From Trend Analysis to New Virtual World System Design Requirements and Requirement Satisfaction Study

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Abstract Virtual worlds have become global platforms connecting millions of people and containing various technologies. The development of technology, shift of market value, and change of user preference shape the features of virtual worlds. In this paper, we first study the new features of virtual worlds and emergent requirements of system development through trend analysis. Based on the trend analysis, we constructed the new design requirement space. We then discuss the requirement satisfaction of existing virtual world system architectures and highlight their limitations through a literature survey. The comparison of existing system architectures sheds some light on future virtual world system development to match the changing trends of the user market. At the end of this study, we briefly introduce our ongoing study, a new architecture, called Virtual Net, and discuss its possibility in requirement satisfaction and new research challenges.

Keywords: Virtual world, Trend analysis, Design requirement, Distributed architecture
1. Introduction

Virtual worlds have been evolved from simple text-based games to sophisticated three-dimensional graphic environments, covering both game worlds (Dionisio et al., 2013) and social worlds (Fitzpatrick et al., 1996). In this evolution, they have developed some important features such as immersion and persistency (Nevelsteen, 2018). Supported by these features, the growth of virtual worlds has brought millions of people to participate and innovation in many fields, including education, medicine, tourism, commerce, and entertainment. As can be expected, they will play an important role in the future economy and society.

Virtual worlds are global computing infrastructure. They are synthetic, sustainable, and immersive environments, facilitated by computer networks connecting multiple users in the form of avatars, who interact in real-time (Girvan, 2018; Nevelsteen, 2018). Therefore, the evolution of virtual world is closely related to the underlying technologies. Virtual world related technologies, including hardware and network, graphics, artificial intelligence, peripherals, human interface, etc., have a wide range over the whole information and communications technology (ICT) sector. These technologies are also evolving and upgrading over the years, spirally changing virtual worlds and bringing new features. Based on technology innovation, this paper identifies the impetus which advances virtual world development to quest for the architectural reflection and transformation.

Firstly, we need to answer the question of what changes virtual world. To answer this question, the trends of the related technologies are thoroughly studied for eliciting new design requirements, which compliments existing requirements of consistency, scalability and security. Following the trends and their implications, new features of virtual worlds are suggested and
summarized as emergent design requirements: sufficiency, reliability, persistency, and credibility. Then, the existing virtual world architectures are scrutinized based on the emergent requirements. By classifying and comparing them in requirement satisfaction, we find that none of the existing system architectures can fully satisfy all the requirements due to their intrinsic limitations. To address this issue, we briefly introduce our ongoing research, a new distributed architecture which leverages the advantages of existing architectures for the purpose to elicit new discussions on virtual world system design and development.

This paper has made two contributions. First, it has conducted a trend analysis on the virtual world related technologies. Based on the implication of trend analysis, it has explicated the emergent design requirements, as well as the commonly known requirements for completeness, which can be treated as a roadmap for system design. Then, it has thoroughly surveyed the existing system architectures, discussed their satisfaction and limitations on the design requirements, and compared their competence on requirement satisfaction.

The remainder of the paper is organized as follows. Section 2 analyses the trends of the virtual world related technologies and their implications. Section 3 discusses the virtual world design requirement space based on the trend analysis. Section 4 studies and compare the existing virtual world system architectures on requirement satisfaction. Section 5 compares the existing architectures. Finally, Section 6 summarizes the paper and introduces the future challenges of a new architecture design.

2. Trends Analysis

The latest trends of the virtual world related technologies can provide the evidence for studying virtual world evolution. We firstly searched Statista (statista.com) with the keyword “Virtual
It returns 821 results, including statistics, forecasts, and studies. We then restricted the search results to the range from 2015 to 2035. After screening the results by relevance and year range, the number reduced to 538. We then tagged them with the relevant topics and created the tag cloud, as shown in Figure 1. This search provides the rudimentary knowledge of the search scopes. With such knowledge, we further looked into each scope and investigated the trends of the related technologies, including mobile computing, social networks, virtual/augmented reality, virtual world applications, internet of things (IoT), wearable devices, game intelligence, multisensory multimedia, and computer graphics. The trend analysis on them can be studied along five directions: mobility, diversity, interconnectivity, immersion, and intelligence. The representative market/industrial evidence, together with academic/online reports, are elaborated in the sub-sections below, followed by the implications to future virtual world design.

![Figure 1 Tag cloud of the most frequently used terms for virtual world.](image)

### 2.1 Mobility

The wide usage of smart devices (e.g., smartphones and tablets) and the pervasion of mobile networks (e.g., the 5th Generation cellular mobile network) promote the concept of play everywhere and facilitate the development of pervasive gaming (Kasapakis & Gavalas, 2015).

Figure 2 shows the trend of mobile virtual world from 2014. By the end of 2017, the number of...
mobile gamers has been more than 1.4 times the number of 2014 (Figure 2 (a)). Figure 2 (b) shows that worldwide mobile social gaming revenue has increased by 2.82 billion dollars from 2010 to 2014. Interestingly, the trend of gamer population by device shows that smartphones gain larger traction than tablets. It is likely that, with the increase of smartphone size and capacity, the distinction of smartphone and tablet are diminishing, which reduces the demand on tablet. Moreover, the investigations in year 2017 and 2018 show that the smartphone-based applications gains the largest market share both in video game (63%) (Statista, n.d.-b) and virtual reality/augmented reality (77%) (Statista, n.d.-a), compared with PC, laptop, game console, and other standalone game device counterparts. In summary, the trends in mobility show that the user population and consumption on mobile virtual world platforms are growing.

![Figure 2. Trends of mobility: (a) Number of mobile gamers in North America from 2014 to 2017 (EEDAR, n.d.). (b) Worldwide mobile social gaming revenue from 2010 to 2014 (SuperData Research, n.d.-a).](image)

2.2 Diversity

Virtual worlds have been designed to serve different purposes. Figure 3 shows the increasing range of investment 2016 to 2018. More investment has been moved from the traditional sectors
(gaming, marketing, and military simulation) to the new sectors (retail and manufacturing). To better satisfy the application requirements, various user contents have been generated, such as the virtual objects in Second Life and Minecraft (minecraft.net), to facilitate user’s innovation and collaboration (Hakonen & Bosch-Sijtsma, 2014). In education, for example, the immersive learning environments provide simulated and controlled situations for improving student’s performance and motivation in study. Dynamic content generation can decrease development effort for teachers to customize learning games (Mildner et al., 2014). In medicine, the realistic models created in virtual environments can facilitate surgical training (L. Li et al., 2017). In tourism, the virtual world technologies can convert heritage relics to digital assets, which can avoid erosion in long-term preservation (Guttentag, 2010). In e-commerce, user involvement in product co-creation (Kohler et al., 2009) can improve product satisfaction.

Figure 3. Investment directions of virtual/augmented reality technology worldwide in 2016 and 2018 (Perkins Coie, n.d.).

2.3 Interconnectivity

Virtual worlds can connect to different people and devices to support various interaction and communication. Multiple access devices lead to various user data input to virtual worlds. One
emergent category is wearable device. Figure 4 (a) shows that the user consumption on wearable device is growing in all categories. The wearable devices can collect user data by tracing various user interaction patterns in play. For instance, Cyberith Virtualizer (cyberith.com) can track user posture in walking, running, standing, crouching, and sitting. Data is also collected from IoT devices, creating a mirrored world to telepresent the real-world data in a virtual environment. For example, Eye Create Worlds (Eye Create Worlds LLC, 2016) visualizes the data in a virtual world from the sensors placed over a city to monitor and optimize the performance of a rail transportation network. Besides connecting to devices, people in virtual worlds are increasingly inter-connected. Figure 4 (b) shows that the market value of social worlds in 2020 is expected to be twice the value in 2011. Moreover, a game industry survey in 2018 shows 54% gamers players feel video games help them connect with friends and spend time with family (Entertainment Software Association, 2016). In summary, the above observation shows the interconnectivity trend from both hardware peripherals and social connection, leading to the growth of in-world user data collection.

![Figure 4. Trends of inter-connectivity: (a) Forecast unit shipments of wearable devices worldwide from 2017 to 2022 (Gartner, 2018). (b) Value of the social gaming industry worldwide from 2011 to 2020 (Xania News, n.d.).](image)
2.4 Immersion

User’s experience of immersion is always an important trend to study, for it generates a sense of presence (Skarbez et al., 2017). By observing the evolution of the multimedia and computer graphics technology, two trends can be found. First, the market revenue in Figure 5 (a) shows the increasing trend of immersive hardware technology adoption. Second, the recent innovation in the multiple sensorial media (mulsemedia) technology (Covaci et al., 2018) provides users more sensorial experience than visual and audio delight, leading to the deeper experience of immersion. Figure 5 (b) shows the trend of new mulsemedia device release in the haptic rendering, olfactory rendering, and gustatory rendering market. The figure for all device categories is growing, especially from 2012. Some VR headsets integrating the multisensory function can provide multiple sensorial experiences (besides audio and video experience). For example, OhRoma (camsoda.com/products/ohroma/) provides different smells during video or audio playing. Feelreal (feelreal.com) can simulate both smell and wind by changing the airflow. These trends show the increasing adoption of immersive rendering techniques, enriching user experience.

![Figure 5. Trends of the immersive technology and market: (a) Immersive technology consumer market revenue worldwide from 2018 to 2021 (SuperData Research, n.d.-b). (b) Number of new](image)
virtual reality sensory device releases along with the years, by category. All the figures before 2000 are aggregated to 2000. See the complete list in the supplemental material (Shen, Tan, et al., 2019).

2.5 Intelligence

The game intelligence (i.e., Game AI) techniques have been widely applied in virtual worlds for creating the sense of challenging, enriching human-computer interaction, providing better content, and bringing extra experience to users (Yannakakis & Togelius, 2015). Our study has rendered the milestones of game AI innovation in NPC behavior, procedural content generation (PCG), and narrativity (Shen, Tan, et al., 2019). The game AI in NPC can endow NPCs with believable or human-like characteristics in interaction. The game AI in procedural content generation (PCG) can automatically generate a complex world system, many 3D models, and a full scenario with random quests. Moreover, game AI can also develop game plots from interactive storytelling to augmenting users’ dynamic and immersive gaming experience. To make game AI smarter, the machine learning techniques have been applied to games. They have become either the dominant or the secondary method in NPC behavior learning, player modeling, PCG, computational narrative, believable agents, AI-assisted game design, and general game AI (Yannakakis & Togelius, 2015). Summerville et al (Summerville et al., 2017) has surveyed the cutting-edge machine learning approaches applied in PCG. Besides, some artificial intelligence techniques have been applied in story generation (Kybartas & Bidarra, 2017), such as genetic algorithms. The above trends show that we can witness the increasing adoption and improvement of intelligent techniques in virtual worlds.

2.6 Implications
The mobility trend implies the heterogeneous capabilities of client-end devices for running virtual world applications. Compared with desktop devices and game consoles, mobile devices are configured with fewer hardware resources. In terms of floating-point arithmetic computation, for example, the performance of Nintendo Switch (2017, portable mode) and Samsung Galaxy S10 (2019) is 157 GFLOPS and 899 GFLOPS respectively, whilst Sony PlayStation 4 has already reached 4197.8 GFLOPS in 2014. On the other hand, the immersion and intelligence trend imply the increase of rendering complexity and computing tasks. The conflict between the limited client-end resource and the rapid increase of computational complexity implies that existing clients may have limited capability to provide highly immersive rendering and intelligent computing. Thus, computing resource sufficiency is the first emergent requirement.

Moreover, mobile devices are more subject to failure than their desktop counterparts for two reasons. First, the connection to the remote services through a wireless network is less stable than through a wired network, as the former relies on signal quality. Second, mobile devices have limited battery life and battery quickly depletes for resource-hungry applications, such as virtual world, leading to device failure. A poorly connected or highly congested network will even cause extra power consumption, due to the increase of communication overhead (Barbera et al., 2013). Since unstable connection will corrupt users’ gaming experiment, and device failure may cause game state lost, computing reliability is another new requirement.

Diversity implies that more content will be generated by users, including the user-created virtual objects and the virtual wealth generated in gaming (Guo & Gong, 2011). Meanwhile, interconnectivity implies that more user information will be stored in virtual worlds, including the user data collected from multiple peripheral (i.e., wearable and IoT) devices and the
relationships built from users’ online social network. For simplicity, user-generated objects, virtual wealth, user data, and use social connections are uniformly called user content. The increase and importance of user content have two questions drawing our attention. First, intuitively, will user content be lost if the virtual world application is failed, such as infrastructure failure or service discontinuation? To avoid content lost, this question brings the persistency requirement to system design.

Beside content storage, users may also care more than before about how the system will respect their content. For the increase of personal data and social connections, data security is gradually becoming a great concern to users, especially the privacy-sensitive informations, including personal identification, personal (i.e., religion, race, health, sexual orientation, financial, biometric, etc.) information, collected data, and device traceable information. Users have to worry about the security of them. For the increase of virtual properties (i.e., objects and wealth), legal protection is another concern, especially for those having real-world economic value (e.g., the Linden Dollar in Second Life). In the case of service termination, for example, users may worry about the access to or even the economic benefit from them (Hetcher, 2007). Moreover, users may share their content with others, leading another level of security and legal concern. All the above concerns request for a trusted environment of content storage. We call it the credibility requirement.

\[
\text{Mobility} \land (\text{Immersion} \lor \text{Intelligence}) \rightarrow \text{Sufficency} \\\n\text{Mobility} \rightarrow \text{Reliability} \\\n\text{Diversity} \lor \text{Interconnectivity} \rightarrow \{\text{Persistency}, \text{Credibility}\}
\]  

(1)

Bringing together the above implications, Eq. (1) shows the relations between the technology development trends and the emergent requirements of virtual world development, including
sufficiency, reliability, persistency, and credibility. They will be elaborated in the next sections.

3. New Requirement Space

The trend analysis has implied the new requirements of virtual world system design, which are complementary to the existing requirements. The existing requirements include consistency, responsiveness, scalability, and security. We have observed that responsiveness is a common criterion in the sufficiency, persistency, consistency, and scalability problems. Hence, it is more appropriate to express it as a design criterion towards other requirements. Figure 6 shows the taxonomy of design requirements and issues.

Before elaborating the new requirements, for completeness, the existing requirements are briefly introduced first. The consistency models originate from distributed computing (Terry, 2013). For virtual world systems, consistency can be studied in two domains (Mauve et al., 2004). In the discrete domain, it requires that two users can see the same set of events handled in causal order,
called causal preservation. Yet, object state also changes over time, following some internal rules, e.g., physical laws. It then requires that two users can see the same state changes if they have received the same set of events, called perceptive consistency (Khan et al., 2007). In practice, consistency error can be compensated by latency error to achieve the overall fairness, which is called playability (Millar et al., 2017). Scalability is “a desirable … ability of a system to accommodate an increasing number of elements or objects, to process growing volumes of work gracefully” (Bondi, 2000). In virtual worlds, the scalability issues can be classified into world scalability and hotspot scalability. The challenge of world scalability comes from two sources (Liu et al., 2012): large scale real-time simulations and simultaneous visualization for many users, caused by the increase of user population. Hotspot scalability comes from another source: multiple heterogeneous actors with different operating characteristics. When many users gather at a small place, a hotspot is formed (Bezerra & Geyer, 2009). The scalability issues aim at minimizing system performance reduction with the increase of users and user interactions, either globally or regionally. For security, cheating is an ubiquitous issue in online gaming communities (Irdeto, 2018), caused by the combination of malicious attempts and system faults. (Yahyavi & Kemme, 2013) has classified them into 3 types of security break and further divided them into 13 categories. They summarized that cheatings in virtual worlds need either be prevented or be detected for providing a fair playground.

3.1 Sufficiency

Sufficiency is the first emergent requirement such that users can access highly immersive environments from any device. It becomes outstanding with the growth of mobile devices and computational complexity. Partially/completely offloading computing tasks to remote sites for meeting the resource requirement is an evident choice (Wei Cai et al., 2016; Cuervo et al., 2010).
Based on the choice, two concerns can be derived: energy efficiency and quality of service (QoS)/quality of Experience (QoE). Energy efficiency concerns about the device energy consumption for local computing or communication to remote sites (Miettinen & Nurminen, 2010). (Altamimi et al., 2015) provided an energy consumption model for smartphone task offloading in WLAN and mobile network (3G/4G). QoS/QoE concerns about the cost and benefit of offloading (Wei Cai et al., 2016). The cost includes the communication overhead and response latency. The benefit includes graphic (i.e., image or video) quality improvement, quantified by bitrate or frame rate. Moreover, both energy efficiency and QoS/QoE are sensitive to network condition. If the network availability is low, code offloading will increase both energy consumption and latency (Barbera et al., 2013).

3.2 Reliability

Reliability also comes from the mobility trend, as both mobile devices and mobile networks are subject to failure. Redundancy can add reliability to a system by replicating the data and program to multiple sites so that a device can both tolerate connection failure (i.e., failure tolerance) and recover the state after client failure (i.e., failure recovery). Redundancy brings the consistency problem (called replica consistency to distinguish it from the consistency requirement), since all replicas have to maintain the same game state for game state integrity. Consistency is a hard problem in distributed computing, due to the notorious CAP theorem (Brewer, 2012). It states that if a design cannot tolerate network partition, availability and consistency cannot be simultaneously achieved, because a network failure may prevent a replica from being synchronized (Gilbert & Lynch, 2012). On the other hand, if a design can solve the network partition problem, consistency and responsiveness will then become the conflicting requirements, since consistency control protocols normally add additional communication steps (Abadi, 2012).
Thus the reliability property seeks for a computing redundancy design which can achieve high availability, consistency, and responsiveness, meanwhile without or tolerating network partition.

Additionally, reliability is an important requirement for device interoperability (Nevelsteen, 2015) in pervasive games. In Hot Potato (Chatzigiannakis et al., 2010), for example, player mobile devices are locally connected with wireless sensor network (WSN) and P2P neighbor discovery. They also need to connect to a backbone network for coordinating heterogeneous devices, providing global interaction and storage for all game instances.

3.3 Persistency

The persistency requirement has two aspects: state and content. State persistency requires that when a player leaves a game, his/her game state is well-kept for the next-time retrieval and play (Fan, 2009). State data normally has a small size, but could be frequently updated. Thus, data read/write efficiency is the main concern. (Zhang & Kemme, 2011) found that some states only require approximate consistency between write and read (e.g., avatar position), while others require exact consistency (e.g., user inventory). Thus, different persistency strategies can be applied for different consistency requirements to minimize system overhead and response delay. Game state storage also needs to be reliable and robust to any failure. If redundancy is applied for fault-tolerance, the replica consistency, responsiveness, and load balance issue also have to be studied (Gilmore & Engelbrecht, 2012).

On the other side, user content persistency in virtual world is still short of attention. With the growth of user content, however, this aspect is becoming increasingly important. Content persistency requires that user’s data and content can be permanently preserved, as long as the user has not departed from the virtual world, which falls into the field of file storage. Compared
to state data, user content files normally have a larger size (e.g., multimedia files), but are less frequently updated. Thus, the main concern is distinctive (Nachiappan et al., 2017), which includes storage efficiency (i.e., reliability to storage space), bandwidth cost, data access latency, and content integrity. Furthermore, if user content can be shared to other users, view consistency is needed, which requires that two users can see the same set of objects if both are interested in them.

### 3.4 Credibility

Credibility (or trust) comes from the increase and importance of user content on virtual worlds. It is more complex and thus deserves some detailed explication. In the context of information system, trust is a subjective belief that a system or a system component will behave as expected (Jøsang et al., 2007), which is established based on direct evidence, recommendation, and reputation (Z. Li et al., 2017). In virtual world, users can have the belief on the underlying system in content management only if their content is securely preserved and legally protected. Thus, the credibility requirement has two concerns: user data security and content legal protection.

Data security (to distinguish it from the security requirement), though new to virtual worlds, has been widely studied in cloud services, which includes privacy and confidentiality. Both require that user’s sensitive content is confidential to unauthorized access, whilst data privacy stresses more on the interest users have in controlling the handling of the data about themselves (Bélanger & Crossler, 2011). (Theoharidou et al., 2013) divides the top threats into 5 categories, including data breaches, account or service traffic hijacking, API or shared technology vulnerabilities, malicious insiders, and insufficient due diligence. The categories of threats imply
that data security is not only a technical issue but also a regulatory issue. From the technical perspective, secure data access needs to be achieved by mitigating the above threats from privacy-enhancing technologies, security mechanisms, data obfuscation, or anonymization. From the regulatory perspective, data security involves procedural solutions for committing legal and contractual requirements in a verifiable way. For verifying requirement commitment, accountability (Pearson, 2017) and compliance are the key issues.

Legal protection concerns the legitimate interest of the involved parties, mainly including virtual world users and platforms. The first issue is content ownership. If users only have control of their created content but not the ownership, such separation will become the barrier to user innovativeness due to the additional cost (Tietze et al., 2015). If users have content ownership, secondly, they may need to control the distribution of their content to others through digital rights management (DRM), which only allows users to represent and constrain content usage but also provides traceability of service violation. Moreover, user-created content may also bring legal risks, including plagiarism, offensive content, spam, soft hacking, etiquette breach, personal exposure, etc. (Coutinho & José, 2019). These risks push the content moderation techniques to a new frontier.

4. Virtual World Architectures

The existing virtual world system architectures can be classified to client-server (C/S) architecture and peer-to-peer (P2P) architecture, and hybrid architectures. Figure 7 illustrates the conceptual structure of them. This section introduces the existing virtual world architectures and conducts a qualitative study on their design requirement satisfaction and limitations. Table 1 lists the representative solutions to the design issues. In this paper, only the issues with respect to
emergent requirements are elaborated.

![Central server](a) ![Client](b) ![Central server](c) ![Client](d)

**Figure 7.** Conceptual classes of virtual world architecture: (a) client-server, (b) peer-to-peer, (c) Hybrid-I, (d) Hybrid-II.

**Table 1.** The representative solution of the design issues.

| Requirement | Design Issue          | C/S | Hybrid-I                          | P2P                      | Hybrid-II                  |
|-------------|-----------------------|-----|----------------------------------|--------------------------|----------------------------|
| Sufficiency | Energy Efficiency     |     | Energy trade-off (Miettinen & Nurminen, 2010) |                         |                           |
|             | QoS/QoE               |     | MAUI (Cuervo et al., 2010)        |                         |                           |
| Reliability | Reliability           |     | Database replication (Yi Lin et al., 2006) | Database replication (Yi Lin et al., 2006) | Pithos (Engelbrecht & Gilmore, 2017) |
| Persistency | State Persistence     |     | Centralized control (Richerzhagen et al., 2014) | Centralized control (Richerzhagen et al., 2014) | Backup virtual node (Carlini et al., 2013) |
|             | Content Persistency   |     |                                       |                          | State Action Manager (Carlini et al., 2013) |
| Credibility | Secure Access         |     | Policy-based access control (Amini & Osanloo, 2018) | Blockchain-based access control (Shen, Guo, et al., 2019) |                           |
|             | Regulation            |     | Data compliance (Henze et al., 2017) |                         | N.A.                       |
|             | Ownership             |     | User representative (Zhou et al., 2018) |                         |                           |
|             | DRM                   |     | License Server (Kim et al., 2016) |                           | DRMChain (Ma et al., 2018) |
|             | Content Moderation    |     |                                       | Content approval or social accountability (Coutinho & José, 2019) |                           |
| Consistency | Causality             |     |                                       | Local-lag and timewarp (Mauve et al., 2004) |                           |
|             | Perceptive Consistency|     |                                       |                          |                           |
| Scalability | World Scalability     |     | Cloud gaming (W Cai et al., 2014) | Cloudlet (Chi et al., 2018) | Red-Black (Ghaffari et al., 2015) |
|             | Hotspot Scalability   |     | KIWANO (Diaconu & Keller, 2017) | Peer-assisted (Richerzhagen et al., 2014) | AOI-cast (Ricci et al., 2015) |
|             |                       |     |                                  | Cloud resources (Carlini et al., 2013) | Virtual server transfer (Carlini et al., 2013) |
| Security    | Cheating              |     | Cryptographic measures (Mönch et al., 2006) |                          |                           |
4.1 Client-server

In the C/S architecture (Figure 7 (a)), the simulation logic is processed at the server end, while the clients only render the updates, which are sent from servers, to users. A C/S virtual world has a definitive platform owner (e.g., Linden Lab, the owner of Second Life). The online services (e.g., the authentication, inventory management, and region management in Second Life) and application data (e.g., user items, user inventory, and virtual property in Second Life) belong to the platform owner. The C/S architecture has predominated the virtual world industry (See the list of sampled virtual worlds in the supplemental material (Shen, Tan, et al., 2019)).

4.1.1 Requirement satisfaction

The C/S architecture adopts a centralized structure, which is easy to satisfy sufficiency and reliability. For sufficiency, by applying dedicated servers to run the main services, client heterogeneity will not be a problem. The simulation codes, depending on the capability of a client device, can be partly or completely offloaded to remote servers through function invocation (Flores et al., 2015). In code offloading, (Miettinen & Nurminen, 2010) has provided an energy trade-off model to maximize the energy efficiency in terms of the ratio of energy cost to device-specific cost in local computation and additional communication. For QoS/QoE, MAUI (Cuervo et al., 2010) has shown the improved video refresh rate from 6 FPS to 13 with low energy consumption, latency, and data transfer overhead. Cloud gaming (Wei Cai et al., 2016) can also address the sufficiency issue through interactive remote rendering (Shi & Hsu,
As such, energy consumption and QoS/QoE remain the main focuses of cloud gaming.

The C/S virtual worlds can resolve the reliability problem with replication. (Yi Lin et al., 2006) applied a database replication approach to multiplayer online games to provide fault tolerance. Game operations are handled with a Read-One-Write-All-Available approach. The work provides four alternative synchronization approaches for propagating updates to all the replicas to maintain consistency. It also shows fast responsiveness (specifically, $\leq 20$ ms for read-only transactions and $\leq 100$ ms for write transaction). Database replication can also improve reliability in game state storage. Yet, to the best of our knowledge, existing C/S virtual world systems have not fully addressed the connection failure issue. Directing communications to nearby fog facilities might be a solution (Yuhua Lin & Shen, 2017), since the shorter distance between fog facilities and mobile clients can reduce the chance of connection failure.

For data security, policy-based access control (Amini & Osanloo, 2018), together with secure hardware (Gunes et al., 2015) or cryptographic measures (H. Wang, 2018), can be applied in data sharing (H. Wang, 2018), keyword search (J. Li et al., 2017), and public audit (B. Wang et al., 2014). Fog computing can also mitigate insider data theft (Stolfo et al., 2012). Moreover, security policies can be enforced through data protection compliance (Henze et al., 2017) and accountability check (Pearson, 2017). For legal protection, Kim et al (Kim et al., 2016) proposed a user-centric rights representation model for the DRM of user-generated content by employing a separate license server (Kim et al., 2016).

Moreover, the content moderation issue has been discussed in (Coutinho & José, 2019), which proposed a risk management framework for user-generated content with 7 moderation techniques, respectively employed by platform owner, system, trusted curator, and the public. Notably, the
solution to this is applicable to all architectures.

4.1.2 Limitations

The centralized ownership creates a single point of failure, leading to two issues. The first issue is persistency. When the entity owning a virtual world dies, bankrupts, or withdraws its operations, the affected virtual worlds will collapse together with the loss of its user-generated contents (Among the 126 virtual world applications based on OpenSimulator\textsuperscript{a}, 28 of them has no longer in operation). The result is that user content will become non-persistent. Temporary infrastructure failure may also cause user content lost. For example, the World of Warcraft game server crash on 21 Jan 2006 led to the inventory damage of thousands of players (Yi Lin et al., 2006).

The second issue is credibility, which involves information and legal protection. When a virtual world deposits user data, it may include sensitive information, such as location information in context-aware games (Kasapakis & Gavalas, 2015). One of the key privacy compliance issues is to provide a transparent and controlled environment to data owners (Modi et al., 2013), which is, however, at the cost end of platform owner, subject to many external factors (e.g., global societal trends), firm-specific factors (e.g., industry best practice and corporate culture), and ethical frame (e.g., rule utilitarianism or moral relativism) selection (Sarathy & Robertson, 2003). There are also some trust-level issues related to transparency, including requirement propagation along the sub-contract chain and malicious insiders (Modi et al., 2013). Thus, the gap remains between platform owner’s claims and user’s trust of their sensitive information protection.

\textsuperscript{a} See the inactive virtual world list in http://opensimulator.org/wiki/Grid_List
Moreover, storing user-created content on a C/S platform separates the content ownership and control, creating a legal dilemma. On one side, users do not have the control over the actual data and a platform may unilaterally terminate their accounts with their virtual asset confiscated, as in the Bragg case (Dougherty, 2007) and the Evans case (Ryu, 2014), which leads to ownership tensions and inhibits user innovation (Zhou et al., 2018). (Hetcher, 2007) have shown that platforms tend to have such ownership separation either for competition purpose or for liability safe harbor, which discloses the second problem. Storing user content imposes legal pressure on platform owners for copyright infringement or offensive content (George & Scerri, 2007). Though content moderation can mitigate such risks (Coutinho & José, 2019), it largely increases the cost paid by platform owners and the risks still exist.

4.2 Peer-to-peer

P2P virtual world aims at resolving the scalability issue of the classic C/S architecture (Knutsson et al., 2004), which is jointly promoted by the P2P computing and virtual world researches. In the P2P architecture (Figure 7 (b)), the services are collectively run by user devices which play the role of both server and client. All user devices are connected to a P2P overlay network (Buyukkaya et al., 2013). When a user is accessing a virtual world application, he/she is also providing services to others of the same application through his/her accessing device. Such a virtual world is supported by a reciprocal economy. A P2P virtual world can have an application provider who develops and distributes the application software to run on the P2P overlay network. Currently, P2P virtual worlds are still staying at the laboratory stage and far from wide industry acceptance (Yahyavi & Kemme, 2013).

4.2.1 Requirement Satisfaction
P2P virtual worlds, firstly proposed in Knutsson et al (Knutsson et al., 2004), remove the single point of failure. By running applications on user devices with open protocols, application data are no longer owned or controlled by any entity. Thus, they are promising to address the persistency issues. (Gilmore & Engelbrecht, 2012) provided a comprehensive survey of P2P game state persistency. Later, (Engelbrecht & Gilmore, 2017) proposed a two-tier architecture. An overlay storage employs a distributed hash table (DHT) and super-peers to provide high reliability and fault-tolerance. A group storage employs a distance-based grouping approach to improve availability and responsiveness.

For content persistency, P2P virtual worlds can also employ a P2P file storage protocol to store user content. Existing P2P file storage systems, such as BitTorrent (bittorrent.com), has shown their persistency property without central storage. Varvello et al (Varvello et al., 2009) designed a communication infrastructure for distributing and storing virtual objects to Kad, a global P2P storage network. The Total Recall (Bhagwan et al., 2004) storage protocol provides optimized storage efficiency with high responsiveness and low bandwidth cost. (Shen & Guo, 2018) proposed a content retrieval approach based on Total Recall to provide efficient content integrity check. These properties are requested by the content persistency requirement. Moreover, (Hu et al., 2008) proposed a P2P 3D object streaming scheme from nearby peers, which can be used in virtual world content sharing. (Çevikbaş & İşler, 2019) improved it in efficiency.

For data security, P2P virtual worlds can leverage the Blockchain technology, combined with cryptographic measures, to achieve user-centric secure data access (Cruz et al., 2018). Blockchain-based privacy-preserving access control has been widely discussed in many fields, including personal identity management (Lee, 2018), healthcare record sharing (Shen, Guo, et al.,
2019), collected data access (Reyna et al., 2018), etc. The Blockchain technology has some advantages. First, it does not need a third-party service for stewarding user data, on which users have to put their trust. Second, security policies added to Blockchain (Neisse et al., 2017) is transparent to all users and data compliance can be achieved through the consensus mechanism. Moreover, the Blockchain data structure is tamper-proof, which have some additional merits, including integrity and non-repudiation, etc.

The Blockchain technology can also be used in digital rights management (Ma et al., 2018). Its non-repudiation property can enable the conditional tractability of license violation. Moreover, a P2P virtual world does not have a definitive platform owner, attributed to its decentralized structure. It removes ownership inconsistency issue and users really have the ownership of their virtual assets as well as the underlying data. Thus, a P2P virtual world can achieve higher credibility.

4.2.2 Limitations

Sufficiency and reliability are the two weakness of the P2P architecture, and they are becoming outstanding with the increase of mobile clients. In pervasive games or augmented reality, user clients could be wearable devices, IoT devices, and custom-built devices. They have nonstandard interfaces and heterogeneous capabilities (Kasapakis & Gavalas, 2015; Nevelsteen, 2015), which exhibits several limitations in the P2P design. First, the resource-limited wearable devices may not have sufficient computing resources or standard interfaces to play the role of a server for running full game logic. Yet, the pervasive games have to connect to a central platform for data exchange (Kasapakis et al., 2015). Moreover, mobile devices are hard to provide a high quality of experience with limited processing capacity. For example, Final Fantasy XV Pocket Edition
provided lower graphics (Vogel, 2018) and AI experience (Gillham, 2018) than the desktop and console edition.

Moreover, P2P virtual worlds may also suffer from heterogeneous peer resources. Mobile devices can run fewer services than the desktop ones. Let alone wearable devices. When users of more resources leave the application, they also remove their resources provisioning and unduly stress the rest peers (Carlini et al., 2010).

Mobility also greatly increases the chance of client failure due to connection lost (Flintham et al., 2003) or battery depletion (Bujari et al., 2018). Client failure may cause unsaved state lost. On the other hand, reliability is important to gaming experience. Pervasive games require high connectivity to game masters (i.e., specially selected players) for content distribution, diegetic communication, and game progress track (Nevelsteen, 2015). Although Pithos (Engelbrecht & Gilmore, 2017) adds reliability through a two-tier game state replication, the design does not address the replica synchronization issue, which may lead to inconsistent game state.

4.3 Hybrid-I

The C/S and P2P architecture can be combined to a hybrid architecture. In a hybrid architecture, the weakness of one architecture is overcome by the strength of another. According to the ways of combination, hybrid architectures can be divided into two classes. The first one, denoted by Hybrid-I (Figure 7 (c)), leverages the P2P computing techniques to the C/S architecture for computation offloading, since P2P resources can be easily scaled with user population. In Hybrid-I virtual worlds, e.g., (Richerzhagen et al., 2014), clients disseminate updates to each other through P2P communication to save the server’s outgoing bandwidth and thus the operating cost. Cloud gaming can also exploit P2P techniques to reduce game latency (Wei Cai
et al., 2016) and service operating cost (Wei Cai et al., 2014; Chi et al., 2018).

4.3.1 Requirement satisfaction and limitations

The Hybrid-I architectures have different requirement satisfactions, depending on how clients participate in a simulation. This section introduces some typical examples. Firstly, in (Najaran & Krasic, 2010), the cloud servers form a P2P publish-subscribe overlay for the communication between game servers. Clients do not involve any simulation. Then, in (Richerzhagen et al., 2014), a central server is employed to control and store the game state, while clients are only in charge of message dissemination to save the server’s outgoing bandwidth. Their requirement satisfaction is similar to that of the C/S architecture, except that the latter design provides more cost-efficient scalability solutions, because the efficiency of message dissemination scales with user population. They also share the same single point of failure with the C/S architecture due to the existence of the central point for content storage, including the limitations in content persistency, data security, and legal protection.

In (Goodman & Verbrugge, 2008), the central server stores the game state and relays client messages for security check. The clients compute and disseminate the game state with P2P techniques. The requirement satisfaction of this approach is in between the C/S architecture and the P2P architecture. Specifically, the P2P clients allow it to have similar requirement satisfaction and limitation to the P2P architecture. The centrally controlled game state allows it to have the similar requirement satisfaction and limitations to the C/S architecture in persistency, credibility, and security, while the P2P clients allow it to have the similar requirement satisfaction and limitations to the P2P architecture with respect to the rest issues.

In (Carter et al., 2010), moreover, the P2P clients manage the game state for each other, while
the central server only keeps the sensitivity data (e.g., user profile) and provides the utility 
functions (e.g., authentication). This design is similar to the P2P architecture, except that the 
satisfaction of the data security requirement can approach to that of the C/S architecture because 
of the centralized storage of sensitive data.

4.4 Hybrid-II

The second hybrid class, denoted by Hybrid-II (Figure 7 (d)), introduces cloud resources to the 
P2P architecture to improve the overall performance. In (Ahmed et al., 2009), for instance, 
special server nodes play the roles of zone masters. They do not retain game state but only help 
clients in intra-/inter-zone communication. The Hybrid-II architecture was initially proposed by 
(Carlini et al., 2010) after they identified the heterogeneous peer resource issue. In their design, 
the cloud resources are introduced to complement the peer resources and both are virtualized to 
nodes (called virtual nodes, VN). The VNs construct two P2P overlays for providing the 
common services: the state action manager (SAM) and the positional action manager (PAM). 
The SAM nodes, organized to a structured overlay, manage the state of virtual objects (Carlini et 
al., 2013). The PAM nodes, organized to an unstructured overlay, manage the user position 
information for neighbor and object discovery (Carlini et al., 2015). In an application of Hybrid-
II architecture, a client firstly receives the nearby users and objects by querying the PAM service. 
Then the client can interact with them through the SAM service for state update and state 
synchronization.

4.4.1 Requirement satisfaction

The Hybrid-II architecture shares some similarity with the P2P architecture, but there are some 
differences between them. Firstly, the Hybrid-II design has enhanced the scalability by resolving
the resource heterogeneity issue with reliable cloud resources to cover resource deficiency from user departure. The optimal cloud resource assignment problem with respect to system load has been studied in (Kavalionak et al., 2015) to minimize the economic cost from cloud resource utilization. Resource virtualization can also bring some load balance to the system to further improve scalability. In (Carlini et al., 2013), load imbalance is evaluated with the Gini Coefficient. If a device is overloaded, it will migrate some of the VNs to other devices with minimized visual inconsistency.

Cloud resources also have a contribution to state persistency Carlini et al (Carlini et al., 2010). The SAM service provides two layers of replication. First, each VN assigned to a user device (called uVN) is backed up with a cloud node (called bVN). An uVN periodically synchronize its node state to the bVN. Such fault tolerant mechanism is called coarse-grain data replication. Moreover, a VN in SAM also dynamically replicates its objects to a VN (i.e., overlay replicas) in the neighbor address space (Lua et al., 2005), which is called fine-grained data replication. In case of uVN failure, the SAM service will forward requests to the overlay replica. If the overlay replica has become overloaded, it will inform the clients to forward their requests to the bVN. In such a design, the coarse-grain data replication can reinforce storage reliability, and the fine-grain one can improve service responsiveness through neighbor address access (Lua et al., 2005).

Though not mentioned by the authors, we believe that content persistency can be achieved with the same approach as that in the P2P architecture, since the overall Hybrid-II architecture is decentralized. Likewise, the overall Hybrid-II architecture can achieve the same credibility requirement satisfaction is the same as the P2P architecture, for it does not have a centralized control entity.
4.4.2 Limitations

Similar to the P2P architecture, the Hybrid-II architecture is limited in resource provisioning for resource-limited devices. In the SAM service, objects stored on a VN have the identifiers close to the VN’s address (Carlini et al., 2013). That is to say, objects are not group by their users but by the mapping of identifiers to the address space of the DHT overlay (Lua et al., 2005). Thus, a SAM node may not have all the content of a user for running the complete simulation logic. Moreover, even cloud resources have been introduced, which may have higher computation capabilities, they are partitioned to many VNs for service and data storage backup. Thus, cloud gaming cannot be run on the Hybrid-II architecture for code offloading (Flores et al., 2015) or interactive remote rendering (Wei Cai et al., 2016).

For reliability, though the two-layer data replication mechanism can double the reliability of the SAM service, as in the P2P architecture, the consistent state synchronization between replicas is not addressed by the authors. When an uVN fails, it may not timely and successfully synchronize the latest state to the bVN or the overlay neighbor, leading to state lost or inconsistency. The extent of inconsistency between replicas depends on the length of synchronization interval. State consistency could be critical to the integrity of a game, including, e.g., in-game trade and user inventory (Zhang & Kemme, 2011).

5 Architecture Comparison

In this section, we compare the virtual world architectures in requirement satisfaction. The introduced architecture classes include C/S, P2P, Hybrid-I, and Hybrid-II, and Virtual Net. In the discussion, they are further classified to centralized architectures (C/S and Hybrid-I) and the decentralized architectures (P2P and Hybrid-II). Table 2 shows the comparison result.
Table 2. Features comparison of virtual world architectures.

| Requirement | Feature                              | C/S                      | P2P                  | Hybrid-I                      | Hybrid-II                     |
|-------------|--------------------------------------|--------------------------|----------------------|-------------------------------|-------------------------------|
| Sufficiency | Lightweight Device Support           | Code offload, Cloud gaming | No                   | Code offload, Cloud gaming   | No                            |
| Reliability | Connect Failure Tolerance            | No                       | No                   | No                            | No                            |
|             | Replica consistency                   | Yes                      | No guarantee         | Yes                           | No guarantee                  |
| Content    | Content lost due to platform failure | Likely                   | Unlikely             | Likely                        | Unlikely                      |
| persistence| Transparency to Compliance           | No                       | Yes                  | No                            | Yes                           |
| Credibility| Content Ownership                    | Separated                | User-owned           | Separated                     | User-owned                    |
|            | Platform Owner’s Liability           | Yes                      | No                   | Yes                           | No                            |
|            | for illegal content                  |                          |                      |                               |                               |
|            | DRM Violation Traceability           | No                       | Yes                  | No                            | Yes                           |
| Scalability| Scalability Cost to Application Provider | High                     | Low                  | Moderate                       | Medium to low                 |
| Security   | Client-side Code Tampering           | Highly secure            | Vulnerable           | Highly secure                 | Vulnerable                    |

Sufficiency can be satisfied with the separation of client and service. In centralized architectures, since most computational complex tasks are moved to the service end, including simulation logic, physics computation, and graphics computation, a lightweight client only needs to render the results generated from servers. In contrast, the decentralized architectures require client devices to play the role of both server and client, imposing large computation load on them. A lightweight client device may not have the capability to render a highly immersive environment. Compared to the rest architectures, moreover, P2P virtual worlds may suffer from heterogeneous peer resources. Some peers may located on low-performance or unreliable devices, which will provide less services to other peers and even slow down the entire system.

Reliability can be satisfied with replication and synchronization. In centralized architectures, each state update will be synchronized from client to server. Since the centralized architectures preserve a copy of user state at the server end, they can tolerate client failure. A recovered client can catch up with the latest state by retrieving the data from the server. Moreover, the database synchronization approaches can maintain replica consistency between replicated databases. But
centralized architectures only maintain a connection between a client and a server, which does not tolerate connection failure. The decentralized architectures also provide replication for backing up client state. Thus, client state can be recovered after client failure. But they neither provide replica consistency guarantee nor tolerate connection failure.

Content persistency can be satisfied with decentralization. The centralized architectures contain a central entity for stewarding user content, creating a single point of failure. As above-shown, even if advanced fault-tolerance techniques can minimize the failure of a system, the failure of the control entity will cause the service to discontinue. Decentralized architectures, on the other hand, are immune from system-level failure, since such a system is not controlled by a single entity. Moreover, the underlying P2P storage techniques (Bhagwan et al., 2004) ensure that the failure of a node will not spread over the entire system, and local failure can be recovered from data replicas.

Data Security can be satisfied also from the decentralization. The security compliance of the centralized architectures is normally non-transparent to the external and is subjective to many firm-specific factors. Users only put limited trust in the protection of their data and information, even for cloud-based systems. An industry observation has shown that security and compliance are still the significant challenges to cloud computing in 2019 (Flexera Software, n.d.). The decentralized architectures, on the other hand, does not have a single stakeholder. Every user is the stakeholder of the system, and P2P-based security mechanisms can be applied and effective as long as most users are obedient to the system rules (Oualha et al., 2012). Thus, users need to trust no entity but only the system per se, which is the also argument why Blockchain-based solutions can achieve higher security in data access (Shen, Guo, et al., 2019). Thus, the
decentralized architectures can provide more trust in data security to users.

Legal protection can be satisfied with unitary ownership. In the existing virtual worlds, which are centralized, the control entities own all the digital assets (i.e., file and data), while the users own the virtual assets, leading to ownership inconsistency and disputation (Zhou et al., 2018). The decentralized architectures, on the other hand, do not have a control entity. Both the virtual objects and the digital assets belong to the users. Thus, users’ virtual property can be legally protected by property or copyright law. Moreover, application providers do not need to worry about their liability for, e.g., plagiarism or offensive content, since they do not own them. Thus, the decentralized architectures can offer higher legal protection to both users and application providers.

Table 2 also shows the architectural comparison for existing requirements, including scalability and security.

Scalability cost refers to the economic cost imposed on someone or some entity, who provides the virtual world application, for scaling up the system to accommodate the growth of the user population. In the C/S architecture, the cost is solely paid by the platform owner who pays the cost of the entire infrastructure. In the hybrid-I architecture, since some functions (e.g., state distribution) are distributed to user clients, the platform owner’s cost can be largely decreased. In the hybrid-II architecture, the cost depends on who provides the cloud resources. Since a hybrid-II virtual world is collectively run by the cloud resources and user devices, the cost in the hybrid-II architecture will not be larger than the one in the hybrid-I architecture. In the P2P architecture, the infrastructure cost is fully shared by all users. Thus, application providers nearly do not need to pay for the infrastructure.
Game cheating is the main factor leading to the low acceptance of decentralized architectures in the industry (Yahyavi & Kemme, 2013). Compared to the centralized structures, the decentralized structures, due to the lack of a central arbitrator, are more vulnerable to player escaping, network flooding, suppress-correct cheat, etc. than their C/S counterparts, while time cheat, blind opponent, consistency cheat are only possible to P2P games (Yahyavi & Kemme, 2013). In P2P architectures, though some cheatings can either be prevented or detected through cryptographic measures (Mönch et al., 2006) or mutual verification (Schuster & Weis, 2011), a more general approach either needs a central server for rule enforcement (Goodman & Verbrugge, 2008; Matsumoto & Okabe, 2017) or lockstep message check which largely increasing communication overhead. In the Hybrid-II architecture, a referee anti-cheating scheme is applied for detecting illegal messages in communication (Webb et al., 2007). Nevertheless, a malicious user still can tamper the code of VN s and change the simulation logic which becomes favorable to them and cannot be detected by the scheme. Moreover, the deterministic mapping from object identifiers to the VN address space (Lua et al., 2005) enables an attacker to guess the content maintained by the controlled device, increasing the attack success rate.

6. Summary and Ongoing Work

6.1 Summary

We have analyzed the trends of the virtual world related technologies and their implications for future virtual worlds. The trend analysis study is important, since the new requirements have not been commonly recognized in the virtual world community. Based on the trends and implications, we have discussed the emerging requirements of virtual world system design in
detail. These requirements, including the design issues and criteria, provide a complete requirement space for design reference. We have also thoroughly examined the existing virtual world architectures and discussed their satisfiability and limitations to the new requirements. A complete list of requirement satisfaction examples have been provided for function implementation reference. Then, the comparison between architectures shows that none of the existing architectures can fully satisfy for all requirements. The detailed comparison results provides new avenues for virtual world system development. We hope that the results of this study, the surveyed content, and the analysis provided here have laid a solid foundation and research avenues for future virtual world development.

6.2 Ongoing Work

For future virtual worlds, currently, we are working on a new architecture, called Virtual Net. The central idea of Virtual Net is that nobody owns a virtual world but all users collectively create a self-organized one, which is similar to the decentralized architectures at this point. In Virtual Net, users contribute a part of their computing resources, such as a certain amount of CPU time, memory, storage, bandwidth, and GPU resources of their computing devices, which can be laptops, desktops, workstations, etc. The contributed part of each device is virtualized into one or multiple nodes. All virtual nodes have the same computing resources, managed by a node pool. Users of Virtual Net can store their contents or deploy their applications on the nodes without a central server.

Figure 8 shows the overall structure of Virtual Net, which consists of three types of component: Multi-node storage and synchronization (Mesh), P2P cloud, and client. In Virtual Net, Mesh is a logical unit composed of nodes for running virtual world programs. The nodes in a Mesh are
called Mesh nodes. As user-contributed devices are subject to (temporarily or permanently) failure, a Mesh node is replicated to multiple nodes, called replica group or replicas. Externally, each Mesh can be treated as a reliable peer. Thus, the inter-Mesh interaction is equivalent to the inter-peer interaction in the P2P architecture. The P2P cloud consists of the reliable nodes and provides the services commonly needed by all Meshes. The persistency service is the primary service of the P2P cloud, which stores user content (programs, user data, virtual objects, etc.). A Mesh retrieves the user content from the P2P cloud at initialization, saves it back at termination, and periodically checkpoints the updates through the persistency service. Client is a special node in a Mesh, which provide the user interface for receiving user operations and rendering updated states to users. A Mesh can receive the operations from or send the updates to a client. Moreover, a special Mesh can be assigned to an NPC for running AI program, which does not have a client node.

![Figure 8. Virtual Net architecture.](image-url)
Virtual Net is designed for providing more requirement satisfaction. For sufficiency, Virtual Net, thought lack of a central server, adopts the similar separation paradigm to the centralized architectures. The computational complex tasks are moved to the remote service end from the client. So, the computing resources of a lightweight client device only needs to concentrate on limited computing tasks. For reliability, Virtual Net replicates simulation logic and Mesh state to multiple virtual nodes. It also applies a replica synchronization protocol to maintain replica consistency (Shen & Guo, 2018). Thus, Virtual Net can provide client failure recovery as much as the centralized architectures. In Virtual Net, moreover, a client can simultaneously communicate with all the replicas of a Mesh node to provide connection failure tolerance. Thus, the overall reliability of Virtual Net is higher than the existing architectures. For persistency, data security, and legal protection, the Virtual Net structure does not have a central control entity, belonging to the decentralized paradigm. Thus, Virtual Net can inherit the advantages from the decentralized design paradigm in persistency, data security, and legal protection.

To implement Virtual Net, there are some key technical issues urgent to be addressed. First, virtual nodes need to be created from user-contributed devices and allocated to Meshes and the P2P cloud by device virtualization and node pooling. Device virtualization provides the virtual nodes for fine-grained resource management. Node pooling provides the managing container for virtualized nodes. The second issue is replica management. To maintain Mesh reliability, a number of replicas are maintained for each Mesh node. The key problem of replica management is to look for the optimal group size such that replication cost is minimized and meanwhile the required content availability is maintained. To correctly execute programs on a Mesh, the key problem is replica consistency for ensuring that all replicas can reach the same state after executing the same set of events. As aforementioned, availability, consistency responsiveness,
and network partition tolerance are the main performance criteria. Moving to the application
layer, the replica consistency problem is complicated by the composition of event handling and
object simulation. The object simulation is determined by the object current state and the
duration length of execution. Thus, the different event arrival time on different replicas may
result in object state divergence. Moreover, the existing solutions in P2P virtual worlds can be
reused and adapted for inter-Mesh interaction. It may rely on some global information provided
by the P2P cloud. Since the P2P cloud can be simultaneously accessed by multiple Meshes and
their replicas, scalability is an important criterion in evaluation.

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