2023) create shared virtual spaces where people can participate in emotional moments together. Finally, these technological features collectively foster a strong sense of co-presence-the feeling of being together despite physical separation. When combined with real-life activity simulations and real-life activities (e.g. watching movies or virtual dancing) (Sra, Mottelson, and Maes 2018), they create a spatial and temporal experience that closely mirrors authentic social interactions (Freeman and Acena 2021; Wang et al. 2023).

Unlike traditional communication tools like video calls, *telepresence robots* allow users to simulate being physically present, significantly enhancing the feeling of togetherness during daily interactions (Kratz et al. 2014). Many studies have emphasised the ability of telepresence robots to create a stronger sense of presence for remote users through physical embodiment, like supporting everyday mediated visits and spontaneous social interactions (Boudouraki et al. 2022), articulating key design dimensions to enhance presence (Rae et al. 2015), fostering emotional closeness through autonomous movement and embodied communication (Yang, Neustaedter, and Schiphorst 2017). They have also supported richer emotional exchanges which are often limited by traditional video chat tools (Fitter et al. 2020) and facilitated remote participation in household tasks, outdoor activities, and family routines (e.g. cooking, shopping, or simply providing quiet companionship) (Heshmat et al. 2018; Seo et al. 2024; Heshmat et al. 2018).

Building upon these basic capabilities, the integration of telepresence robots with smart home devices has further showcased how such a combination could enhance the remote user's ability to participate in household activities. By allowing remote control of

Table 5. XR and Immersive Telepresence for Long-Distance Relationships.

Category	Subcategory	Reference	Solution Approach	Research Purpose
XR and Immersive Telepresence	XR	(Orts-Escolano et al. 2016)	Holoportation (Immersive 3D Telepresence)	PP
		(Cohen et al. 2017)	3D Communication Tools with Haptic Devices	PP
		(Sra, Mottelson, and Maes 2018)	Shared VR Spaces Mapping	PP
		(Zamanifard and Freeman 2019)	Embodied Interactions in Social VR	PP
		(Keil et al. 2020)	AR-Based Holographic Grids for Spatial Cognition	PP
		(Freeman and Acena 2021)	Social VR	PP
		(Zhang et al. 2021)	AR/VR Telepresence System	PP
		(Surale et al. 2022)	Real-Time AR Communication System	CA
		(Nanda, Maddali, and Lazar 2022)	Social XR Prototypes	TA
		(Maddali and Lazar 2023)	XR Reconstructions of Meaningful Spaces	CA
		(Wang et al. 2023)	Loving-Kindness Meditation in	PP
		(Yazaki et al. 2023)	Symmetric Wearable Telepresence System	TS
	Telepresence Robots	(Kratz et al. 2014)	Wearable Telepresence Device	PP
		(Misawa and Rekimoto 2015)	Human Surrogate Telepresence	PP
		(Rae et al. 2015)	Design Framework for Telepresence	PP
		(Yang, Neustaedter, and Schiphorst 2017)	Telepresence Robot for Naturalistic Interaction	PP
		(Heshmat et al. 2018)	Outdoor Telepresence Robots with 360° Viewing Telepresence Robots for	PP
		(Yang & Neustaedter, 2018)	Mundane Routines, Companionship, and Partner Interaction	PP
		(Yang et al., 2018)	Telepresence Robots for Shopping Activities	PP
		(Fitter et al. 2020)	Telepresence Robots with Personalisation	PP
		(Yang and Neustaedter 2020)	Combining Telepresence Robots with Smart Home Tools	PP
		(Boudouraki et al. 2022)	Mobile Robotic Telepresence	PP
		(Fischedick et al. 2023)	Collaborative Telepresence Robot	PP
		(Seo et al. 2024)	Telepresence Robots for Family	PP

Abbreviations: Emotional Expression (EE); Physical Presence (PP); Technological Asymmetry (TA); Technological Symmetry (TS); Temporal Constraints (TC); Contextual Awareness (CA).

appliances through voice commands, the setup created a more immersive shared home experience (Yang and Neustaedter 2020). Taking this integration a step further, a recent study demonstrated how a collaborative telepresence approach allowed remote users not only to navigate the space but also to interact directly with objects using advanced visualisation and control features, such as highlighting items with a projector (Fischedick et al. 2023).

Beyond the functional aspects, research has revealed the profound impact of telepresence robots on emotional connections and relationship dynamics. The use of body language and the spontaneous nature of 'surprise visits' through the robot, such as moving closer or further away, enabled couples to express emotional states like affection or displeasure, playing a critical role in conflict resolution, naturalness and intimacy of interactions (Fitter et al. 2020; Yang, Neustaedter, and Schiphorst 2017).

While telepresence robots offer enhanced presence and interaction, several studies noted issues related to asymmetry of control. The presence of the robot in only one partner's home often leads to an imbalance in the interaction dynamics, with one partner feeling less in control (Yang and Neustaedter 2020). Using a human surrogate to embody the remote user's presence introduces challenges related to appearance discrepancies (Misawa and Rekimoto 2015).

Overall, technological interventions, such as advanced visualisation and interaction modalities for LDRs-ranging from XR to robotic telepresence—provide multifaceted solutions to spatial separation (Table 5). Empirical research reveals the nuanced dynamics of technological mediation, emphasising that effective telepresence requires not just technical sophistication, but also a deep understanding of human relational needs, including the subtleties of body language, spontaneous interactions, and emotional intimacy.

4.4.5. AI-based companions

Current research on AI-based companions in the context of LDRs predominantly focuses on *conversa- tional agents*, including chatbots (Zheng et al. 2021) and virtual assistants (Armony and Hazzan 2024). Chatbots can act as mediators by providing personal and empathetic responses, which is especially useful when physical cues are absent. This mediation enhances relational satisfaction, and users interacting with chatbots are more likely to reveal deeper personal feelings (Lee et al. 2020). In a recent study of chatbots, AI-driven features, such as humour and deep-talk prompts, help couples navigate conflicts and sustain intimate conversations (Zheng et al. 2021). During this process, the integration of emotion recognition capabilities enhances the conversational agents' effectiveness by allowing them to respond

Table 6. AI-based Companions for Long-Distance Relationships.

Category	Subcategory	Reference	Solution Approach	Research Purpose
AI-based Companions	Conversational Agents	(Lee et al. 2020)	Chatbot for Self-Disclosure	EE
		(Zheng et al. 2021)	Chatbot	EE
		(Assuncao et al. 2022)	Emotion-Integrated AI	EE
		(Zimmerman, Janhonen, and Beer 2023)	AI Relational Agents	EE
		(Armony and Hazzan 2024)	AI + VR Integrated Systems	EE

Abbreviations: Emotional Expression (EE); Physical Presence (PP); Technological Asymmetry (TA); Technological Symmetry (TS); Temporal Constraints (TC); Contextual Awareness (CA).

to the user's emotional state through emotion recognition and adaptive responses (Assuncao et al. 2022). Despite the benefits, studies have noticed that the tendency of users to attribute human-like qualities to AI companions can lead to emotional dependency, potentially interfering with real-life human relationships (Zimmerman, Janhonen, and Beer 2023).

In summary, AI-based LDR companions are becoming innovative conversational tools with a focus on conversational agents (e.g. chatbots) that increase relationship satisfaction through empathic responses, humour, and deep conversational cues (Table 6). Emotion recognition capabilities further improve their effectiveness through adaptive responses. However, despite the rise of commercial AI-generated digital replicas like Replica ('Replika' 2024) for companions, no current AI studies involve interactive digital representations of real people to facilitate LDR interactions.

5. Discussion

This section discusses the limitations of DT research within the context of HCI, highlighting the relative immaturity of studies in this domain compared to more established fields, such as manufacturing, where DT concepts are more developed. The section also explores the feasibility of asynchronous interactions based on DT concepts and identifies remaining limitations in existing solutions for supporting LDTs, as derived from the research purposes of the previously reviewed studies. These limitations include restricted emotional expression, the absence of physical presence, technological asymmetry, limited customisation options, temporal constraints, and insufficient integration with contextual awareness.

5.1. DTs in HCI

5.1.1. Limited presence of DT research in HCI

The presence of DT research in HCI is still very limited compared to other fields. This scarcity is mainly due to the fundamental and powerful characteristics of DTs, including precise simulation, predictive modelling, and analytical capabilities (Tao et al. 2022), which have been primarily developed and applied within manufacturing and industrial environments. While these features have demonstrated significant value in industrial applications, they have unintentionally fostered a narrow focus. This constrained perspective may lead to overlooked broader applications, restricted views of phenomena, incomplete data collection, and an insufficient understanding of complex interactions (Vainionpaa et al. 2022). As a result, important perspectives and potential applications, especially in areas such as HCI, may be inadvertently suppressed or ignored, thus preventing a true dialogue between different research areas.

5.1.2. Broadening DT concepts in HCI

Furthermore, current DT research in HCI obscures and broadens DT concepts to include Digital Models and Digital Shadows. It is crucial to distinguish between DTs and the concepts related to Digital Models and Digital Shadows. All these represent different levels of digital representation (Kritzinger et al. 2018), as shown in Figure 3. DTs are systems with bi-directional data flow between physical and digital entities that are able to influence and control each other. Digital Models are digital representations of existing or planned physical objects that may utilise data but lack automated data exchange. Digital Shadows are systems characterised by an automated, unidirectional data flow from physical to digital entities (Kritzinger et al. 2018).

While many publications in HCI claim the application of DTs in their studies, many of them fail to achieve the essential bidirectional data flow that defines a DT and use them conceptually rather than technically. Instead, these studies often rely on predefined models, which more closely resemble Digital Models or Digital Shadows. For instance, although one study labels the VR system a DT, it only partially aligns with DT concepts, incorporating data-driven feedback and simulation optimisation but lacking real-time bi-directional synchronisation and a unique physical counterpart (Kumar, Cecil, and Tetnowski 2024). Another article details a system that integrates AR and VR for collaborative exploration of virtual museums connected to their physical counterparts. However,

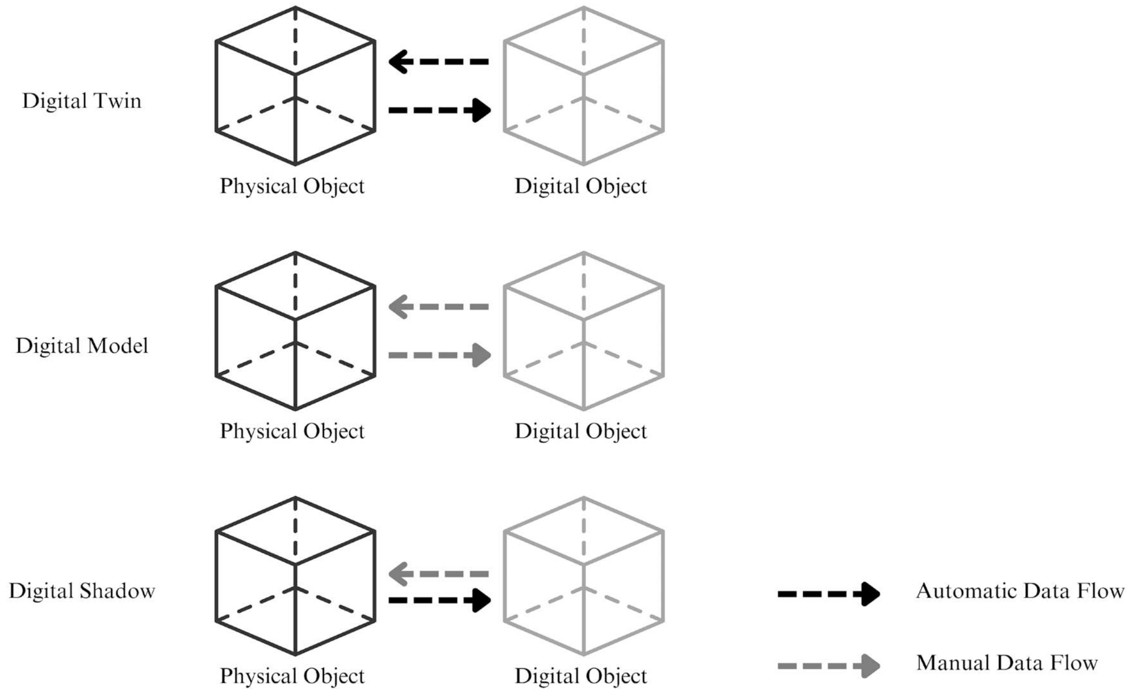

Figure 3. Data Flow in a Digital Twin, a Digital Model and a Digital Shadow (Kritzinger et al. 2018).

due to the lack of real-time synchronisation and two-way interaction, the system is more like a Digital Shadow or augmented virtual model than a true DT (Schott et al. 2023).

If the HCI community adopts broader interpretations of DTs, encompassing Digital Models and Digital Shadows, many studies in HCI can be reclassified under the broader DT umbrella. This is particularly true for XR-based research, such as Holoportation, which involves high-quality, real-time 3D reconstructions of entire spaces (Orts-Escolano et al. 2016), XRmas, an IoT (Internet of Things)- based AR/VR telepresence system (Zhang et al. 2021), and asymmetric intergenerational social interactions (Nanda, Maddali, and Lazar 2022). These studies often focus on enabling remote interactions through virtual systems that mirror physical environments in real-time. However, they do not explicitly reference DT terminology or concepts. This phenomenon reflects the evolving understanding of DT concepts in HCI and the challenge of consistently applying DT terminology across different research areas.

This disconnect stems largely from the diversity of areas of interest in different disciplines. Since DT research in the field of HCI is still in its relative infancy, while establishing a common definition is critical, the diversity of perspectives can also foster innovative approaches to understanding DTs in HCI. In addition, the development of reference models that can meet the needs of specific domains, as well as the integration of currently isolated research efforts, are critical next steps in the development of the field.

5.1.3. Asynchronous interaction in DTs

Asynchronous interactions are widely used to maintain LDRs, especially when time differences make synchronous (real-time) communication challenging. At first glance, this seems like a paradox, especially when considered in conjunction with DT implementations, which emphasise real-time, bi-directional data flow. When discussing asynchronous interactions, generative videos, such as Heygen (Morales-Chan, Amado-Salvatierra, and Hernandez-Rizzardini 2023), an AI-powered platform designed for asynchronous video communications. It allows users to create lifelike, prerecorded video avatars that give recipients a sense of presence despite the time difference. This approach helps to enhance the communication experience without the need for simultaneous usability. From a DT perspective, systems like Heygen can be interpreted in two ways: either aligning with broader DT views in HCI or resembling Digital Models and Digital Shadows, as they primarily involve a unidirectional data stream rather than the dynamic real-time feedback loops typical of DT.

However, asynchronous interactions can still align with DTs for LDRs. While traditional DT applications in manufacturing or industrial environments require synchronised data exchange, social interactions of LDRs in DTs operate on a different time scale. In

LDRs, we argue that the bi-directional data flow can be maintained even in asynchronous communication. In asynchronous communication, the physical entities and their digital representations are constantly updated in response to new interactions and data, thus maintaining the essential two-way relationship that characterises DT. Also, while interactions may not occur simultaneously, both physical and digital entities remain synchronised over time, thus maintaining the basic DT requirement of bilateral influence. In addition, deliberate asynchronous communication in LDR is an effective form of bi-directional data flow where both entities are actively involved in exchanging information and influencing each other's state.

5.2 Limitations of current LDR solutions

5.2.1. Emotional expression

Current solutions do not fully integrate the physical aspects of co-presence (e.g. telepresence robots) with the emotional aspects (e.g. AI agents) (Ploderer et al. 2025). Studies primarily facilitate the exchange of explicit information and struggle to convey the subtle emotional and nonverbal cues necessary for intimacy (Li 2018). While video-based methods (Neustaedter et al. 2015) provide a visual connection and wearables or tangible interfaces (Cheok 2020) strive to replicate the touch and implicit expression, they often fail to capture the full emotional spectrum, as well as the nuanced context and environment factors. Even state-of-the-art solutions (e.g. XR and immersive telepresence) that attempt to simulate physical intimacy through haptic feedback mechanisms or other sensory stimuli often produce experiences that users perceive as artificial, ultimately failing to establish authentic emotional resonance.

5.2.2. Physical presence

In addressing the challenges of LDRs, most current research focuses on overcoming the barriers of physical separation (Zamanifard and Freeman 2019). Various methods, such as video calls (Tang et al. 2017), VR co-presence (Orts-Escolano et al. 2016) and conversational agents (Lee et al. 2020), have been developed to facilitate communication and connection between separated individuals. However, the most direct and effective solution for LDRs would be to create the possibility of physical co-presence, allowing individuals to interact as if they were truly together. Despite advancements in technology surrounded by VR, like holographic displays (Chae et al. 2023) and co-presence solutions, even with other peripherals (e.g. haptic feedback) (Cohen et al. 2017), existing systems still struggle to replicate the natural experience of physical presence. These technologies typically address isolated instances of physical interaction (e.g. simulated hugs or touches) rather than integrating seamlessly into the continuous, everyday activities of relationship maintenance (Zamanifard and Freeman 2019). This fragmented approach fails to capture the ongoing, dynamic nature of the relationships.

5.2.3. Technological asymmetry and customisation

Asymmetric communication preferences and capabilities, particularly evident in intergenerational relationships, pose significant challenges due to differences in communication styles and technological comfort levels —for example, older people may prefer synchronised, longer conversations, while younger users tend to prefer intermittent, asynchronous communication (Wallbaum et al. 2018). Also, telepresence robots, despite enhancing physical embodiment, introduce asymmetric interaction dynamics when present in only one user's environment (Yang and Neustaedter 2020). These asymmetries can lead to unbalanced experiences and interaction limitations between users. Therefore, the need to personalise technologies to meet individuals' unique needs and preferences in LDRs is crucial. One-size-fits-all solutions may not adequately address the diverse challenges faced by LDR people (Jarusriboonchai et al. 2020; Li 2018).

5.2.4. Temporal constraints

Traditional communication technologies, although widely available, are severely constrained by the time factor. While very common, video-mediated communication requires synchronised availability between users in different time zones (Massimi and Neustaedter 2014). This requirement tends to hinder spontaneous interactions and natural relationship dynamics. While asynchronous modes of communication, such as social media and messaging platforms, attempt to address this limitation, they tend to result in delayed affective feedback and reduced quality of interaction (Wei et al. 2019). Also, time zone differences complicate synchronised interactions.

5.2.5. Contextual awareness

Although recent research has explored integrating IoT devices and AI-based companions with emotional response generators to enhance ambient awareness (Ambe et al. 2022), current studies still demonstrate limitations in emotional depth and context awareness (Zheng et al. 2021). Most existing solutions operate in isolation rather than as integrated systems capable of understanding and adapting to the relational context, like emotional nuances or environmental presence (Neustaedter et al. 2015), and lack contextual depth (Jarusriboonchai et al. 2020). Although XR and telepresence robots are powerful in integrating context, they often lack personalisation, and their interactions feel more task-oriented than relational. Also, existing solutions often ignore the diverse needs of remote interaction in different cultural and social contexts. These limitations are particular for the lack of seamless integration with daily activities, inadequate understanding of the environmental and social context, limited ability to adapt to changing relationship dynamics and poor integration between different modes of communication (Maddali and Lazar 2023; Mason and Carr 2022; Zamanifard and Freeman 2019).

6. HDT in LDRs

This section explores the envisioned HDTs in the context of LDRs, categorising their impact on microscopic (individual) and macroscopic (dyadic) levels. It envisions how HDTs can model and enhance personal emotional states, behavioural patterns, and adaptive learning at the individual level while optimising communication patterns, shared activities and contextual integration at the dyadic level. It also gives examples of scenarios leveraging Ihde's relation framework (Human-Technology-World relationship) (Ihde 1990) to illustrate how HDTs mediate and transform LDR interactions through innovative configurations and immersive experiences.

6.1. Envisioned HDTs for LDRs

Humans can be conceptualised as microscale, mesoscale, and macroscale entities in the physical world, which are mapped to their DT representations in the virtual realm (Lv et al. 2022). These mappings integrate tangible elements with social dynamics, such as interpersonal relationships (Lv et al. 2022). Furthermore, these entities exhibit evolving adaptability and learning potential over time (Katsoulakis et al. 2024). Building on the concepts from these studies and the reviewed papers, along with their identified limitations as previously discussed, this section provides a basis for further exploration of HDT in LDRs. Specifically, we categorised HDTs into microscopic (individual) and macroscopic (dyadic) levels in the context of LDRs (Figure 4). At a microscopic level, HDTs focus on modelling personal behaviour, emotions and patterns at the individual level according to the data from their physical entities. This provides a detailed understanding of personal dynamics and targeted recommendations to promote connection and harmony in LDRs. At the macroscopic level, the HDTs go beyond individual representations and are able to capture the intricate

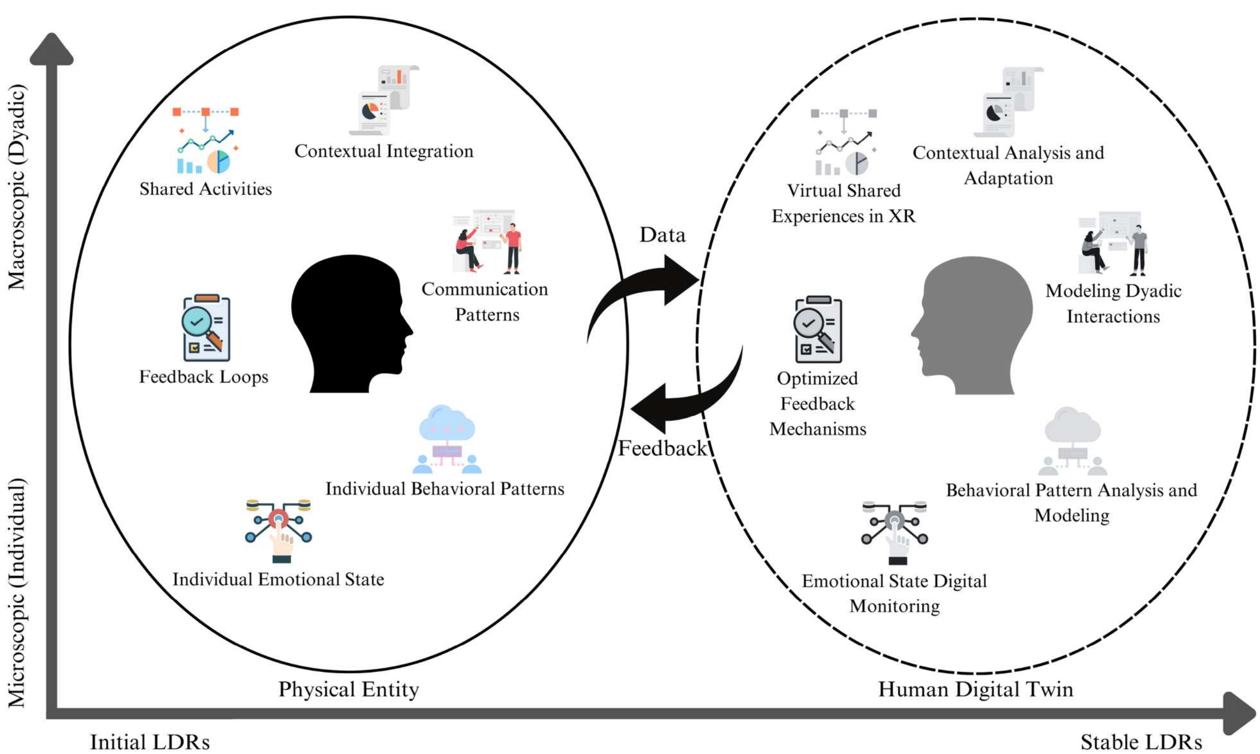

Figure 4. Envisioned Human Digital Twin for Long-Distance Relationships.

dynamics between humans in LDRs. This level focuses on modelling and optimising two-way interactions, shared activities and contextual integration.

6.1.1. Microscopic (Individual) levels

6.1.1.1. Sentiment and emotional states. As LDR people often lack access to physical cues like body language and touch, HDT can integrate real-time emotional expression data such as voice tone, facial micro-expressions, and verbal emotions in messages to provide a more accurate representation of a person's emotional state. Additionally, physiological metrics such as heart rate variability, sleep patterns, and stress markers provide insight into the emotional context (Dias De Oliveira, Khanshan, and Van Gorp 2023), thereby bridging the gap between explicit communication and implicit emotional presence. By synthesising these data points, DTs allow LDR individuals to perceive and respond to each other's emotional states in a more authentic and emotionally resonant way, thus facilitating deeper connection and intimacy despite physical separation.

6.1.1.2. Individual behavioural patterns. Understanding individual behavioural patterns can be effective communication in the context of LDRs (Jiang 2022; Zebua and Kartikawati 2023). HDTs can analyze an individual's schedule of activities, communication preferences (e.g. response times or preferred styles) and personal habits to identify patterns that affect relationship stability. For example, communication preferences and temporal patterns can be carefully mapped to create detailed profiles of individual interaction styles. This behavioural mapping extends to activity schedules and personal habits, enabling HDTs to analyze and predict how individuals organise their daily lives. By identifying patterns and meaningful routines, HDTs can provide insights into optimal times and methods of communication, helping geographically dispersed individuals maintain meaningful connections and enhancing relationship stability across physical distances.

6.1.1.3. Feedback loops and adaptive learning. HDTs can be adaptive in learning from past interactions and optimising responses (Bolender et al. 2021). By analyzing the dynamics of past exchanges, HDTs can suggest improved ways to handle disagreements or facilitate meaningful conversations. These feedback loops ensure that HDTs evolve in parallel with the relationship, continually improving its effectiveness.

6.1.2. Macroscopic (Dyadic) levels

6.1.2.1. Communication patterns. Based on every individual pattern data from the microscopic level, dyadic data from the interplay of individual behaviours would be encompassed. The macroscopic view synthesises data from both individuals to model and optimise communication dynamics and relationships across the LDR. The HDTs analyze two-way interactions' frequency, quality, and contextual patterns while considering external factors such as time zones, availability overlap, and shared relationship goals.

6.1.2.2. Virtual-shared activities and events. As aforementioned, current solutions often fail to replicate the sense of co-presence needed for meaningful interaction. By combining HDTs with XR technologies and their peripheral devices, these experiences can be enhanced to create much more immersive environments and personalised interactions that transcend physical boundaries. Additionally, HDTs can integrate personalised personal and dyadic data (e.g. behavioural patterns, preferences, and past interactions) to craft customised virtual environments, interaction models and physical needs. Furthermore, asynchronous interactions due to different time zones or conflicting schedules for LDRs can be more effective in HDTs. HDTs can store and process interaction data, allowing one party to leave meaningful input, such as recorded virtual avatars, messages, virtual notes, or interaction content, in the shared XR space for the other party to experience later. This truly asynchronous form of interaction mimics the occasion of co-presence and interaction, even if both parties are not present simultaneously.

6.1.2.3. Contextual integration. Context awareness in DTs can be adapted to environmental changes and unpredictable events (Ma, Qi, and Tao 2024). External factors such as cultural, environmental and social factors often determine the context of LDRs. By incorporating these variables, HDTs can provide a comprehensive understanding of their impact. For example, cultural backgrounds may influence communication styles, and then HDTs can mediate cultural differences in expression and interpretation. This integration ensures that digital representations capture not only individual and two-person behaviours but also the broader context of relationships.

6.2. HDT scenarios in LDRs

For HDT technologies-based possibilities in LDRs, such technologies can be understood as mediators of remote human interactions and experiences. Human-

Table 7. Ihde's Relational Framework (Ihde 1990).

Relation Type	Arrow Representation	General Example
Embodiment	Human → (Technology) → World	Glasses extending vision
Hermeneutic	Human → Technology → (World)	Thermometer interpreting temperature
Alterity	Human ↔ Technology	Chatbot interacting with the user
Background	(Technology) → Human + World	Smart home system adjusting lighting

Table 8. Examples of Human Digital Twin Configurations in Long-Distance Relationships.

Configuration	Scenario	Use Case
H1 → HDT1 → H2 or H2 → HDT2 → H1	Sensory-Based Immersive Telepresence	HDTs transmit real-time biometrics (e.g. heartbeat) and enable interaction through avatars in XR (AR/VR), allowing virtual experiences of each other's spaces and activities.
H1 → (HDT1 → H2) or H2 → (HDT2 → H1)	Past Asynchronous Communication	HDTs send pre-recorded immersive experiences, including emotions and sensory data, allowing recipients to experience past events as if present.
(H1 → HDT1) → H2 or (H2 → HDT2) → H1	Task Management or Skill-Sharing	HDTs replicate expertise, offering personalised resources or teaching skills remotely.
H1 → (HDT2 → H2) or H2 → (HDT1 → H1)	Adaptive and Simplifying Interactions	HDTs analyze emotional states, offering timely emotional support and improved communication.
H1 → HDT1 → HDT2 → H2 or H2 → HDT2 → HDT1 → H1	Collaborative Virtual Worlds	HDTs build shared interactive virtual spaces for joint activities, adapting environments based on preferences.
(H1 → HDT2) → HDT1 → H2 or (H2 → HDT1) → HDT2 → H1	Now/Future Asynchronous Communication	HDTs facilitate offline communication, allowing creation of personalised experiences or event planning through interactive simulations.
(H1 → HDT2) → (HDT1 → H2) or (H2 → HDT1) → (HDT2 → H1)	Adaptive and Learning Relationships	HDTs evolve through past interactions, becoming more personalised and responsive, deepening connections.

Technology-World relation frameworks proposed by Ihde (Ihde 1990) (Table 7), which emphasises the relational and experiential aspects of technology, offers a deeper analytical perspective on how these technologies can actively shape human perception, interaction and remote connection. By applying this framework, Table 8 discusses some potential examples of HDT-based scenarios, focusing on the LDRs between two humans (H1 and H2) and their HDTs (HDT1 and HDT2). Ihde's research emphasised how technology mediates our experiences, perceptions, and interactions with the world and identified four main types of Human-Technology-World relationships, each of which describes a different way in which technology interacts with and influences human activity. For instance, in an embodied relationship, technology becomes an extension of the human body, perfectly integrated with the human experience (Ihde 1990). It is like a 'disappearing' tool through which the user engages directly with the world (Kocaballi, Gemeinboeck, and Saunders 2010). Building on Ihde's relation framework, HDTs in LDRs can mediate interactions in various ways. From enhancing a sense of co-presence through virtual environments to interpreting affective states through real-time data, HDTs reshape the dynamics of relationships between people in the LDR by acting as various agents. For example, the second configuration of Table 8 realises time-shifted interaction, where the HDT becomes a complex information agent. H1 can record experience or information through HDT1, transmitting it to H2 with contextual improvements. During this process, HDTs can add emotional context and personalisation to messages, and shared experiences can be captured and replayed with even added sensory information. This configuration resolves time zone differences and schedule conflicts in LDRs. Through these potential scenarios, HDTs become agents of change in LDRs. By addressing the challenges of LDRs, such as physical separation and fostering emotional resonance, these scenarios illustrate how HDTs can redefine communication in LDRs compared to the current solutions.

7. Conclusion

Our scoping review identifies a significant research gap: while extensive evidence demonstrates the role of DTs, including their subfield HDTs, in connecting people remotely across various domains, their application in fostering human-centred contexts and interpersonal relationships – particularly in LDRs – remains largely unexplored. To address this, we first searched the four databases through separate search strategies encompassing HCI, DTs and existing research on LDRs. Our results unveiled two critical insights. First, we observed a fragmented understanding of traditional DTs within HCI communities, which has hindered comprehensive DT development in relationship support. Also, this fragmentation has led to an extensive exploration of certain aspects of the field – such as the reliance on Digital Shadows or simplified Digital Models for environmental simulations – resulting in a proliferation of research in these areas. Consequently, other potentially valuable directions, like using DTs with two-way data flow and their applications in fostering human connections, remain marginalised, and even overlooked. Second, we categorised various LDR solutions across commercial and academic domains, identifying the specific types of such solutions and their limitations. Then, we propose an envisioned HDT tailored to the unique challenges of LDRs, which existing technologies fail to adequately address.

Furthermore, we present potential scenarios for integrating HDTs into LDRs to illustrate how they can foster deeper remote human connections and lay the foundation for future research into this promising area.

Author contributions

CRediT: **Qing Li:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing; **A. Baki Kocaballi:** Conceptualization, Methodology, Project administration, Resources, Supervision, Writing – review & editing; **Jaime Garcia:** Conceptualization, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

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