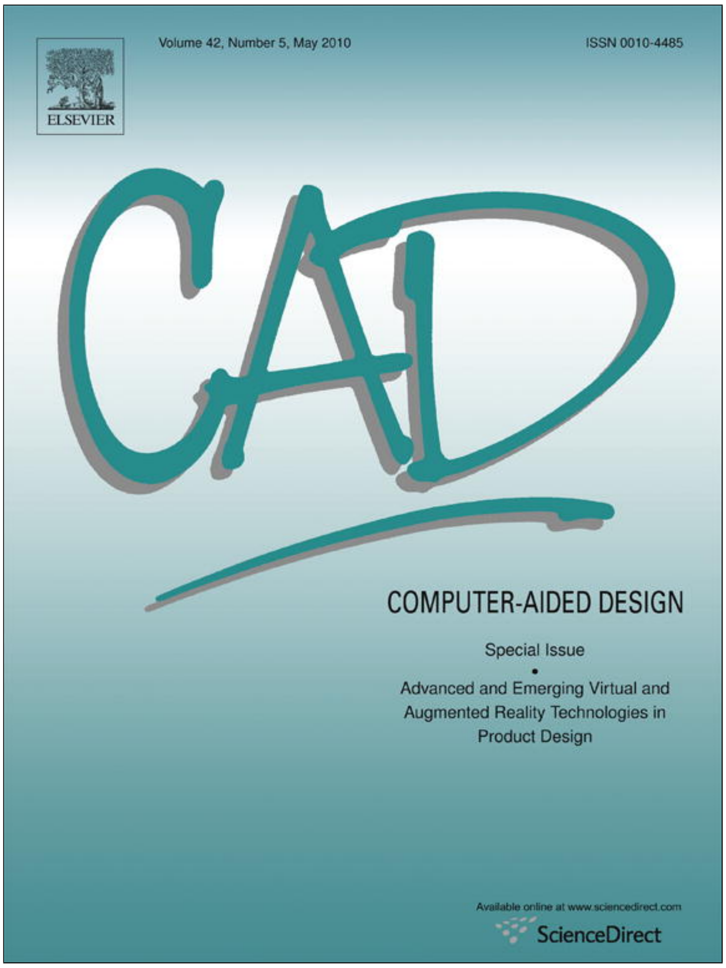
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AR interfacing with prototype 3D applications based on user-centered interactivity

Seungjun Kim *, Anind K. Dey

Human-Computer Interaction Institute (HCII), School of Computer Science, Carnegie Mellon University (CMU), 5000 Forbes Avenue, Pittsburgh, PA 15213-3891, USA

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A B S T R A C T

Augmented Reality (AR) has been acclaimed as one of the promising technologies for advancing future UbiComp (Ubiquitous Computing) environments. Despite a myriad of AR applications and its influence on the human–computer interaction field, end products that integrate AR are less commonplace than expected. This is due to a lack of being able to forecast in which direction mainstream standardization of AR-oriented platform components will be framed. It is mainly due to a focus on technology issues in implementing reasonable AR solutions, which also results in difficulty in initiating AR research and creating prototype test-beds. Thus, this paper provides a comprehensive review of AR prototyping trends and AR research activities. Through the technical review of a *de facto* AR prototyping method, we remark upon the key elements of AR techniques, and then present an alternative view of the AR environment centered on end-user advantages in interaction, which is characterized by three features: *intuitive observation*, *informative visualization*, and *immersive interaction*. In addition, we believe that these features can be used to motivate the integration of AR technology into custom-built 3D applications. In this paper, we propose a conceptual schema and an architectural framework for generic AR prototyping. On the basis of these, a video see-through AR interface is integrated into three prototype 3D applications in 3 different domains: *engineering systems*, *geospace*, and *multimedia*. As the case studies for validating our integration, we present three sample AR applications; (a) an AR-interfaced 3D CAE (Computer-Aided Engineering) simulation test-bed, (b) a two-stage distributed Traveler Guidance Service (TGS) test-bed based on a GIS database and AR, and (c) a haptically-enhanced broadcasting test-bed for AR-based 3D media production. For each application, a description of the test-bed implementation, demonstration of the feasibility and usefulness and AR-specific technical challenges are included in this paper.

1. Introduction

Amid the flood of digital information and multimedia services, our physical world has become increasingly complicated, but also progressively systematic. With the rapid growth of computing and interfacing technology it has been possible to facilitate easy and comfortable use of these services as exerting a significant influence on the Human–Computer Interaction (HCI) field. In addition, Computer-Aided Design and Manufacturing (CAD/CAM) tools have enabled us to reproduce physical world elements in computing space. Furthermore, newly-designed hardware or novel multimedia services can be tested and evaluated in advance of their practical application. Hence, the burden of unexpected cost and pitfalls of designing and implementing new services has been dramatically reduced, while facilitating the exploration of how they can be applied to enhance real-world task performance.

Although the creation of interactive virtual environments originates in the computer graphics or interfacing domain, the ultimate goal is to apply it to the real world for practical purposes [60](a). Fundamentally, computer-generated artificial world has confined user interaction and user's attention to the computing space. In virtual environments, the user has to be divorced from the real environment in order to be completely immersed in an artificial world. In particular, in the case that a user has to decide when to simultaneously engage in real world, divided attention and divorced interaction can unexpectedly and negatively impact task performance and safety. At this point, as a recent effort to resolve this problem, we need to note the concept of IAP (Interactive Augmented Prototyping) or tangible virtuality which employs augmented (or mixed) reality and rapid prototyping technologies to combine virtual and physical prototypes for the purpose of creating product models with an embodied/tangible high level of engagement and with a shorter manufacturing time than high-fidelity physical prototypes [61](a, b).

At the same time, we should note that the recent sweeping shift toward ubiquitous computing makes computers become invisible

* Corresponding author. Tel.: +1 412 268 9288; fax: +1 412 268 1266.
E-mail addresses: sjunikim@cs.cmu.edu (S. Kim), anind@cs.cmu.edu (A.K. Dey).

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and pervasive by degrees. Also in this context, AR (Augmented Reality) has been increasingly noted as one of the interfacing technologies that promise future UbiComp environments in that it acts as a mediator between the physical space and computing space by associating virtual information processed by a computer with the current physical environments of the end-user. Through the use of see-through displays combined with 3D tracking technologies, the virtual information can be seamlessly and dynamically superimposed on the real environment in the user's dynamic eye-view. In spite of the fact that the appearance of an AR scene looks like a composite image of artificial graphic images and a real environment photograph, AR blurs the cognitive distinction between the physical world and the user interface, which is analogous to the idea of ubiquitous computing as described by Weiser [63]. While ubiquitous computing focuses on the computer becoming invisible among the objects of everyday life, augmented reality seeks to add to the experience of reality by creating new forms of interaction between humans and computers [47]. Nevertheless, according to a comprehensive review of AR prototyping trends and the accompanying technical issues conducted in this study, we note that the major difficulty in designing AR-based test-beds has been due to technology-specific approaches as well as to the ambiguity of the system elements required for minimal AR prototyping. In addition, the advantages for end-users in adopting AR systems have not been made clear, making it particularly challenging researchers, developers or designers when they first initiate AR research.

To address these issues, in this paper, we provide a conceptual schema and an architectural framework for the generic prototyping of AR-incorporated applications, which support noteworthy user-centered features such as *intuitive observations*, *informative visualizations* and *immersive interactions*. These features can provide developers with the motivation for adopting AR interfacing methodology, especially for extending the effective human–computer interaction and user interface design far beyond current computer graphics. To demonstrate these features, we have integrated our AR interfacing method into three sample prototype applications which have a high potential for 3D technology incorporation for enhanced practical use in the present or near future, and validated their feasibility and usefulness. AR has anchored its origination in 3D space and graphics, thus we could expect these 3D applications have greater potential for being integrated with an AR interface. To further illustrate the generality of our approach, our three prototype applications fall into three very different domains: *engineering systems*, *geospace*, and *multimedia*. Aiming at highlighting the features of the AR-interfaced environment, our test-beds have been implemented with a focus on how the target model virtually reproduced in computing space can be seamlessly combined with the real environment using AR methodology in a reliable test-bed in order to offer enhanced functions or services. After demonstrating our three case studies in detail, we discuss an outlook for the promising direction of future AR-based product design.

2. Review of augmented reality

2.1. AR prototyping trends

The prototyping trends of AR applications can be technically classified by their display system type, which are also a source of different technical concerns. Firstly, a variety of AR research has employed head-worn display systems such as optical and video see-through head-mounted displays (HMDs), heads-up displays (HUDs), helmet-mounted sights and virtual retina displays (VRDs). In these cases, computer-generated (CG) images appear just in front of the viewer's eyes like an illusion such that in the screen view, virtual objects actually appear to be in the real workspace. To this extent, one of the main focuses is how the displayed CG images can be interactively modified to follow the eye gaze of the user. Including the early discussion in [7](a, b), plenty of technical issues related to the HMD-incorporated AR system setup have been widely addressed. In AR applications using head-worn display systems, both the 3D content to be overlaid and 3D space context are so important that there have been a significant number of reports regarding immersive 3D media as well as accurate 3D tracking [20,27]. HMDs have also been an indispensable subsystem in wearable computers for outdoor navigation, such as in the Tinmith [59,41] and MARS [37] project.

The next approach is the direct projection of CG images onto physical environments like real desks or walls, which are also tracked in the 3D space context. Rekimoto [48] have presented this type of display as an augmented surface system; projector-based display systems and holograms are included in this type of display. In the view of informatics and ubiquitous computing, projected graphic images are complementary superimposed as auxiliary informative aids, so designing realistic 3D information media to be overlaid can be relatively less emphasized, even though accurate 3D tracking technology is still indispensable for user's tangible interaction. Therefore, in this case, the technical issues are mainly concerned with how the CG images can be properly laid out onto the real workspace where users want the visual information, rather than on how the CG images can be interactively modified according to user's view position. The IBM Research Division in the Thomas J. Watson Research Center illustrates examples of projector-based ubiquitous interactive displays [57]. Their ED (Everywhere Displays) projector has been tested in various applications: an electronic phone directory, a file cabinet, an emergency sign, and in retail uses [43,42]. We have noted that AR shows informative visualization aspects effectively even if the superimposed CG image is not in a photo-realistic 3D form. Such attention to visualization aspects has been investigated in depth by Bimber & Raskar [9] in terms of 'Spatial AR'.

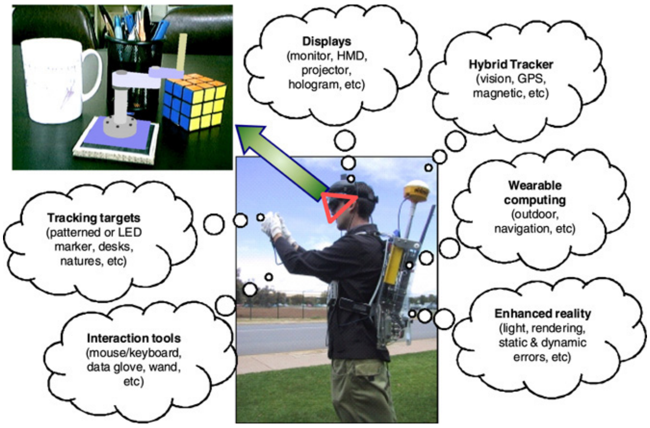

Fig. 1. Near full-featured AR system setup (Central subimage: Tinmith AR system [59]).

2.2. Technical review of an AR prototyping system

Fig. 1 shows the near full setup of an AR system, which can be utilized in both indoor and outdoor applications. To register computer-generated (CG) objects seamlessly with the real environment in the view of the user, as shown in the top left subfigure, we need to estimate the spatial relationship between the viewer's present viewing position and the physical environment. Consequently, tracking components have become one of the most indispensable modules in AR system setup, and are also the main difference between an AR environment and a fully synthetic VE (Virtual Environment). To date, VR (Virtual Reality) techniques have been devoted to the reproduction of the physical objects in the form of fancy and manipulatable CG objects, and therefore high-performance rendering with immersive displays have naturally been taken into consideration. However, AR has mainly focused on placing CG objects pervasively around the real environment to complement reality such that see-through displays or accurate tracking methods have become the main technical concerns.

To overcome some of these obstacles, first we need a 3D *tracking module* and *physical targets to be tracked* in the real environment. A typical tracking method in AR is the vision-based approach in which one or two cameras are usually attached on the top-front of an HMD to acquire the user's viewpoint, and some fiducials are deployed as the tracking targets including LEDs, patterned markers, colored dots or even real objects. Computer-vision and image processing techniques can be used in this vision-based approach. Ultimately, the 3D tracking module enables the positioning of CG objects in the 3D real environment scene. In his dissertation, Piekarski [41] discussed 3D tracking technologies used in AR system frameworks and summarized the different characteristics of various tracking systems based on a survey of Holloway [29].

Continuing the descriptions of problems to overcome, we now discuss the *AR contents* (computer-generated images) to be overlaid on the real environment scene. The AR contents are directly related to the purpose of supporting AR interfaces in an application. If the contents have to be supplied so as to appear as a kind of complementary visual information, graphical quality or fidelity matters less. Instead, the informative layout of the contents at the right service time is more important. However, if the pervasiveness of the contents is very critical in the application, the operations of a number of graphical techniques have to be considered in the rendering or tracking process. For example, if the contents have to react responsively to the lighting condition of the real environment, then a light sensing and analyzing module is additionally required in the system setup stage for the realistic generation of shade or shadows of the contents based on accurate 3D tracking. It is noted here that subsystem modules in an AR system can be arranged differently according to the required role of the AR contents in the overall application.

Another indispensable module of an AR system is the *display system*. In Section 2.1, we discussed two major trends in display systems for AR applications: Personal Head-Worn Displays and Spatial Displays. In fact, a number of various display systems have been selectively employed in AR test-beds; however, these fully-integrated 3D display systems can be set aside while prototyping a sample AR application, especially while trying to understand the application's feasibility and usefulness in the validation stage. An early monitor-based AR system setup is sufficient for validating the effectiveness of the AR interface with new prototype applications.

Finally, user-friendly 3D interface and wearable computer have been also very promising research branches of AR. Poupyrev [45] have divided the AR interface design space along two orthogonal approaches: 3D AR interfaces and tangible interfaces. The 3D AR interfaces [33,51,28,3] let the user interact with virtual content through different input devices due to the use of a head-mounted display; however the user must work with special-purpose input devices, separated from the tools used to interact with the real world. Conversely, tangible interfaces [48,64,22] let users access interface functions and use traditional tools in the same manner—through the manipulation of physical objects leveraging the characteristics of seamless interaction. However, changing an object's physical properties dynamically is difficult, and these interfaces usually project virtual objects onto 2D surfaces. To this extent, the type of interaction method in AR applications can be devised differently according to the overall system configuration and interaction purposes. For example, in outdoor applications like Tinmith [59] and MARS [37] project, a wearable computing module should be incorporated for mobility although it can be dispensable in other applications. Furthermore, in a typical vision-based setup, hybrid tracking or complex image processing modules may be required for the reliable registration of CG entities on target placement because light conditions can easily interfere with captured video images.

2.3. AR research activities

In this paper, comprehensive AR research activities have been investigated centered on the authors of AR survey papers; while we attempted to include all significant groups, limited time and space may have resulted in some unintended omissions. In Fig. 2, the AR research has been summarized more focused on the linked collaboration activities between researchers and the detailed review on each group has been dealt with in [32](b). We can perceive how their present AR items have evolved and been affected by the others.

3. Overview of our sample prototype applications

3.1. Application itemization

Based on a comprehensive review of AR interfacing technologies, we have specified the key elements of AR techniques as well as the features of the AR environment to be remarked upon. An AR environment can be initiatively set up with four essential elements: *target places*, *AR contents*, a *tracking module*, and a *display system*. A *target place* represents an object to be tracked or surface to be augmented in the real environment. *AR contents* refer to a computer-generated object or visuals to be superimposed onto the real objects. They should be informative so as to be valuable and useful media. The *3D tracking module* helps us to determine where and in which pose the AR contents have to be overlaid. This has been determined to be the main difference with respect to a fully synthetic virtual environment. The final element is a *display system* which renders and projects the AR contents in such a way that they are superimposed seamlessly on the target place. With these primary elements we can cause the AR contents to be pervasively placed on the real environment as if it were an actual physical object in the user's dynamic eye-view. Consequently, this AR environment displays the characteristics of *intuitive observation*, *informative visualization* and *immersive interaction*. Fig. 3 demonstrates that augmented reality can be used for more that just purely its visual aspects, but is extendable to anything that can be artificially virtualized, including other sensations such as auditory and haptic elements. Our physical world contains the resources of artificial (computer-generated) sensations. At the same time, the components in it can be virtualized in computing space (artificial world). By placing the reproduced artificial elements back into the original physical world, we can help end-users intuitively interact with them at an appropriate place in a very natural way in a newly-enhanced physical world out of computing space. This conceptual schema has been the basis of our architectural framework for each prototyped application in this paper.

And, the sample applications have been itemized among the prospective prototype 3D applications, i.e. they have a high potential for 3D technology incorporation with enhanced practical use in near future. Moreover, AR interfacing technology also exhibits its excellence without being divorced from the 3D contexts; hence there are strong possibilities of future integration of AR methodology into them. Thus, we have tried to reflect on the remarked features of an AR environment in the sample

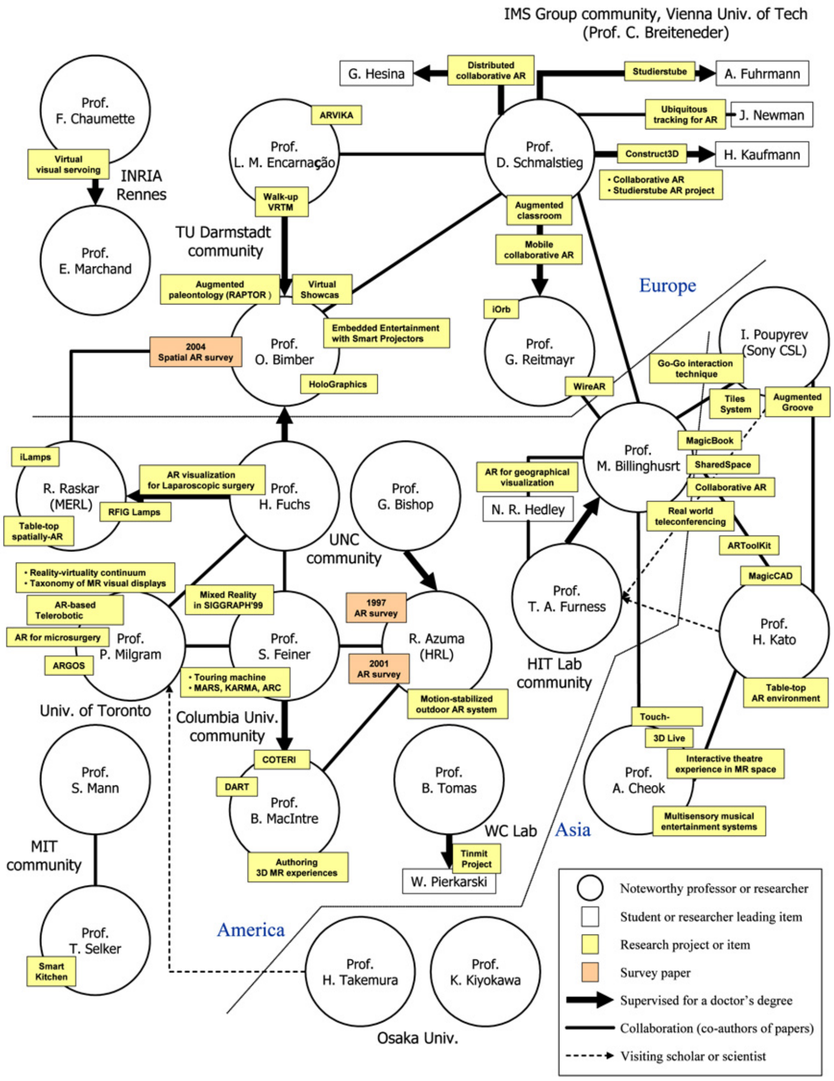

Fig. 2. Collaborative AR research activities.

Table 1
Reflection of AR features in sample prototype applications.

Physical world	Artificial world	Enhanced world	
	3D purpose	Incorporation of AR properties	
Engineering systems Geospace Multimedia	Intuitive analysis Informative service Immersive attention	Pull the artificial world into the real world	Intuitive observation Informative visualization Immersive interaction

prototype applications by focusing on the processes of: (a) how the target models of interest existing in physical world can be virtually reproduced in computing space so as to provide valuable AR content according to the application type or its requirements; and (b) how computer-generated objects can be combined with a real environment by using AR methodology in a reliable test-bed in order to offer enhanced functions or services.

As shown in Table 1, the specific sample applications can be categorized according to the different components in the real world: *engineering systems*, *geospace*, and *multimedia*. As an example of engineering systems, 3D technology has been widely incorporated in their simulators to facilitate a user's intuitive analysis of system motions beyond the conventional 2D graph style representations. At this point, by leveraging the AR feature of *intuitive observation* thanks to the interactive viewpoint of the simulators, we can amplify the user's intuitiveness through his natural viewpoint navigation. Above all, the computer-generated systems can be pulled into the same place as the real workspace with respect to the worker, realistically enhancing the effectiveness of experiments and displayed information. In the same manner, the other two applications serve as demonstrations of the effects of AR incorporation.

3.2. Architectural framework

A conceptual schema in Fig. 3 has been set as the basis for each item implementation. As noted in Section 2, system setups and the way in which related technical issues are dealt with vary significantly across test applications and experiments, therefore the architectural framework for our prototype applications (See Fig. 4) has been designed to be as generic as possible for future extendibility and applicability. As presented, the framework has

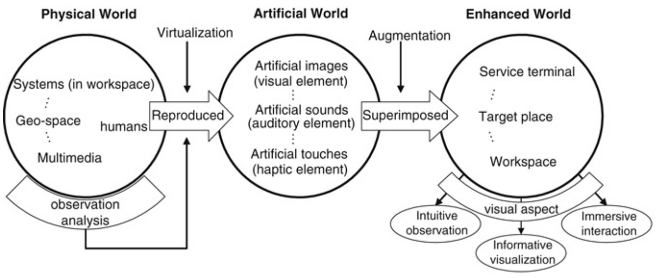

Fig. 3. A conceptual schema—A step toward to real-world enhancing using augmented reality.

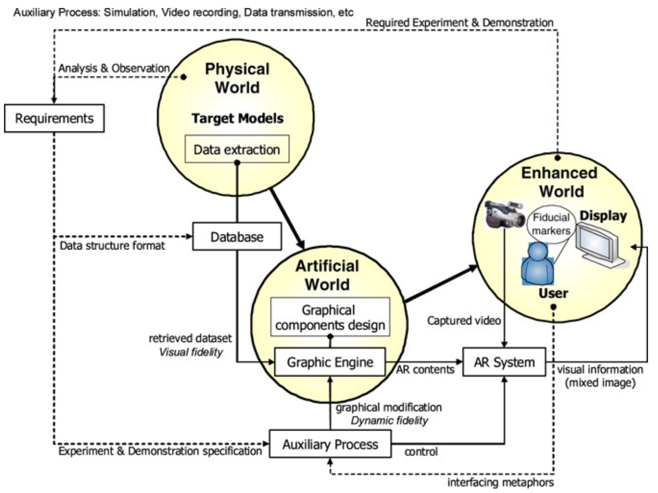

Fig. 4. A generic architectural framework for test-bed implementation.

been adjusted for visual aspects; but it is very extendable to other sensations such as auditory and haptic elements, which can be artificially virtualized, as noted in Section 3.1. In addition, our research scope has been more focused on demonstrating the feasibility and usefulness of incorporating AR in the prototype 3D applications, rather than resolving the specific technical problems issued in existing AR-related research.

In this paper, a video see-through AR method has been employed by using ARToolKit in which a marker-based tracking module is embedded. ARToolKit [4] is a C and C++ language software library which has been developed by Hirokazu Kato and Mark Billinghurst for vision-based prototyping of AR applications. The main function of ARToolKit is the calculation of real camera position and orientation relative to physical square markers, so it allows programmers to overlay virtual objects onto these markers. With head-mounted video cameras and a display system, the merged images of CG entities and live videos of the user's view can be obtained in near real-time. We can estimate the relative position of the marker to the camera location from the outline of the square marker because its size is known, and the black pattern printed on the marker determines which CG entity has to be overlaid, i.e. a physical marker can identify the visual information to be superimposed on it.

3.3. Test-bed requirements

For the test-bed implementation, we have specified the key requirements of our test-bed which should be arranged in each prototype application, on the basis of a usual software requirement analysis process, as below. To forecast latent probability of future AR incorporation, feasibility validations have been respectively conducted in each setting. And, Fig. 5 shows the target models adopted in this research.

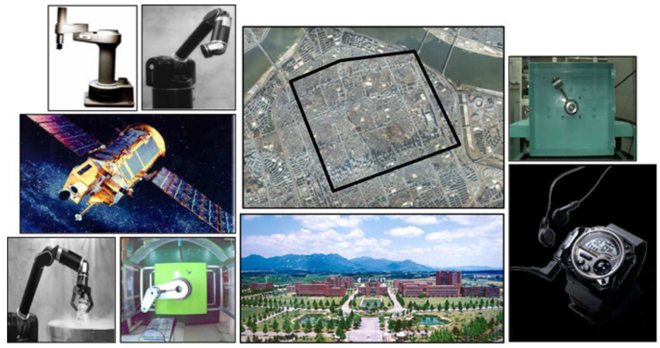

Fig. 5. Target models to be virtualized—Engineering systems (robots & spacecraft), Geospace (metropolitan road network & research institute as destination place of interest), Multimedia (commercial product as broadcasting production).

- Sample AR application 1: AR-interfaced 3D CAE simulation test-bed
  - 3D dynamic-fidelity simulators.
  - Compatible AR interfaces with real-time control simulation.
  - Feasibility demonstrations—Experimental validation focused on user's intuitive observation.
- Sample AR application 2: Two-stage distributed TGS test-bed based on a GIS database and AR
  - A modular (macroscopic- & microscopic-) representation method of a target site.
  - GIS-based geospatial data structures—layered structures applying a persistent topology approach.
  - Multi-stage service architecture for a 3D TGS (Traveler Guidance Service).
  - Feasibility demonstrations—Usability validation focused on informative geospatial visualization.
- Sample AR application 3: Haptically-enhanced broadcasting test-bed for AR-based 3D media production.
  - A distributed AR system for haptic client interaction.
  - AR broadcasting production—focused on a haptically-enhanced broadcasting chain.
  - A MPEG-2 TS-based transmission mechanism for AR media service.
  - Feasibility demonstrations—Scenario-based validation focused on TV-viewer's immersive interaction.

3.4. Related work

In this section, distinct from the comprehensive review of AR in Section 2, we have collected and classified related work that demonstrate a similar integration purpose for using an AR interface with each of our application or domain areas.

Intuitive observation for real-world task aid: As an early effort, in Milgram's studies, the AR technique has been employed in the domain of human–robot communication [36](d) and telerobotic control [36](c). Graphic information has been seamlessly superimposed around the real workspace of the real robots, which has aided in a user's intuitive engagement in communicating with a computing space. For a comprehensive view of AR research trends, we also need to note his taxonomy of MR (Mixed Reality) visual displays, reality–virtuality continuum [36](a, b) as well as ARGOS (AR through Graphic Overlays on Stereovideo) [18](a), a display system for AR, and perceptual issues in AR domains [18](b) discussed in his group. Actually, in a lot of research, we can find that 2D or 3D information conveyed by virtual images has been directly associated with the real artifacts or entities of interest in the user's workspace in order to aid the user's intuitive appreciation of the target entities and user's real-world tasks; selectively, Navab [38](a, b) have registered 3D CG pipelines in the user's view of a factory taking into account the 2D factory floor planes and structural properties of the real pipelines installed in the factory; Rosenthal [49] has shown needle biopsies using a 3D AR-based guidance system as an early medical AR application; Schwald [53] has presented an AR-based training and assistance system for the maintenance of industrial areas. For such industrial AR applications, we also need to track the early research on a laser printer maintenance application built by Feiner [21](b) where the computer-generated wireframe guides the user in removing the paper tray. In addition, one of the noteworthy projects in the field of AR, ARVIKA [5], has also incited industry to form R&D groups that study industrial AR applications and rapid AR prototyping [23]. In a recent effort, Gelenbe [24] mixed the virtual domain with the AR domain in real-time in order to examine how novel simulated conditions can interact with a real system's operation. Synthetic moving objects has been inserted into live video in real-time; the Lagadic INRIA team [6,14], has successfully demonstrated the realistic 3D simulation of virtual objects colliding with physical artifacts using real-time markerless tracking. As we noted, when AR-based interfacing is utilized to associate CG media with a real object of interest and we this is placed around the object in the real space, we can expect a decrease in the cognitive load required to interact with the CG media for practical use.

Informative visualization of geospatial data: Related to our second application, we need to examine the geospatial AR applications performed in the Tinmith project [59] and the AR PRISM interface [26](a). The Tinmith project has focused on the development of a mobile outdoor AR system that integrates a number of subsystem modules with a wearable computing platform, which includes head-mounted displays, a compass and interaction tools. It could be applied to city model creation, metro 3D building construction, and wire frame campus building design. In Hedley and his colleagues' work [26](a, b), [56], explorations in the use of hybrid user interfaces for collaborative geographic data visualization were shown with a summary of GIS- and VR-related demonstration. Due to the convenience of network service and user-friendly control, integration of 3D technologies has taken momentum to improve the visualization capability in GIS [46,69]. Further, we have emphasized that the design of user-friendly interfaces is becoming a kind of *de facto* principle in realizing effective GIS [35]. Of late, Dunston's group has been also envisioning MR-based visualization interfaces for the AEC (Architecture, Engineering, and Construction) industry and demonstrated AR CAD (Computer-Aided-Drawing) [19,54,62]. According to [13], user's extraneous cognitive load can be controlled by modulating the representation manner of information and its modality, which indicates AR-based visualization in a system or service can also be linked to the degree of user's engagement and appreciation for the information in all its aspects; thus we can additionally expect the amount of information being absorbed by users to increase if it is accorded with one's contextual needs and presented in a very user-friendly manner. Further, the features of informative visualization can be combined with the feature of intuitive observation to design a more practical application in the real world as in the mobile AR user interface prototyped for botanical species identification [65].

Immersive interaction with multimedia contents: Lastly, the cooperation between AR and haptics technology have been importantly dealt with in the multi-modal user interaction domain. The CSIRO ICT Centre in Australia has integrated the ARToolKit with the Reachin Core Technology API (formerly Magma) created in order to better integrate haptics and graphics rendering [1](a). A face-to-face collaborative environment has provided a coherent mix of real world video, computer haptics, graphics and audio. The test-bed has employed the CSIRO haptic workbench using the Phantom haptics device and Stereo shutter glasses [1](b). In addition, The HIT (Human Interface Technology) lab in New Zealand, one of the active AR research groups, has used small electronic buzzers to provide feedback for tracked fingertips [10]. The fingertip-based haptic feedback devices have enabled users to feel virtual objects in AR environments. From a media perspective, a study on applying AR in a broadcasting production environment has been carried out by BBC creative R&D groups [66,34]. They conducted three separate case studies on entertainment, education and information contents, and used them in the studio, classroom and home, respectively. Their main focus was to introduce prospective features of AR technology for future media production. In addition, AR-based sports broadcasting via MPEG-4 [15] has taken place in the framework of the PISTE (Personalized Immersive Sports TV Experience) project; Kammann [30] has introduced Augmented Television where interactivity can be extended since the viewer is granted full control over the editing process of the video material. An application was implemented using the television standard of Media Home Platform (MHP) running alongside the Digital Video Broadcasting (DVB), which has presented the typical Basque ball sport pelota in a new way, offering augmented digital video material, interactivity, virtual camera flights and observer positions; in the meantime, Media Interaction Group of Philips Research in Eindhoven [11] reported on the recent efforts to apply interactive television to a storytelling application. We note that AR-based interaction shows a higher degree of adaptability to interactive media contents rather than conventional audio–visual contents and supports a greater possibility of personalized interaction for publicly-broadcasted content. In a recent supportive study on presence and engagement in an interactive drama [17], it has been found that immersive AR can create an increased sense of presence, confirming generally held expectations, and mediation may be necessary for some service-takers (e.g., TV viewers, game players, etc.) to fully engage with certain interactive media experiences.

4. Sample prototype applications

4.1. Case study 1: AR-interfaced 3D CAE simulation test-bed

The first application originated from the results of two former projects[1] in which the major technical concerns were about the development of 3D simulators to evaluate newly-proposed control algorithms. However, in conventional 3D simulators including ours, 3D virtual (computer-generated) objects had been superficially animated according to simulation data, and visualization of implicit numerical data separated the user's interaction with the computing space from the real ambient workspace. Therefore, in our first sample application, we leverage the intuitive observation of high-fidelity CAE (Computer-Aided Engineering) simulations with naturally-interactive user interfaces [32](h). We have combined the AR methodology with custom-built 3D simulators of an engineering system, in particular, robots.

4.1.1. System implementation

In this case study, our target system consists of five types of robotic systems with deferring joint configurations: (a) *Custom-*

[1] Supported by MOST (the Ministry of Science and Technology) of South Korea: 'The developments of HMI (Human-Machine Interface) system in virtual environments' and 'Spacecraft attitude and orbit precision control—A new methodology for spacecraft control'.

built one-link manipulator (b) *Custom-built 2-link SCARA type robot* (c) *2-link vertical type robot* (target model: WAM ARM of Barrett Technology, Inc) (d) *3-link SCARA type robot* (e) *3-link elbow type robot*. In the test-bed, the target system database component produces a parametric dataset for the target system, and a typical dataset is composed of robot type identifier, robot parameters, controller properties and target positions of links. Therefore, graphical models and simulation control properties can be attributed to the datasets retrieved.

For the high-fidelity simulation, the motion equations are represented on the basis of the system kinematics and dynamics in form of Euler–Lagrange equations; and two kinds of joint control algorithms are embedded; PD controller and output feedback controller developed by Ailon [2](a). Lastly, the 2nd order Runge–Kutta method is applied to find numerical solutions for differential equations of system dynamics. The 3D simulation can be enabled in an AR environment using threading so that the virtual models can be simulated independently of the rendering frequency of the AR process. In addition, several functions for robot system analysis such as inverse kinematics and the stability test using the Lyapunov function and phase portraits are available independently on the AR service. The system architecture and mathematical concerns have been addressed in [32](a, d, g, h).

For the virtual representation, we have developed a graphics engine module by using OpenGL which enables a perspective view, light effects, materials modeling as well as detailed object modeling in 3D domain. The rendering is mainly processed by hardware, which is much faster than performing this in software. In this module, several graphic primitives have been modeled to be frequently rendered so that we just have to consider the combination of their coordinate frames simply when calling these primitives. Thus, the graphics engine facilitates graphical modeling of primitives and system components based on system parameters such as system type, link length, load existence, etc. This engine creates all graphical effects including annotation and information panels. Basically, we have followed the Denavit–Hartenberg (DH) frame assignment of robot joints and the procedure for selecting frames of reference in robotic systems whose outlines are flexibly modifiable according to the retrieved information such as masses and lengths.

In the AR process component, video captured by cameras is analyzed using the ARToolkit to detect areas containing fiducial features. Fiducial features refer to patterned markers which the system has been well trained to recognize and track. Appropriate target models and simulation configurations are automatically summoned, when matching fiducial features are detected. In the AR-based simulator, a 2D panel is provided for reporting system features and annotation panels for each robot joint. To preserve global awareness of the real environment scene, a blending technique is applied to the panels, and their viewing volumes are independent of each other.

Technical challenges in AR incorporation: When transforming 3D simulations in desktop-based computing space to use an AR-based environment, a few technical challenges arise. Firstly, we have noted that simulations are observed mostly in the static view state after dynamically configuring the markers. However, the four vertex data detected from the marker vary slightly impacting the elements of transformation matrices (T_{cm}) from the marker coordinates to the camera coordinates. Consequently, the trembling of augmented virtual models in the static view state can disturb a user's observation in the dynamic state. Thus, we have applied a noise filter to give the elements the average of several previous values if the variation is within a constraint. If the variation crosses this constraint, the motion of the marker is regarded as being in the dynamic state and the filtering stops. Secondly, we had to embody a simple and reliable estimation procedure for robot collaboration in the AR process. The base of a robot is fixed on the marker orientation, with its end-effector able to move in a limited fashion within a boundary. For collaboration between two robots, there has to exist a common volume where end-effectors of both robots can reach. Even if it is given, however, it is hard to estimate that both end-effectors have arrived at a particular point in the volume because of the respective representations in their own marker coordinate frames. Therefore, the present positions of the end-effectors have to be analyzed in a common coordinate frame. The detailed procedure and discussion of technical concerns can be found in [32](b, h).

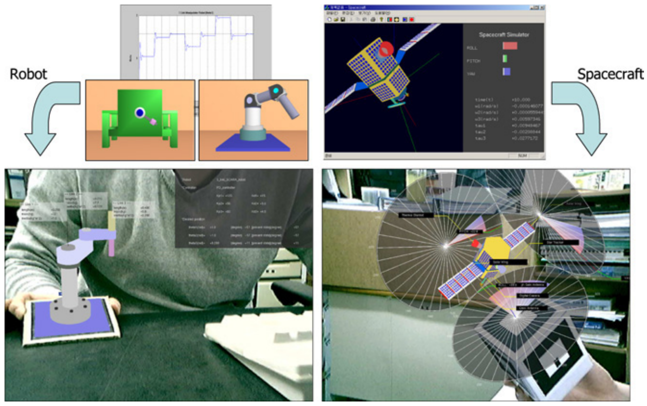

Fig. 6. Two AR-interfaced 3D simulation test-beds compared with typical 3D simulators.

4.1.2. Demonstration

In our AR-interfaced simulation test-bed, a patterned marker identifies a virtual robot model to be overlaid on a live captured image, which means that a marker having a different pattern indicates the other robot model. As shown in Fig. 6, three informative items are configured as visuals to aid users in obtaining the present simulation state: (a) information panel, (b) annotation board and (c) auxiliary surroundings. Firstly, the information panel in the top-right corner reports the system control parameters, real-time simulation states, etc. It has a fixed global coordinate system regardless of eye-position. Secondly, the annotation board represents information about a system component. The board, suspended on the top of a guide branch, is positioned according to the present eye-position (=camera aim pose). Although the branch follows a 3D spatial relation, the visible face of the board is always pointed toward the user's viewpoint. Thus, all the information on the board is faithfully visible all the time to the user unlike in a real environment where mutual occlusion frequently occurs between a physical board and other artifacts. Lastly, auxiliary surroundings report the simulation states in a visually-enhanced form close to the target model. In addition, graphically blended visuals help users keep a global awareness of the surroundings in an AR environment, so users can engage in a simulation without cognitive conflict by interacting with graphical control buttons using a keyboard and mouse.

Validation: Three control experiments have been conducted in our AR-interfaced 3D robotic simulation environment. Firstly, we have demonstrated the performance of the output feedback control algorithm for the 1-link manipulator model. The controller enforces that the robot link will reach its target destination by compensating for the difference between the present link position and the target position at each time step. Whenever the position state of the link converges to a steady position, a parametric vector in the controller is updated so that the link can finally reach the target position. In the experiment, when the link being controlled finally arrives at the commanded target position +90°, we add a load to the end of link, which varies the link mass so that the link position deviates from the target position. However, due to the controller, the link bearing the load again approaches the target position. Even after we remove the load again, the re-deviated link position finally reaches +90° by means of the controller. In the 3D simulation, we can observe how robot links physically oscillate, how the characteristics of the controller is being reflected on the motion of robot links and how the position of end-effector varies, more explicitly than typical 2D graph-based representation. In addition, the AR-based simulation environment allows users to change their viewpoints flexibly and interact with virtual models in a natural manner, which helps a user's intuitive observation.

In the next experiment, robot collaboration has been demonstrated in an AR environment. In practice, there are a number of virtual objects that exist in an AR application, and interaction between them can frequently occur during simulation. However, such mutual interaction is not simply realized in the AR-interfaced 3D simulation because each CG model has its own local reference coordinate system within the AR environment. In this experiment, we considered a situation in which two robots were collaborating: 2-link and 3-link SCARA type robot (Robot 1 and Robot 2, respectively). The gains of each PD controller were purposely given to generate oscillations in the motions of robot links, which was supposed to make the transfer timing of a load mounted on the Robot 1 onto the Robot 2 uncertain. At the moment that end-effectors of both robots come across a same location accidentally, the load on the Robot 1 can be automatically transferred to the Robot 2. Since the transfer is completed, controller gains of the Robot 2 change and its end-effector moves to the next target position predetermined. In the fully virtualized world, local reference coordinate systems of virtual robots are numerically setup in a virtual world coordinate system, thus their spatial relationship such as when and where both end-effectors meet together is relatively easy to pre-estimate. While, in the AR environment, such local reference coordinate system of a virtual object is represented by each marker (=real artifact), so its dynamic orientation needs to be updated with a real-time estimate and additional real-time monitoring (to see the end-effectors of both virtual robots now occupy a certain position together in the camera coordinate system) is necessary in order to determine when and where the load can be transferred. It validated the procedures proposed in [32](b, h) where we also foresaw the extensibility to the case of interaction of virtual objects with real objects.

Lastly, for further demonstration of our approach's applicability we have incorporated an AR-interface into a spacecraft simulator. Unlike most industrial robots, the spacecraft is floating in 3D void space, thus we needed to design box-style configurations by using five markers for the registration of virtual models. All five markers are indicating a single orientation in the marker coordinate system so it ensures reliable augmentation in the situation of graphical occlusion interrupting image analysis which frequently happens when users are interacting with or manipulating the models. In addition, the order of transformations in graphics has to be arranged in the reverse order of rotational motions (*roll-pitch-yaw*) of the spacecraft. In the AR-based attitude control simulation, a modified output feedback controller [2](b) has been applied to the dynamics of the spacecraft derived according to its actuator type, *gas-jet* or *reaction wheel*. In the previous 3D simulator without an AR interface [32](g), despite the high-fidelity animation of 3D spacecrafts, it was hard to understand spacecraft motion because the spacecraft system has no reference plane or prop, unlike the case of the 3D robot simulator. However, through our experiment, we demonstrate that the AR interface allows the user to flexibly move their viewpoint in AR, providing a natural way to observe the spacecraft's motion floating in 3D space. Also a user's intuitive perception of the spacecraft motion can be effectively aided by visually reporting the present angles on three circular planes located around the virtual spacecraft.

4.2. Case study 2: Two-stage distributed 3D TGS system based on GIS database and AR

The second application has been planned to succeed the project 'Web-based 3D dynamic traveler guidance system'.[2] Most of the traveler guidance services (TGS) are based on GPS technology and are generally concerned with the mapping position data on the simplified 2D electronic map in order to provide macro-level service facilities such as driving direction notifications. Undoubtedly, digital GIS (Geographical Information System)-based GPS entails *in situ* informative visualization. Further, the visually-enhanced TGS can improve the global and local awareness of unknown areas. However, the microscopic areas (we name it '*section*' in this paper) have been very rarely structured in a digital GIS format so that it has been very hard to use them in an auto-formatted visualization process. Above all, the effective user interaction for the micro-level service has been considered much less in existing TGS. Therefore, in our second sample application, we propose a new TGS system that provides 3D street as well as pin-pointed destination information in two stages of its interactive services; *web-based* and *AR-based* [32](f). Firstly, we have implemented a 3D web-based system with newly-proposed GIS data structures of an urban area, and then shown how it can be converted into an AR interaction service for a specific *section* in the *area*. The AR-based service helps users interactively obtain detailed micro-level information of a specific section with their fingertips.

4.2.1. System implementation

In this section, we show a TGS (Traveler Guidance Service) system with two different service types taking into account real-world constraints of the target regions in a metropolitan district. Firstly, we selected a test area and a section: a subset of the test area. The '*area*' means a region composed of a metropolitan road network such as streets and avenues, a matrix of paths where public transport is available and travelers can mainly pass through using a vehicle. On the other hand, the '*section*' in the area implies a smaller region like a kind of prepared land for building lots such as a town, a complex or a zone of interest. Hence, the section is very likely to be a destination place to travelers. Accordingly, we have defined the macro- and micro-service in a 2-stage TGS system as web-based TGS for the *area* and AR-based TGS for the *section*, respectively. A 5×4 road network of Gangnam in Seoul, Korea, has been selected as a test area and a research institute GIST (Gwangju Institute of Science and Technology) as a section and destination for users.

For the configuration of service items and a post-validation, we conducted a requirement analysis using e-mail questionnaire before implementing the system; we note that (a) the most helpful information in a real-life driving situation is the road signs and intersection information, (b) the first problem is the absence of road signs and neighborhood building information and (c) in graphic representation, the external appearance of road to the level of road width and the number of car lanes will be more helpful for users than other traffic facilities such as signal light. To reflect these analysis results, we designed our own geospatial data structure formats, SMFs (GIS metafile format co-produced by SimTech, Inc and GIST [55]), which is built in a layered structure applying a persistent topology approach to enforce data consistency and store geospatial data more efficiently. To build a novel GIS format, we have categorized the DB format into eight data structures; one for the links, another for the nodes, and the others for traffic facilities.

[2] Supported by MOCT (the Ministry of Construction and Transportation) and was carried out as collaboration with SimTech Systems Inc, in Korea.

In addition, a field investigation on texture images based on the electronic topographical maps on scales of 1:1000 and 1:5000 of Korea National Geographic Information Institute was conducted at the same time. The test area is composed of 102 links (L) and 43 nodes; 20 general nodes (N), 17 entry nodes (EN) and 6 dummy nodes (DN). The '*link*' a half side of a straight roadway and the '*node*' is a crossroad between diverged links. The neighboring nodes are connected with two opposing directional links. A '*dummy node*' is defined for the creation of curved links and '*entry node*' marks the outer border of the area. The specific data sections of each of each structure were described in [32](e, b). By developing a custom-built DEPM (Data-Editing Program Module), we could incorporate detailed driveway data (e.g., road width, median strip, stop-line location, car lanes, U-turn pocket, footway, bus bay, arrow marks, traffic island, safety zones, etc.).

In the web-based service, there are two subsystems, a video retriever and a path generator, which work while a client user connects to the traveler guidance site via Internet. If s/he selects a departure and a destination place in the test area, the path generator determines the shortest path between them and creates a list of animation sequences for a path. Then, the video retriever mounts the link and node videos recorded in the graphic engine sequentially on the server according to the list. In this service, the user can obtain 3D street information and 2D guide path of the area. And, in the 2nd stage service for the microscopic areas (=the destination sections of interest in the area), AR-based interactive traveler guidance service has been incorporated on the platform of monitor-based video see-through AR system with ARToolKit.

Technical challenges in AR incorporation: As technical challenges, we have considered the user interaction with bare hand, which is one of the most initiative approaches for natural gesturing in AR applications. Using this integrated system, users can control virtual icons with their fingertip navigating over the map, which acts like a mouse pointer. Fingertip detection is conducted when a hand encroaches on the patterned area. If a fingertip stays on the virtual icon areas for a second, it is recognized as a mouse clicking and a set of pre-determined functions are executed. Dynamic region searching technique is applied to reduce searching area and a fixed threshold value is used to detect the hand feature. The fingertip position determined by the minimum value of the hand feature in screen coordinates is compared with the screen-projected coordinates of the virtual icons in 3D world space. The task flow diagram with respect to the hand estimation process and augmentation process was presented in [67]. In addition, for stable augmentation, we have employed a multi-type pattern formed by four markers as a tracking feature. Although hands or fingers occlude some of markers, augmentation is ensured by detecting other visible markers. Lastly, in order to make both AR-based TGS and web-based TGS systems interoperable in an integrated system, we have proposed a data flow mechanism using three control parameters: micro-service request, node ID request and arrival flag.

4.2.2. Demonstration

In our test-bed, the user has established a connection to the web-based traveler guidance site. At this point, departure and destination place can be chosen. The website then displays the shortest path on a 2D guidance map, which in turn provides information on crossroads and/or turns. The travel time to and distance is automatically predicted. In the demo, a subway station and GIST are selected as the departure place and as the destination place, respectively. Street information with 3D car-driving animation comprises five items; (a) a main 3D view, (b) a 2D path map, (c) a front directional board, (d) turning direction indicators, and (e) animation control keys. While passing along the

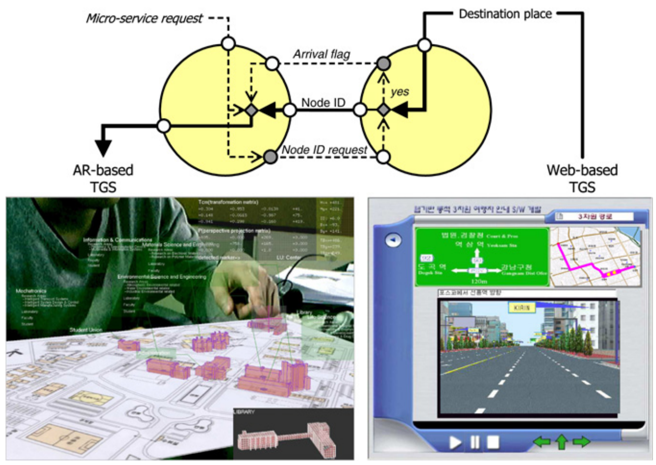

Fig. 7. Two-stage 3D TGS system with a service interoperable mechanism.

3D streets, the site informs us about the next turning direction, the present position on the 2D path map, and a directional board that the traveler would meet at the front crossroad. Moreover, the details of the street condition of unknown area (e.g., the road widths, lined-up buildings with nameplate, the availability of U-turns and the existence of bus bays or pockets) can be known in advance. Since the traveler has arrived in a destination section, the search for the specific building should start. The last animated node prompts the traveler to use the AR service for the desired section. The 2D electronic map of the section is augmented on a multi-type pattern. The map imagery to be overlaid can be switched according to the sections. To get the detailed information, the user clicks on one of virtual icons, which are located at the exact building positions on the map, with bare fingertip. Then, the appropriate 3D building model is overlaid on the map. Its appearance and pose are reflected on it, as well as text information like the building name is annotated. The user can move and rotate the patterned board as if the destination section is miniaturized on it. Additionally, there are two extra views independently displayed on the board motion; (a) right-top view which reports the present fingertip position and the detected marker ID, and (b) right-bottom view which shows the outlines of the building in 3D animation (see Fig. 7).

Validation: For the validation of the proposed implementation, the prior subjects have been asked to visit our demonstration site again as participants. Reliability and usability are tested using a questionnaire by scoring; specific procedures and interim results were reported in [55,32](e). Interestingly, the participants demanded a higher viewpoint than a driver's real view in 3D screen. And, even though most of participants have most preferred 3D driving simulation synchronized with 2D map, as a single info item the path guidance on 2D map was evaluated higher than 3D driving simulation for the same path contrary to the prior requirement. We conclude that 3D information item for traveler guidance service enhances users' immersion as expected, but aiding user's global awareness of the target area (e.g., 2D map) is basically prior to realistic representation of it (e.g., 3D driving simulation).

4.3. Case study 3: Haptically-enhanced broadcasting test-bed for AR-based 3D media production

The last application has been performed through the collaboration with the Realistic Broadcasting Research Center (RBRC)[3]

3 Located at GIST (Gwangju Institute of Science and Technology) and supported by MIC (the Ministry of Information and Communication) of South Korea.

launched to forecast next-generation broadcasting. We believe that enhanced future broadcasting networks integrated with communication network technology can enable us to enjoy attractive bi-directional services by dynamically immersing the users into broadcast content. So, in this sample application, we have adopted AR and Haptics technology into a prototype test-bed in order to demonstrate how the enhancement of TV viewer's immersive interaction can augment his/her realistic experience for multimedia contents [32](c). The present camera tracking system of virtual studios is robust and highly accurate; however, it is only effective in a special chroma-keying material space of a fully synthetic 3D stage. For this reason, the people in the studio have to pretend to be immersed in pre-scripted animation scenario of virtual content in the empty space. Compared with this, despite a short disappearance of virtual objects for the fast feature motions, AR technology can support interactive visualization while providing a simple and user-friendly interface [34]. In this section, we demonstrate an immersive and interactive broadcasting production system with a new haptically-enhanced broadcasting chain, the concept of which had been suggested by Cha [12](c, b). The prototype test-bed is composed of a 3D media database, an AR module (called *AR process*) for broadcasting production and a Haptic module (called *Haptic process*) for client interaction. Viewers at the haptic multimedia client can interact with AR broadcasting production transmitted via a communication network.

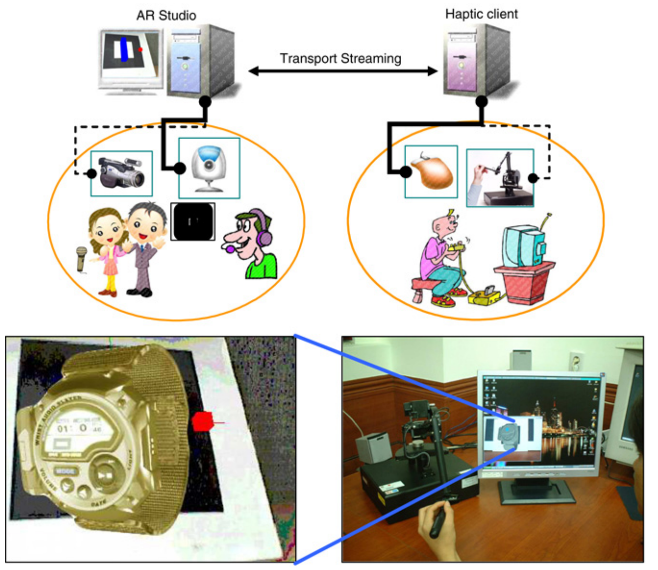

Fig. 8. Haptically-enhanced broadcasting test-bed for AR production—Home shopping scenario (wrist-held MP3 player).

4.3.1. System implementation

A prototype test-bed system has been designed to test a haptically-enhanced broadcasting chain Cha [12](c, b) proposed and validate potential scenarios using AR. In the proposed chain, viewers may touch or manipulate objects in broadcasted contents, which can be simulated using haptic technology. One of the related researches was performed by [39] who presented Touch TV by showing two test scenarios: the creation of authored haptic effects for children's cartoons and the automatic capture of motion data to be streamed. Also,Vallino [60](b) demonstrated haptic–graphic, virtual-to-virtual haptic and virtual-to-real haptic interactions with relationships between multiple coordinates. However, they did not demonstrate their work for the broadcasting chain. Our test-bed has been implemented by configuring a 3D media database, an AR process using ARToolkit, streaming modules and a haptic process with a 6-dof haptic device, Phantom [40]. The 3D media database contains 3D object model information such as geometry, color, texture, depth, material and haptic (tactile & force or motion) data. These data are overlaid on the captured video, which thus makes haptic interaction possible at the client site. In the case of a passive touching interaction, a haptic-related data (i.e. force and torque vector when touched to an object) may be produced and stored in the studio and sent to the viewers. However, in an active touching setting, haptic interaction data generated by collision detection and force computation procedure [31] should be created and displayed in a standard desktop PC at the client site where the viewer can explore and manipulate the designated object. So, in the current test-bed, we have made all the related 3D media be downloaded to client at the beginning of televising a broadcasting production.

Technical challenges in AR incorporation: In this application, our technical challenges have been in data stream transmission and consistency between the visual augmentation and haptic interaction. Firstly, TCP/IP network programming using the multimedia streaming technologies is used. Key transmission data is specified as 3×4 transformation matrices for projection (P), and model viewing (T_{cm}) in AR coordinate system are transmitted as payloads, which are used to set up the haptic probe navigation space. In addition, six haptic probe data (H) are streamed to represent the present position of the probe in the navigation space. Two packet types, the first header byte for one is 0x01 ('0x' means hexadecimal value) and the other is 0x02, are assigned for transmission and reception, respectively. However, to provide backward compatibility with the current digital television broadcasting system, AR-related data (e.g., pattern images, 3D computer-generated objects data, etc.) including encoded video data should be delivered by using MPEG-2 TS (Transport Stream). So, we additionally proposed AR stream transmission over MPEG-2 TS (Transport Stream) [32](i). Due to the limited bandwidth of a broadcasting stream, all data for the AR service are unable to be carried over MPEG-2 TS at a given time. Therefore, a two-stage transmission mechanism has been utilized; (a) raw data for the basic AR-service are conveyed over MPEG-2 TS and (b) optional data, which are comparatively huge, for the full AR-service is offered through Internet. This architecture requires additional Internet provision of the broadcasting receiver. Our main focus was on two technical aspects: (a) PMT (Program Map Table) configuration for AR stream transmission and (b) AR-data encapsulation on the PES (Packetized Element Stream) level as PES packet data.

Secondly, in ARToolkit, spatial transformation data are estimated in the frame capturing and processing rate, around 20 Hz, which is very important for seamless augmentation and visually consistent interaction. The image-based process causes high frequency errors making tremors in the CG models' augmentation and in viewers' haptic interaction. It has almost no impact in the user's dynamic view state; however, it can disturb a users' observation in their static view. For a single marker, the farther the marker is apart from the camera and the smaller the tilt angle is, the less the estimated accuracy. In addition, the estimated moving distances can be discontinuous between frames because haptic sensation is rendered in high resolution (almost at 1000 Hz). These conflicts are endurable from a visual aspect, however, very crucial in the haptic interaction aspect. So, in this experiment, we have applied low-pass filtering by using threshold values and interpolated the marker pose between the visual frames. In our demonstration, the trembling is almost completely eliminated so that haptic interaction becomes smoother in the static view state [12](a). Also, the interpolation has been sufficient to provide the apparent continuous force when the CG model is moving.

4.3.2. Demonstration

In the client site, the CG object-augmented scene is displayed and haptic probe is overlaid on it (see Fig. 8). The probe can navigate in the same 3D space of the camera's viewpoint. The control unit processes the video media and the haptic data to control the haptic device by using haptic rendering algorithm that are the main functions of haptic process. Viewers can feel the haptic effects synchronized with application scenarios, for example, passively by putting their hands on the vibrotactile display device. They also can actively touch, explore, and manipulate the 3D CG objects according to the or the viewers' will. In our demonstration, we have used a Phantom which provides a very compelling sense compelling sense of touching virtual objects especially when there is no conflict with the visual cues [40].

Validation: For the validation of the proposed framework, two test scenarios have been demonstrated. In the first 'electric circuit' scenario, we presented an engineering education program to show how viewers' understanding of scientific experiments would be enhanced. A science teacher presents a feature board in front of camera, on which a pre-designed CG circuit model is augmented, and starts its simulation. Then, viewers in the client site touch graphical electric wires and feel the abstract current intensities and directions assigned to them, which helps viewers' understanding of current flows in a circuit. It can be extended to other scientific or engineering applications in which the conversion of physical or abstract data such as force, intensity, strength, and temperature to the physical sense is necessary.

In the second 'home shopping' scenario, a shopping host tries to advertise a product: wrist-held MP3 player. When the host puts a feature board in the camera range, viewers can watch the augmented 3D CG MP3 player model on it. The host can show all the aspects of the model by rotating the board while explaining the features of the product. This board manipulation works more effectively if the real product is too big and weighty to be handled. When haptic interaction is available, viewers can try to push a functional button using his/her own haptic device to know how it works and the corresponding operation or information can be adaptively displayed. Also, they can actively contact the outline frame of the product. Undoubtedly, major information in the broadcasted scene will be conveyed through the live video image. However, we know that by supplementing reality rather than completely replacing it, AR environment can ensure the user's perception and interaction with real world unlike fully virtual environment. Thus, the users' interactivity by haptical & visual augmentation has shown the potentials of contributing to their immersiveness about the entire broadcasted information beyond the case of the live video without any user-interactive objects or the objects are divorced from the real world. In this context, the term, immersiveness, has been supported in this application.

5. Discussion

The major contribution of our work is the demonstration of AR interfaces can improve users' interactions with 3D models. AR interfaces leverage a user's intuitive perception as well as support more natural interaction, which combine to better facilitate user's appreciation of the information being shown. This has the positive result that the demonstrated user-centered AR features help to focus the end-user's attention while interacting with the computing space. As addressed in [44], extraneous cognitive load is generated and also controlled by the manner in which information is presented to learners or operators. Besides, the increase of user's mental workload appears more significantly in cases of multiple tasks or multiple task demands to which end-users should respond simultaneously. AR interfaces, which provide a modulated manner in representing computer-generated media, can be devoted to lessening the cognitive load required to exist in and be engaged in both the physical and information/virtual worlds that users inhabit; more specifically, AR incorporation can be more convincingly formulated to contribute to reducing the end-user's cognitive and physical time and effort spent in switching his/her attention while frequenting two spaces, real and computing.

In this section, we also forecast the direction of future AR research. In particular, we discuss three agendas in accordance with our three proposed AR environment features.

Cooperation with context-aware computing (CAC) for enhanced intuitiveness: With augmented reality, context-awareness also has been noted as a significant feature of future UbiComp environments [63], [16](a, b). Compared with AR for seamless mediation between the real environment and computing space, CAC has been devoted to providing proactive services by determining user-specific service timings and the most pertinent information at those times by interpreting user's historic and on-going contexts. For example, in its applications, location information of users has been significantly exploited as one of the key indices to trigger services; however the focus was not on the spatial alignment based on precise 3D tracking as in AR. Both technologies are still promising to help end-users seamlessly communicate and interact with a smart environment; nevertheless the different perspectives on intuitive services and the different platforms have been interrupting their integration into a single holistic application. Thus, as a first stage, several applications may need to be piloted by integrating one technology intentionally into the other's existing applications, and vice versa, focused on how to present a vision of ARCA (AR + CAC)-based UbiComp world where end-users can intuitively interact with smart environments.

Diverse encountering with versatile informative media beyond visualization: The AR world has been pursued for the symbiosis between informative CG contents and physical elements (e.g., artifacts, buildings, etc.) in the same space, where humans could encounter the contents as if they are *in situ* physical elements. However, such a seamless coexistence is not constrained only in visual alignment. Despite the presence of versatile computer-generated media (e.g., CG visual, CG audio, CG haptic, etc.) in the computing space, most of AR research has considerably focused on visual support. Even if the visualization is the most effective and inspiring method for presenting information, it may entail heavy system components and significant rendering loads. Besides, visual inconsistency and discontinuity can make users experience motion sickness unexpectedly. Thus, the display of informative media may need to exploit other senses like audio AR [8,50,58,68]. At the same time, we should think about how users can be more engaged in the sequential story of CG contents rather than just focusing on visual-based interaction. In this context, efforts in non-engineering fields also need to be explored, like the HARP project [25] in the education field.

Implicit human–computer interaction for less-immersive interaction: Lastly, we need to seek the minimized but indispensable role of AR interfaces in an application in order to foresee the near-future AR practicality. In many AR applications, a user explicitly interacts with the CG contents, which consumes most of the user's attention. For now, adopting AR has directly purported to aid the user's task so that the superimposed contents have been the main concern of interaction and the users had to concentrate on them. As an interesting perspective, on the other hand, Schmidt [52](b) has introduced the concept of *implicit Human–Computer Interaction* (*iHCI*) using ambient displays. In his definition [52](a), *iHCI* is an action performed by the user that is not primarily aimed to interact with a computerized system but which such a system understands as input. Thus, it makes output of a computer not directly related to an explicit input (e.g., by command-line, direct manipulation using a GUI, gesture, or speech input) and seamlessly integrated with the environment and the task of the user. He has also illustrated the 'walking through an automatic door' as one of the typical examples of iHCI. Motivated from this concept of embedded information, less-immersive interaction in incorporating AR may need to be considered for users to be minimally aware of the interaction with the computer system without distracting their attention too much in their everyday life, which may require situational scenario-based approaches.

6. Conclusion

In this paper, we have presented an architectural framework for the generic prototyping of AR applications on the basis of our conceptual schema focused on the interactivity of end-users. To validate this framework, our AR interfacing methodology has been integrated into three sample prototype 3D applications in three distinct real-world domains: *engineering systems*, *geospace*, and *multimedia*. In the first prototype application, we have verified the feasibility of an AR-interfaced 3D CAE simulation aimed at pulling desktop-based 3D simulations divorced from the physical workspace into the same space as the real world. AR-based user interaction enhanced a user's feeling of intuitiveness in observations in control experiments for engineering systems. In the second application, the applicability of the AR interface has been validated in a multi-level 3D TGS (Traveler Guidance Service) system. The proposed system provided 3D street and pin-point destination information in two stages of its interactive services: web-based and AR-based. In the demonstration, we showed effective awareness of street environments and versatile visualization for geospatial information in this new TGS system. In the final application, we have presented a haptically-enhanced broadcasting test-bed for servicing 3D interactive media. AR techniques were adapted for broadcasting productions and the 6-dof haptic device, Phantom, has been installed at a client's site to provide a user's immersive interaction. In the scenario-based validation, we showed that the incorporation of AR- and haptic-interaction to conventional audio–visual contents can improve the immersiveness and interactivity of viewers.

Above all, the motivations for incorporating AR interfaces have been technically formulated on the basis of user-centered features of AR environments we presented; *intuitive observation*, *informative visualization*, and *immersive interaction*, respectively for each application. Rather than using a conventional technology-specific approach, our alternative view of the AR interfacing strategy has demonstrated its far-reaching applicability to the heterogeneous application fields of 3D prototyping with only the most primitive AR set-up; accordingly we have also noted these features need to be first considered in order to facilitate a developer's decisions for adopting AR interfaces into existing applications or to pre-examine the synergy effects expected by incorporating with other technologies. As a result of our work, we expect further progress in the mainstream standardization of AR-integrated end product prototyping, and in the integration of AR interfaces and prototyping in future UbiComp environments, which will likely cause changes in user interfaces and interactions supporting the prototyping process, especially in the stages of design and manufacturing.

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[4] Byungha Ahn (email: bayhay@gist.ac.kr) is a Senior Professor and was the director of the System Integration (SI) laboratory with additional administrative position as Vice-President at the institutional level. Prof. Ahn initiated and managed two projects related to the case study 1 and 2 in this paper.

[5] Jeha Ryu (email: ryu@gist.ac.kr) is a Professor and the director of the Human Machine Computer Interface (HMCI) laboratory. Prof. Ryu has been leading a project related to haptics-incorporated broadcasting system, which concerns the case study 3 in this paper.

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