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Ubiquitous Virtual Reality: The State-of-the-Art

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Abstract—Today, virtual reality is becoming ubiquitous and tremendous trends. Ubiquitous virtual reality (uVR) realizes virtual reality on ubiquitous smart space. In this platform, u-Content has been introduced as a new kind of realism that will realistically mediate real space. To go beyond the boundary of virtuality, pervasive virtuality has been introduced as a better fusion of reality and virtuality that will enhance visualization of virtual environments towards what is considered as the 'true' virtual reality. This paper addresses the state-of-the-art of uVR by deciphering its definition, dimensions and features, the concept of pervasive virtuality and its characters, as well as a case study on intelligent machine space, called DIGILOG space.

Keywords— Ubiquitous virtual reality, u-content, virtuality, pervasive virtuality

I. INTRODUCTION

The emerging new computing paradigms have accelerated the convergence amongst different technologies and, thus, make the border between the actual and the virtual reality indistinguishable. Eventually, virtual reality and augmented reality (VR/AR) technologies are going to converge and align into a merging hardware which can either be wearable or carriable around by users all the time. For illustration, leap motion controller – a sensor device for hand tracking in virtual reality, it is designed as a small USB peripheral device which can be either placed on a physical desktop or mounted onto a virtual reality headset. The controller supports motions tracking using hand or finger motions as input, which requires no hand contact or touching [1]. Leap motion has taken a very big leapfrogged on the state-of-the-art of virtual reality, giving users the ability to control what is on their computers with hundredth of a millimeter accuracy and introducing touch-free gestures like pinch-to-zoom. This brings VR devices will become more ubiquitous than the smartphones in years to come.

Recently, users show tremendous demands to have more control in generating, sharing, and consuming digital contents in the various forms of VR/AR devices. Voice search is increasingly in demand. In 2018, 171 million people world-wide own virtual reality devices. The 360-degree video offers immersive content that drives higher emotional responses than 2D experiences to users. Augmented reality games like Pokemon-GO does not require specialist hardware and can be played through a mobilephone [2]. This tremendous trend has motivated us to draw a snapshot upon the application of VR that nowadays is becoming ubiquitous. This paper provides an overview on the concept of ubiquitous virtual reality for academicians and practitioners who are newly knowing about this concept. Section 2 describes the concept of ubiquitous virtual reality (uVR), Section 3 provides an overview of uVR key dimensions and features, Section 4 introduces the ubiquitous content (u-Content) and context (u-Context) in the uVR environment, Section 5 introduces the extended virtuality platform, so-called pervasive virtuality, Section 6 discusses the characters of pervasive virtuality, and Section 7 provides an illustration on intelligence machine space, i.e., Digilog Space. Finally, Section 8 provides summary on the topic as well as an insight on future research in ubiquitous virtual reality.

II. Ubiquitous Virtual Reality

Over the past few years, *ubiquitous virtual reality* has been studied by many researchers in order to apply virtual reality and its technology into ubiquitous computing environment. Ubiquitous computing and virtual reality reside in different realms, they have opposite characteristic, and yet have the same purpose, i.e., to maximize the human ability [3]. In this context, ubiquitous computing extends human abilities in the real space by developing networked infrastructures, smart objects, intelligent interaction, etc., while virtual reality extends human abilities in a virtual space which is constructed by computers.

Kim et al. [4] define ubiquitous virtual reality (u-VR) as the concept of realizing virtual reality on ubiquitous smart space, by making virtual reality *pervasive* into our daily lives and *ubiquitous* by allowing virtual reality to meet a new infrastructure, so-called ubiquitous computing. The basic concept of uVR is based on the seamless mapping between a virtual to world and the corresponding real world. The uVR becomes a means to extend the ability of human beings by letting things unable to work to have its power to do, in both virtuality and reality unless it is definitely impossible to perform in a virtual environment.

III.uVR: Key Dimensions and Features

Since the initial development, virtual reality has strived to build a computer-generated virtual environment to enable users to feel realism through their interaction with the environment that will stimulate the human beings basic senses: sight, hearing, touch, smell, and taste. Today, the advanced computing technologies in computer graphics, parallel/distributed computing, and high-speed network communications have enabled us to build alive virtual environments [5], which might embody distinguished features such as the sense of space, the sense of presence, the sense of time, a way to share and a way to communicate with [6]. Meanwhile, ubiquitous computing has become popular in our daily lives by allowing us to access computing resources and services anywhere, at any time [3]. By synchronizing these two capabilities in the form of uVR, we are looking forward ways to evolving virtual reality in the ubiquitous computing environments [7].

The uVR is featured by three key dimensions: reality, context, and human activity [8]. *Reality* can be represented as a reality-virtuality continuum (Figure 1), which introduces the concept of real-world and virtual-world simply as lying at the opposite ends of a continuum. On the left-side, real-world defines any environment solely consist of real objects. On the right-side, virtual-world defines environment solely consist of virtual objects, which might include conventional computer graphics simulation either monitor-based or in immersive environments. Within this continuum, a generic mixed reality environment exists as one, either in the form of augmented reality or augmented virtuality, in which real-world and virtual objects presents together within a single display that might occur at any point in the continuum [9].

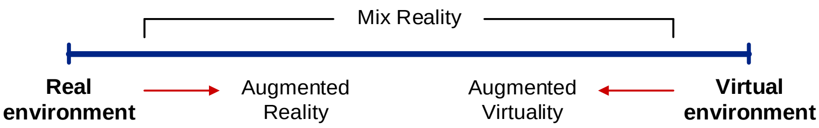


Fig. 1 Reality-virtuality continuum [7]

Context can be represented as a static-dynamic context continuum (Figure 2), which describes the outgrowth of information from static-context to dynamic-context used to create wisdom by intelligent analysis. Context is any information that can be used to characterize situation of an entity, whereby it can be a person, place, physical or computational object [10]. Context in real-world is changing according to time and space, so it can have different representation according to temporal and spatial granularity.

Fig. 2 Static-dynamic context continuum [7]

Activity in this context refers to an activity from a single user to a large community. Human activities can be classified into personal, community, and social activity and represented as a personal-social activity continum (Figure 3). Here social relationship and cultural context are crucial. Social relationship refers to relationship between members of a group and the digital contents, while they are interacting each others either directly or indirectly. Cultural context is a specific context which distinguish one community, populated by various individuals who come from different nationalities, cultures, educations, etc., with the others.

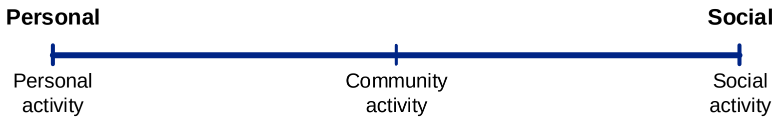
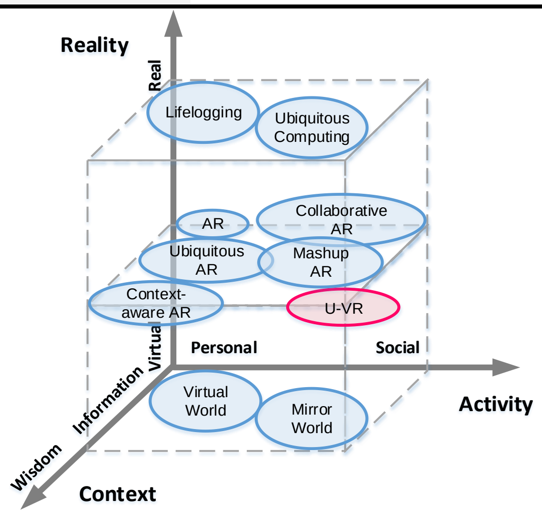


Fig. 3 Personal-social activity continuum [7]

Come across these three continua, various computing paradigms are found and can be classified as described in Table 1. The first paradigm is *virtual-world*. A virtual-world has low-resolution of reality, static context, and fairly low social activity since it is disconnected from the real-world. *Mirror world* is also static, but it reflects knowledge about users and social activities of real-world [11]. Mirror world has low-resolution of reality, but there exists dynamic context and social activity. On the other side, *real-world* has high-resolution of reality, nevertheless it has no context-awareness and no prior information on activity that will enable us to make personalization and adaptation of multiple information to a specific user or environment. Whilst, *collaborative augmented reality* (AR) [12], *mashup AR* [13],[14], *ubiquitous AR* [15], and *context-aware AR* [16] as well as *ubiquitous computing* support context-awareness and social activity. *Lifelogging* [17] tracks personal data generated by own behavioral activities. It has high-resolution of reality and supports context-awareness upon personal activity. Amongst those, *ubiquitous virtual reality* (uVR) takes place in between ubiquitous computing and mirror world. The uVR has middle-resolution of reality in comparison to real-world and mirror world, and it supposes to have rich context and social activity (Figure 4).

TABLE I
CLASSIFICATION OF COMPUTING PARADIGMS [5]

Computing Paradigms	Reality	Context	Activity
Virtual world	virtual	information	personal
Mirror world	virtual	knowledge	social
Collaborative AR	mixed	information	social
Mashup AR	mixed	knowledge	community
Ubiquitous AR	mixed	knowledge	personal
Context-aware AR	mixed	intelligence	personal
Ubiquitous VR	mixed	wisdom	social
Lifelogging	real	information	personal
Ubiquitous Computing	real	intelligence	community



Figu. 4 U-VR key dimensions [7]

The uVR has been developed to create seamless connection on dual reality environments. The uVR can superimpose and extend VR capabilities into a physical space, instead of confining VR to a simulated space. In this environment, digital content is augmented and seamlessly registered as linking information between the real and virtual spaces.

In general, uVR has three features: linking information, content registration between real and virtual spaces, and bidirectional interaction. In this regard, the *context of interest* (CoI) is a key technology used as a reference linking method to combine the real and virtual spaces. The CoI refers to context that receives user's attention about a specific target (e.g., point, object, person, position, movement, content, etc.) [16]. Using the CoI, users can collaborate with each other by sharing realistic content and the resources-sharing is achieved by directional interaction between the real and virtual spaces.

IV. U-CONTENT AND U-CONTEXT

The version of this template is V2. Most of the formatting instructions in this document have been compiled by Causal Productions from the IEEE LaTeX style files. Causal Productions offers both A4 templates and US Letter templates for LaTeX and Microsoft Word. The LaTeX templates depend on the official IEEEtran.cls and IEEEtran.bst files, whereas the Microsoft Word templates are self-contained. Causal Productions has used its best efforts to ensure that the templates have the same appearance. With the development of uVR and smart objects, the requirement for realistic content has changed [3],[18] which demands more high-quality of realism. Users expect to have more actual experience of the contents by using the human beings basic senses. At this point, the need to develop a new concept and representation of contents for uVR is inevitable.

Today, u-Content has been introduced as a new kind of realism. Kim et al. [19] define u-Content as any multimedia content used in the uVR environments, whereby '*u*' here stands for Ubiquitous Computing enabled contents. The u-Contents have three main properties: u-Realism, u-Mobility, and u-Intelligence. The proposed u-Contents offer some advantages. First, they improve realism based on personalized multimodal feedback with u-Realism. Second, they enable users to share the contents with other users through u-Mobility. Finally, they evoke users' interest through personalized response suitable to the users' experience, preference, emotion, prior information and so forth based on u-Intelligence [20].

The u-Contents will realistically mediate real space, intelligently respond to the user-centric contexts, and seamlessly migrate amongst the selected entities. Here the user-centric context, also called as u-Context, refers to user-centric information amongst a variety of contexts in the service environments that can be interpreted in terms of the u-Content descriptors, i.e., 5W1H: who, when, what, why, where, and how [21]. Whilst, the selected entity represents the closely related entities in one community that can be any person, place, or object [22]. In this context, mediated reality offers an environment where not only visual object can be added to augment the real-world experience, instead reality may also be diminished or altered, if desired [23].

Figure 5 illustrates the u-Contents continuum, where each axis represents three different level of completion: low, medium, and high. The u-Contents continuum starts from the existing multi-media contents at the origin and ends up at the proposed u-Contents services.

u-Realism. The u-Realism is a realistic mediation that adds virtual contents into or removes real entities from the real space by reflecting the users' and environmental contexts. In the continuum, the '*decoupled*' stage means that the contents are separated from the real space. '*Loosely-coupled*' means that the contents are linked and registered with real entities, but they can easily be distinguished. '*Seamless*' means that it is unknown whether the augmented content is real or virtual. Noteworthy, the image formation pipelines of the virtual contents and the real images are basically different, so this difference will reduce the realism of the contents. The enhancement of u-Realism can be achieved by reducing the differences between the augmented contents and the real scene. On this scene, in addition to matching different resolutions between two different contents in each space, issues related to calibration and tracking techniques for seamless registration of the contents must also be considered.

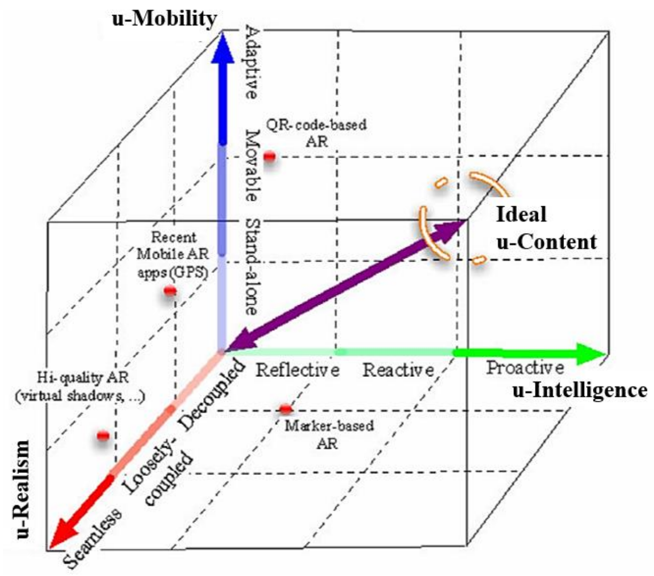


Fig. 5 The u-Contents continuum: u-Realism, u-Intelligence, u-Mobility [19]

u-Mobility. The u-Mobility is a property that enables u-Contents to be transmitted and translated in accordance with the characteristics of u-Mobility from one environment to the others as well as to the selected entities. In the continuum, the '*stand-alone*' stage means that the contents can be viewed through homogeneous devices. '*Movable*' means that the contents can be viewed through heterogeneous devices by migration. '*Adaptive*' contents can be viewed in any devices through the changing properties of the contents in dynamic situations in accordance with the targeted environments or devices. Here, there are three key issues must be considered in order to achieve the u-Mobility property. The first issue is *content transmission*, whereby it is necessary to consider the quality of the contents and support the real-time visualization. The second issue is *context-awareness*, particularly the environmental context information. The u-Contents as multi-media contents exist in real, virtual, and mixed environments. The u-Mobility allows the contents to migrate between those environments and context-awareness is required to adapt with the new environment. The third issue is *content privacy*. If contents are shareable, disclosure and privacy control must be considered. In particular, personal and social context have to be considered in order to determine how to share u-Contents with other users. Here social-context is realized by social network amongst users.

u-Intelligence. The u-Intelligence is a property in which contents respond to situational information with respect to a user and adaptively change its representations according to the user's explicit interaction and implicit states, i.e., intention, attention, and emotions [24]. In the continuum, the '*reflective*' responses happen through external factors directly. The '*reactive*' responses occur through a user, an object, and an environment, where the contents behavior is determined by the processing contexts. The '*proactive*' responses occur through prediction and forecasting. To produce responses, the contents memorize its prior experiences and predict situation and decide a behavior that might happen based on experiences in the past. The goal of using u-Intelligent is to offer users better experiences by providing them with the personalized, responsible content(s) in their everyday lives. Thus, the level of personalized responsiveness of contents can be divided into the following stages. Stage 1: contents respond to the users' interactions, regardless of their contextual information. Stage 2: contents customize the responses and representations according to the users' contexts, such as location, position, movement, etc. Stage 3: contents share the users' implicit contexts (e.g., intention, emotion with the users, etc.). To achieve key characteristics of u-Intelligent contents, basically the contents should have the ability to change the responses and representations in an autonomous way. In this regard, the context-awareness is needed to make contents reflect the user's contexts. Furthermore, in order to make users interact with the intelligent contents, the contents should perceive the users' interactions and respond to those interactions.

V. PERVASIVE VIRTUALITY

Today, most mixed-reality applications found in our daily life is simply juxtaposes real and virtual objects through the projection of visual artefacts. For instance, a common example of augmented virtuality is the video of a real human face projected on a 3D mesh of an avatar's head in a virtual world. At this point, the progress of virtuality has driven us to extend the Milgram and Colquhoun's taxonomy to accommodate other forms of mixed reality that can cope with situations where real physical objects are transformed into virtual objects, and vice-versa.

Valente et al. [25] proposed an extension of the Milgram and Colquhoun's taxonomy by incorporating new concepts: *augmented virtuality* and *pervasive virtuality* (Figure 6). These concepts represent a better fusion of reality and virtuality, which goes beyond a simple mapped visual projection. In these new environments, transformed objects should work as a proxy.

Essentially, augmented reality (AR) consists of a real-world environment augmented by a computer-generated perceptual information, sometimes across multiple sensory modalities – visual, auditory, haptic, somatosensory, and olfactory, superimposed on a user's view of the real-world. Augmented virtuality (AV) is different from augmented reality, as real-world objects are projected into virtual contents and the head-mounted display (HMD) devices that the user wears necessarily are see-through devices. Ubiquitous virtuality (UV) is a type of mixed-reality that integrates virtual objects seamlessly in the real environment and preserves as many human senses as possible. However, transforming virtual objects into real ones is a much more complicated task. In this regard, computational holography is a potential technology, although yet this research area still in its infancy. UV tends to evolve towards what is called as real virtuality (RV) – i.e., a virtual world so convincing that users cannot easily distinguish it from the real-world. As it is shown in Figure 6, a continuum of mixed-reality connects its two ends – real virtuality and virtual reality.

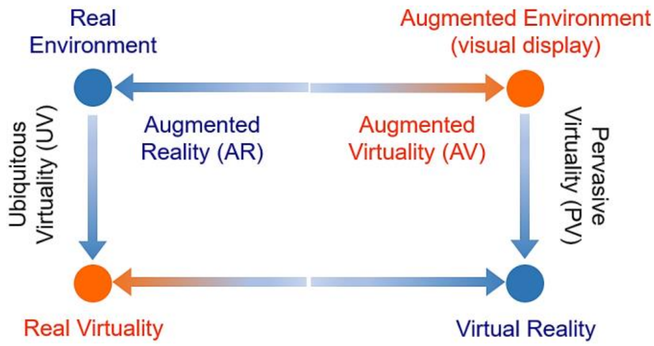


Fig. 6 The extended Milgram and Colquhoun's taxonomy of real and virtual environments [25]

Pervasive virtuality (PV) transforms physical objects into virtual equivalents, also called "proxy objects" [26] by representing their geometry in the virtual environment and tracking them with wireless networking systems. Furthermore, PV maps the real environment into the virtual environment through the compression and gain factors that apply to a user during immersion in virtual environments. PV enhances visualization of virtual environments towards what is considered as the true virtual reality (VR), i.e., an environment with a strong sensation of immersion and presence due to the existence of human senses.

VI. Characterizing Pervasive Virtuality

Pervasive virtuality is a mixed reality where real, physical, objects are transformed into virtual objects by using real-world information sources through direct physical contact and context aware devices (e.g., sensors and wearable technology). In PV users wear non-see-through HMDs all the time, which means that they do not see any real-world contents. PV usually requires intensive use of compression and gain factors on external world variables to adjust the transformation between reality and virtuality.

All content that a user experiences in PV is virtual. The simulation uses digital content and generates virtual content based on real-world information sources. These information sources are: (*i*) physical environment architecture, (*ii*) physical objects that reside in the environment, and (*iii*) context information.

The first source, PV takes place in a simulation stage, or a game stage in the case of games, which consists of a physical environment (e.g, an office, school room, playground, etc.) equipped with infrastructure to support the activities (e.g., wireless networking, sensors, or physical objects). The simulation (or game) uses these elements to create the mixed reality.

The second source, in PV a user wears a non-see-through HMD device and walks in the physical environment, being able to touch physical walls and other elements. In this context, user sees a 3D virtual-world through the HMD and does not see the real-world. The simulation constructs a virtual-world based on the physical environment architecture (i.e., the first information source) in a 1:1 matching and keeping these two worlds superimposed. The simulation detects physical objects (e.g. furniture, portable objects, and users' bodies) as the second information source and maps them into virtual representations, which are then displayed to the user. Users touch, grasp, carry, and move these physical objects, however, what they can see only their virtual representation.

The third information source is context information [22], in which the simulation may use to generate virtual content and to change the rules or simulation behaviour, i.e., unpredictable experiences and emergent gameplay. Some examples of context information include: (*i*) player information (e.g., physiological state, personal preferences, personality traits), (*ii*) physical environment conditions (e.g., temperature, humidity, lighting conditions, weather), (*iii*) information derived from the ways a player interacts with physical objects and input devices, and (*iv*) information derived from relationships and interactions among players in the game, i.e., the social context.

A PV application may respond back to the user through various channels and various types of media. Some of these channels may be worn or carried by users and some of them correspond to physical objects, which are spread in the physical space (e.g., smart objects, smart environment, etc.). Here users may interact in PV through multiple modalities (e.g., voice, body movements and gestures), ordinary physical objects, and context-aware devices.

VII. DIGILOG: INTELLIGENT MACHINE SPACE

Many efforts have been done to merge the real-world and virtual-world with either physical or contextual methods and to provide intelligent services and contents in the environment. In this platform, uVR supports the expansion of human ability in real environment, almost the same as human ability in virtual environments, with the support of various technologies where sensors are installed in the intelligent space to acquire and process data in order to understand the existing situation and context in the environment, and provide adaptive or personalized services to the users.

Lee at al. [27] introduce DigiLog space as an intelligent machine space where virtual and real world are merged and human and robots are coexist. Here ‘merging’ means that matching the real and mirrored (virtual) world with 3D coordinates, context of interest (CoI), and bidirectional exchange of information between the real and mirrored world. The mirrored world represents database for storing data and information of the real world, which can be built by using the uVR infrastructure such as UCAM or CAMAR that is filled with the contextual information.

UCAM stands for Unified Context Aware Application Model, which connects sensors and applications by using a unified context in the form of 5W1H. UCAM has evolved in three areas: ubi-UCAM, vr-UCAM, and wear-UCAM. The ubi-UCAM is built for ubiquitous computing environment in real world, vr-UCAM is for virtual environments, and wear-UCAM is for human body area, i.e. wearable computing environments [28-29]. UCAM has been replaced by Context-aware Mobile Augmented Reality platform (CAMAR) [30-31]. CAMAR enables users interact with smart objects through a personalized control interface on a mobile AR device. It also supports the enabled contents to be not only personalized, instead also selectively and interactively shared amongst users. CAMAR architecture is mainly composed of two parts: context-aware framework for a mobile user (UCAM) and AR application toolkit using OpenScene Graph [32].

In Digilog space, visualization is constructed by combining the physical real world and its mirrored world to realize the 4D+ augmented reality through real-time dual space registration using the CoI-based information. In this process, Digilog space should satisfy the following requirements: (1) *m*:*m* (*many* to *many*) mapping of 3D link between real and virtual space, (2) immersive human-senses augmentation in real space, and (3) bidirectional interaction on the fly in the linked dual space [33-36]. Here, a feature map is set of features for dual space registration that reflects information about the environment (e.g., lighting changes) and detection/tracking information of CoIs. To achieve this capability, Digilog space uses RGB-D feature map that enables real-time registration and update in the dual space which is robust to changes in lighting as well as condition in featureless environment.

For real-time and stable dual space registration, RGB-D feature map descriptor is used for characterizing strong and invariant image features by systematically exploiting color and depth information (e.g., textureless, poor lighting, multiple deformable moving objects, heterogeneous camera devices, etc.) when exploiting the color (RGB) information. The RGB-D feature map is built by taking an object’s texture from the RGB image and an object’s geometry from the depth image, then combined both information for 3D object detection (Figure 7). It provides robust 3D object detection under extreme change in lighting as well as on textureless objects [37-39]. Furthermore, it can also be used for tracking the camera pose through consecutive frame-to-frame image tracking and matching it with its depth image, whereby all data are acquired on the fly [40-41].

Figure 8 shows a textureless 3D object detection and tracking which extracts information on the RGB images and the corresponding depth maps on the fly. The real-time 3D object detection and tracking is done in the following stages:

(*i*) user selects a 3D object (Figure 8a) in the first frame of a training sequence by defining its position with respect to a known pattern and a bounding box. This pattern defines the object coordinate system.

(*ii*) the camera moves and the system captures the DOT (Dominant Orientation Templates) templates of the object and the corresponding depth maps from the new viewpoints (Figure 8b). DOT is a method for real-time object detection, which works well for detection of untextured or textureless objects. DOT is neither based on statistical learning of object’s shapes nor on feature point detection, instead it uses real-time ‘template matching’ recognition with locally most dominant orientations from the Histograms-of-Gradients (HoG) template matching approach [42].

(*iii*) as the results, 3D objects can be tracked under different viewpoints (Figure 8c) including under partial occlusion (Figure 8d) and fast motion (Figure 8e), whereby the whole process need neither any prior information of CAD model nor the objects have to be textured.

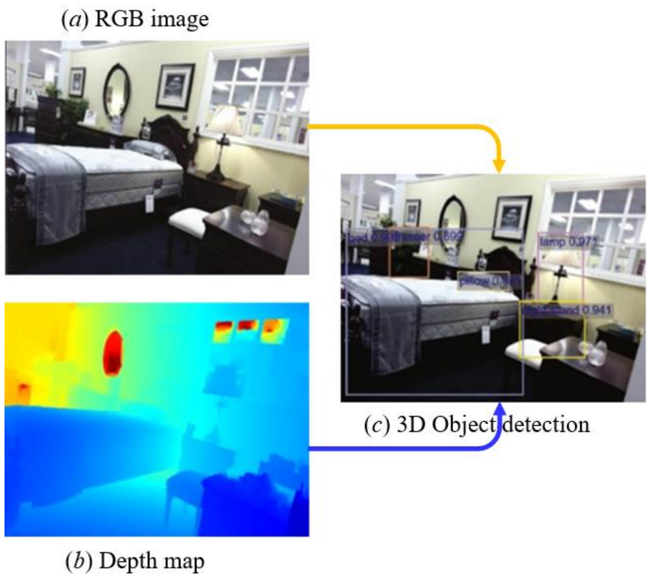


Fig. 7 RGB-D Feature map: (*a*) RGB image, (*b*) depth map, (*c*) 3D object detection [39].

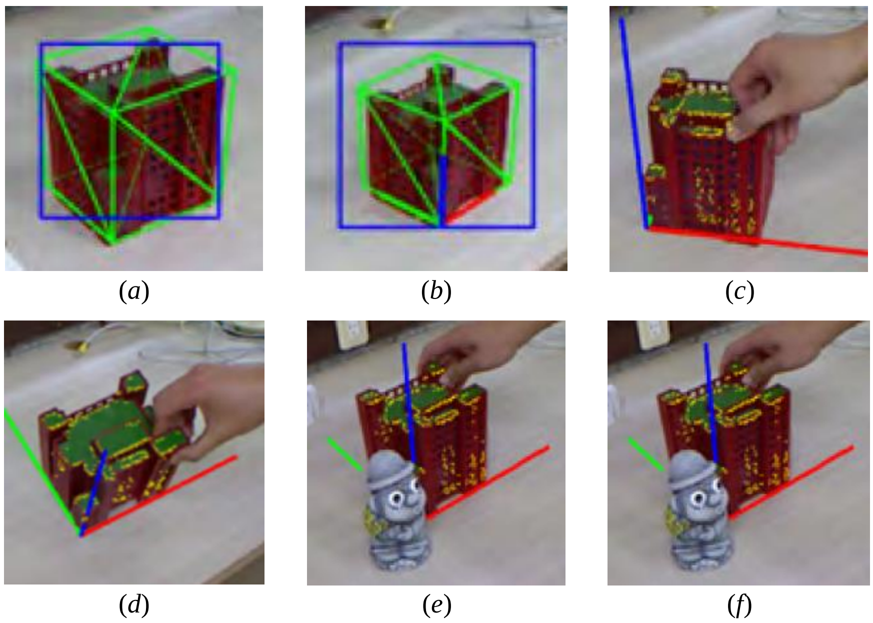


Fig. 8 Real-time 3D object detection and tracking: (*a*) object selection, (*b*) DOT template of the object and the corresponding depth map from the new viewpoint, (*c*) tracking 3D object under viewpoint 1, (*d*) tracking 3D object under viewpoint 2, (*e*) 3D object under partial occlusion, and (*f*) 3D object under fast motion [40].

VIII. CONCLUDING REMARKS

This paper provides an overview on the state-of-the-art of Ubiquitous Virtual Reality. Nowadays, the application of virtual reality is becoming ubiquitous and tremendous trends. The uVR realizes virtual reality on ubiquitous smart space, by making virtual reality 'pervasive' and 'ubiquitous' in our daily lives. The uVR is featured by three key dimensions: reality, context, and human activity. It has three features: linking information, content registration between real and virtual spaces, and bidirectional interaction, whereby the *context of interest* (CoI) is a key technology used as a reference linking method to combine the real and virtual spaces. On this platform, u-Content has been introduced as a new kind of realism that will realistically mediate real space, intelligently respond to the user-centric contexts, and seamlessly migrate amongst the selected entities.

Moreover, to go beyond the boundary of virtuality, pervasive virtuality has been introduced as a better fusion of reality and virtuality. Pervasive virtuality enhances visualization of virtual environments towards what is considered as the true virtual reality, where users can move in and have a strong sensation of immersion and presence using the human beings basic senses.

On this platform, uVR supports the expansion of human ability in real environment, near to human ability in virtual environments, with the support of sensory systems to acquire data from the environment and provide adaptive or personalized information to the users. This is one of the key advantages of uVR.

In this paper, one example of intelligence machine space, so-called DIGILOG space has been discussed. DigiLog space combines physical real world and its mirrored world to realize a 4D+ augmented reality, where human's activity can be spatially and temporally extended by sharing and experiencing the mirror world's information. This could be applicable to VR/AR-based time/space-transcended smart work, next-generation experimental education, VR/AR simulation, video-based survey, VR/AR medical information, and VR/AR entertainment.

REFERENCES

[1] D. Terdiman, "Leap Motion: 3D hands-free motion control, unbound," Cutting Edge, cnet, October 2018, available at https://www.cnet.com/ news/leap-motion-3d-hands-free-motion-control -unbound

[2] Digital Strategy Consulting, "The future of content marketing: VR, AR and video," October 2018, http://www.Digitalstrategyconsulting.com/intelligence/2018/08/the_future_of_content_marketing_vr_ar_and_video.php

[3] M. Weiser, "Computer of the 21st Century," Scientific American, Vol. 265(3), September 1991, pp. 94-104.

[4] S. Kim, Y. Lee and W. Woo, "How to realize ubiquitous VR?" in Pervasive, TSI Workshop, 2006, pp. 493-504.

[5] J.C.S. Lui, "Constructing communication subgraphs and deriving an optimal synchronization interval for distributed virtual environment systems," IEEE Trans. On Knowledge and Data Engineering, Vol. 13(5), September 2001, pp. 778-792.

[6] S. Singhal and M. Zyda, Networked Virtual Environments: Design and Implementation, 1st ed., Boston: Addison-Wesley, 1999.

[7] Y. Lee, S. Oh, C. Shin and W. Woo, "Ubiquitous virtual reality and its key dimension," International Workshop on Ubiquitous Virtual Reality (IWUVR'09), 2009, pp. 5-8.

[8] Y. Lee, S. Oh, C. Shin and W. Woo, "Recent trends in Ubiquitous Virtual Reality,“ International Symposium on Ubiquitous Virtual Reality (IWUVR'08), 2008, pp. 33-36.

[9] P. Milgram and F. Kishino, "A taxonomy of mixed reality visual displays", IEICE (Institute of Electronics, Information and Communication Engineers) Transactions on Information and Systems, Special issue on Networked Reality, December 1994.

[10] G.D. Abowd, A.K. Dey, P.J. Brown, N. Davies, M. Smith and P. Steggles, "Towards a better understanding of context and context-awareness," in HUC'99: Proceedings of the 1st international symposium on Handheld and Ubiquitous Computing, London: Springer-Verlag, 1999 pp. 304–307,.

[11] J. Smart, J. Cascio and J. Paffendor, "Metaverse roadmap overview: Pathways to the 3D web," MVR Summit, 2007.

[12] T. Brockmann, N. Krueger, S. Stieglitz and I. Bohlsen, "A framework for collaborative augmented reality applications," in Hyperconnected world: Anything, anywhere, anytime, The 19th Americas Conference on Information Systems (AMCIS-2013), Vol. 1, New York: Curran, 2013, pp. 83-92.

[13] J. Gliet, A. Krüger, O. Klemm and J. Schöning, "Image geomashups: The example of an augmented reality weather camera," in Proceedings of Working Conference on Advanced visual interfaces (AVI'08), New York: ACM, 2008, pp. 287–294.

[14] H. Yoon and W. Woo, "Concept and applications of in-situ AR mashup content," in Proceeding of the First International Symposium on Social and Community Intelligence (SCI'11) In Conjunction with UbiComp 2011, September 2011, pp. 43-48.

[15] X. Li, D. Chen and S. Xiahou, "Ubiquitous augmented reality system," in Proceeding of The Second International Symposium on Knowledge Acquisition and Modeling (KAM'09), IEEE Xplore, 2009, pp. 91-94, doi: 10.1109/KAM.2009.312

[16] J. Park, C. Kang, S. Oh, H. Lee and W. Woo, "Context-aware augmented reality authoring tool in digital ecosystem," in International Symposium on Ubiquitous Virtual Reality (ISUVR), IEEE Xplore, 2010, pp. 16-19, doi: 10.1109/ISUVR.2010.14

[17] C. Gurrin, A.F. Smeaton and A.R. Doherty, "LifeLogging: Personal Big Data," in Information Retrieval, Vol. 8(1), 2014, pp. 1-125, http://dx.doi.org/ 10.1561/1500000033

[18] M. Weiser, "Some Computer Science Issues in Ubiquitous Computing," Communications of the ACM, Vol. 36(7), July 1993, pp. 75-84.

[19] K. Kim, J. Han, C. Kang and W. Woo, **"**Visualization and management of u-Contents for Ubiquitous VR," in Virtual and Mixed Reality – Systems and Applications, Proceeding of The 4th International Conference on Virtual and Mixed Reality 2011, R. Shumaker (Ed.), Heidelberg: Springer-Verlag, July 2011, pp. 352-361, ISBN: 978-3-642-22023-4.

[20] S. Oh, W. Lee, Y. Park, W. Woo, "u-Contents: New kinds of realistic and affective contents in ubiquitous smart space," International Symposium on Ubiquitous Virtual Reality (ISUVR 2006), July 2006, pp.13-16.

[21] D. Hong, H.R. Schmidtke and W. Woo, "Linking context modelling and contextual reasoning," in the 4th International Workshop on Modeling and Reasoning in Context (MRC), July 2007, pp. 37-48.

[22] A.K. Dey, "Understanding and using context," Personal Ubiquitous Computing, Vol. 5, 2001, pp. 4-7.

[23] S. Mann, "An historical account of the 'wearcomp' and 'wearcam' inventions developed for applications in 'personal imaging'," in Proceedings of the 1st International Symposium on Wearable Computers (ISWC'97), IEEE Xplore, October 1997.

[24] S.B. Cho, K.J. Kim, K.S. Hwang and I.J. Song, "Anidiary: Daily cartoon-style diary exploits Bayesian Networks," IEEE Pervasive Computing, Vol. 6, 2007, pp. 66-75.

[25] L. Valente, B. Feijó, A. Ribeiro and E. Clua, "The concept of pervasive virtuality and its application in digital entertainment systems," in Entertainment Computing – Proceedings of the 15th International Conference on Entertainment Computing (ICEC'16), G. Wallner, S. Kriglstein, H. Hlavacs, R. Malaka, A. Lugmayr, H-S. Yang (Eds.), Vienna: Springer, 2016, pp. 187-198.

[26] F. Steinicke, T. Ropinski, G. Bruder and K. Hinrichs, "The holodeck construction manual," in ACM SIGGRAPH 2008, Posters, New York: ACM, 2008, pp. 97:1-97:3.

[27] Y. Lee, Y.J. Ryoo, J. Choi and S. Moon, "Intelligent machine space for interacting with human in Ubiquitous Virtual Reality," in Distributed, Ambient, and Pervasive Interactions, N. Streitz and C. Stephanidis (Eds.), Springer, 2013, pp. 459-465, ISBN 978-3-642-39350-1.

[28] D. Hong, Y. Suh, A. Choi, U. Rashid and W. Woo, "Wear-UCAM: A toolkit for mobile user interactions in smart environments," in EUC 2006. LNCS, vol. 4096, E. Sha, S.-K. Han, C.-Z. Xu, M.-H. Kim, L.T. Yang and B. Xiao (Eds.), Heidelberg: Springer, 2006, pp. 1047–1057.

[29] Y. Lee, S. Oh, Y. Suh, S. Jang and W. Woo, "Enhanced framework for a personalized user interface based on a Unified Context-aware Application Model for Virtual Environments," IEICE Transaction on Information and Systems, Vol. 90-D, 2007, pp. 994–997.

[30] Y. Suh, Y. Park, H. Yoon, Y. Chang and W. Woo, "Context-Aware Mobile AR system for personalization, selective sharing, and interaction of contents in ubiquitous computing environments," in HCI 2007. LNCS, vol. 4551, Jacko, J.A. (Ed.), Heidelberg: Springer, 2007, pp. 966-974.

[31] S. Oh and W. Woo, "CAMAR: Context-aware mobile augmented reality in smart space," in International Workshop on Ubiquitous Virtual Reality, 2009, pp. 48-51.

[32] D. Hong and W. Woo, "CAMAR core platform," in Proceedings of the 5th International Symposium on Ubiquitous Virtual Reality (ISUVR'07), July 2007, Paper-260.

[33] H. Kim, G. Reitmayr and W. Woo, "IMAF: In-situ indoor modelling and annotation framework on mobilephones," Personal and Ubiquitous Computing, Vol. 17(3), 2012, DOI: 10.1007/s00779-012-0516-3.

[34] Y. Oh, T. Ha, C. Kang and W. Woo, "Conceptualizing u-Content ecosystem in Ubiquitous VR environments," International Symposium on Ubiquitous Virtual Reality (ISUVR'11), 2011, pp. 13-16, ISBN 978-1-4577-0356-0.

[35] Y. Oh, S. Duval, S. Kim, H. Yoon, T. Ha and W. Woo, "Foundations of a new digital ecosystem for u-Content: Needs, definition and design," in Virtual and Mixed Reality - Systems and Applications, R. Shumaker (Ed.), LNCS 6774, 2011, pp. 377-386, ISBN 978-3-642-22023-4.

[36] K. Kim, J. Han, C. Kang and W. Woo, "Visualization and management of u-Contents for Ubiquitous VR," in Virtual and Mixed Reality - Systems and Applications, R. Shumaker (Ed.), LNCS 6774, 2011, pp. 352-361, ISBN 978-3-642-22023-4.

[37] W. Lee, N. Park and W. Woo, "Depth-assisted real-time 3D object detection for augmented reality," in Proceedings of the 21st International Conference on Artificial Reality and Telexistence (ICAT'11), November 2011, pp. 126-132, ISSN: 1345-1278.

[38] W. Lee, Y. Park, V. Lepetit and W. Woo, "Video-based in-situ tagging on mobile phones," IEEE Transactions on Circuits and Systems for Video Technology, Vol. 21(10), 2011, pp. 1487-1496.

[39] X. Xu, Y. Li, G. Wu and J. Luo, "Multi-modal deep feature learning for RGB-D object detection," Pattern Recognition, Vol. 72, December 2017, pp. 300-313.

[40] Y. Park, V. Lepetit and W. Woo, “Texture-less object tracking with online training using an RGB-D camera,” in Proceedings of the 10^{th} IEEE International Symposium on Mixed and Augmented Reality (ISMAR’11), October 2011, pp. 121-126, ISBN 978-1-4577-2183-0121-126.
[41] Y. Park, V. Lepetit and W. Woo, “Handling Motion-Blur in 3D Tracking and Rendering for Augmented Reality,” IEEE Transactions on Visualization and Computer Graphics, Vol. 18(9), 2012, pp. 1449-1459.
[42] S. Hinterstoisser, V. Lepetit, S. Ilic, P. Fua and N. Navab. “Dominant Orientation Templates for Real-Time Detection of Texture-Less Objects,” in Proceedings of IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR’10), June 2010.

