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AN ITERATIVE METHODOLOGY FOR MAPPING MIXED REALITY TECHNOLOGIES TO AEC OPERATIONS

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SUMMARY: *Mixed Reality (MR) technology can create an environment where objects from the digital and real worlds can be combined together in a real time manner. The practical contribution of this paper is a structured and iterative methodology developed for mapping appropriate Mixed Reality technology to a specific architecture, engineering, and construction (AEC) task. To increase the likelihood of success in technology transfer, this methodology for developing user-centered, performance enhancing MR-based systems is formulated, where AEC tasks are generically analyzed and categorized according to common functional features, which could be mapped to a collection of suitable or required MR-related technology strategies. Also, a technology selection process is identified to choose appropriate technology characteristics including information representations, interaction methods and, tracking technology for a specific task category. Such a thorough mapping methodology can be used to guide new MR-based system design as well as to help evaluate existing systems.*

KEYWORDS: *AEC; Augmented Reality; Mixed Reality; specification; technology-task mapping*

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1. INTRODUCTION

Mixed Reality (MR), as formally defined by Milgram et al. (1999), is a special class of Virtual Reality (VR) related technologies for creating environments wherein real world and virtual world objects are presented together in a single display. Human-computer interfaces that blend a view of an existing site with relevant design or field information should be an attractive class of technology for the Architecture, Engineering, and Construction (AEC) industry. The terms, Augmented Virtuality (AV) and Augmented Reality (AR) are the two major subsets lying within the Mixed Reality range of the Reality-Virtuality (RV) continuum. AV describes cases where the real object is inserted into a predominantly computer-generated environment, which has been explored in safety programs and manufacturing (Caterpillar Distributed Virtual Reality System 1996). AR is the converse case within the MR continuum and is a technology or an environment where the additional computer-generated information is inserted into the user's view of a real world scene. Shin and Dunston (2008) have made the case that information-intensive tasks are particularly suitable for support by AR-type systems. AR allows a user to work in a real world environment while visually receiving additional digitally facilitated information to support the task at hand.

Recent advances in computer interface design and hardware processing power have fostered Augmented Reality (AR) research prototypes or test platforms for urban planning (Shen et al. 2001), architectural design (Kensek et al. 2000), design detailing (Dunston et al. 2002), construction operations planning (Behzadan and Kamat 2009), execution and inspection of construction (Webster et al. 1996; Shin and Dunston 2009), maintenance and inspection of facilities (Navab et al. 2002), revitalization (Donath et al. 2001) and other applications. Research has demonstrated that AR systems can be used as field instruction tools (Webster 1996), field detection tools to reveal of hidden systems or structures (Roberts et al. 2002; Schall 2009), collaboration platforms for natural and intuitive cooperative work (Wang et al. 2003), a navigational metaphor to aid mobility for infrastructure field tasks (Hammad et al. 2002), and so on. Though the idea to use AR for construction, maintenance, and repair dates back to the 1990's (Webster et al. 1996), up to now it has not been implemented in standard practice. Technology-related limitations have contributed to preventing these AR systems from maturing beyond the prototype stage, but these limitations are becoming less of a hurdle as enabling technologies are improved and the consideration of specific task requirements come more into view (Shin et al. 2008; Berlo et al. 2009). In addition, larger segments of society are becoming comfortable with routinely relying upon computer-based devices for everyday tasks of communication and information retrieval. These trends are fueling an increasing desire to realize successful, practical implementations of MR in the AEC industry, but to realize acceptance of MR in the industrial setting, more research, particularly regarding user issues, should support the technology trend. A formalized human-centered, research-based approach to specifying deployable, field-ready prototypes is needed to guide the designs of MR systems that will become the tools of choice for performing specific tasks.

A Mixed Reality system may be viewed as a collection of control strategies, which are suitable or required for certain tasks. Various combinations of these strategies may be used to carry out a given task effectively. A bridge needs to be established between the available technology alternatives and the needs of specific AEC tasks. A review of the limited MR-based applications in AEC and other domains increases awareness of the need for a scientifically structured framework for establishing the link between requirements and the suitability of MR technologies for use in AEC. A specification and evaluation methodology is a significant first step toward this objective, and can serve as a foundation for evolving methods to develop performance-enhancing MR-based applications, based on a scientific structured approach as opposed to ad hoc methods. In order to map appropriate MR technology to an AEC task, Mixed Reality technological components must be classified, and the task analyzed. Then a bridge must be established based on user-centered concepts such as perception, cognition, usability and ergonomics issues, etc. Previous research (Wang 2005) investigated MR technological components, setting the stage for mapping the MR technologies to specific application needs. The framework of the global continuum and classification of displays by Milgram et al. (1999) help to identify human factors issues to be addressed in MR system design. Classification methods were developed for four characteristics: media representation, user interface input mechanism (control devices), user interface output mechanism (display devices), and tracking technology. AEC tasks have also been characterized by Wang (2005), also in terms of human factors, to make the appropriate links. There are four factors which need to be considered for AEC tasks: mental requirements, working environments, physical disposition, and hand occupation. These two steps have set the stage for mapping the MR technologies to specific AEC tasks, which is the focus on this paper. Such a new methodology for developing user-centered, performance enhancing systems can increase the likelihood of success in technology adoption. Real, usable MR systems may then be designed.

Therefore, this paper develops a systematic and detailed technology-mapping methodology for application at the task level to explicitly specify MR system elements. Each task or simple operation can be mapped to a collection of suitable technology strategies. The methodology creates the connection between task requirements and MR technology components via human factors considerations through a user-centered approach. This paper also develops an associated design methodology and guidelines. AR, considered to be the most promising form of MR for industrial applications, is chosen as the focus for this discussion. The design methodology and guidelines is an ordered classification, according to which appropriate MR technological components can be selected, developed and evaluated for augmenting a specific AEC task or operation. A case illustration based on an experimental prototype was also developed to demonstrate the application of the mapping methodology.

2. INFLUENCING FACTORS IN THE SELECTION OF MR TECHNOLOGY

As stated above, four significant influencing factors on the task side of the technology-task pairing were identified that should be considered in the design of AR systems: task mental requirements, working environment, physical disposition, and hand occupation (Wang 2005). Even though these factors are not exhaustive, they can act as a minimally comprehensive starting point for conceptualizing designs of an MR system. The four influencing factors are reviewed here for clarity.

2.1 Task Mental Requirements

Task mental requirements have to do with perceptual and cognitive tasks. MR system design should strive to bolster human performance by compensating for limitations in the user's mental capabilities (e.g., working memory limits, attention allocation, and bandwidth capacities). An information-processing profile of task performance provides a description of the encoding (mental translations) of perceptual information, how the different codes are used within internal psychological subsystems, and the organization of these subsystems. The information flow for particular tasks can be captured by diagrams of hypothesized processing subsystems (Proctor and Van Zandt 1994). These diagrams assist in identifying the mental operations that take place in the processing of various types of information from input (receipt) to output (response). The information-processing approach provides a basis for analyzing the task components in terms of their demands on perceptual, cognitive, and motor processes. By analyzing the hypothesized information processing model, one can craft the MR system to minimize working memory load by exploiting different working memory codes. The MR system should also be plugged into the information processing model where it can play a role in maximizing the efficiency of attention allocation. A case study demonstrating how the hypothetical information processing model can be captured for a task of interest is provided in a later section.

2.2 Working Environment

The factors involved in the working environment that need to be considered in regard to MR systems include situational awareness requirements, indoor/outdoor location, noise level, work area hazards, working volume, etc. The working environment may put special limitations on adoption of certain components of MR technology. For example, if the task is to be performed under potentially hazardous conditions, where workers need to maintain high situational awareness and continually update knowledge of their surroundings in real time, the use of solid virtual objects, large amounts of text, and large size images should be avoided because they may occupy too much of the worker's real world view. Another example is that aural display and speech recognition input would be hampered in noisy working environments.

2.3 Physical Disposition

The physical disposition of the work task should be considered in terms of such factors as motion, body position, etc. Many construction tasks require workers to move around, which forces MR systems to be implemented on portable or wearable devices. Construction environments may require both mobile and stationary AR systems. The physical disposition may determine the appropriateness of certain interaction tools or mechanisms. For example, a body-based input metaphor (interaction by the system tracking natural user body motions) may not be a problem when applied in a large working volume or roaming area. However, in a clustered or congested working volume (e.g., HVAC piping corridor or around complex arrangements of special equipment), a body-based metaphor is not appropriate. In this case, hand-based techniques or gestural mechanisms may be appropriate for interaction with the virtual information presented to the user. Users can stand or sit in place while traveling arbitrary distances and directions in virtual space. Thus, for MR systems which involve little or no manipulation, seated users, or limited facility space, tracking by hand may be more appropriate and comfortable for extended use.

2.4 Hand Occupation

Performing a typical construction task augmented by MR technology requires interaction with digital information via a certain input metaphor as well as manual actions for the task at hand. Thus MR may increase both mental and physical occupancy. For example, a worker with hand(s) preoccupied by an assembly task may have difficulty in simultaneously interacting with a digital information source except by speech. Four possible types of hand occupation are possible: (1) hands-free performance of both the work task and the MR display interaction; (2) hands occupied for MR interaction only; (3) hands occupied for the manual task only; and (4) hands used for both work task and interaction. If the worker needs to deal with two interaction modalities together (type 4), that individual's attention must be allocated. Issues of attentional limitations may arise, which is an important consideration and topic of research for augmenting human performance.

3. TECHNOLOGY-TASK MAPPING

Figure 1 illustrates the connection between task requirements and specified MR technology components via a "user" layer that represents the human factors considerations which have been discussed. This figure reflects the essence of user-centered considerations in the overall methodology for technology-task mapping, depicting that a thorough technology-task mapping is accomplished by designing the system within the context of the relevant human factors considerations. Such an approach enhances the usability of the MR system design. Figure 2 depicts the influencing lines between factors of the task of interest and the to-be-determined MR system technological components. These influencing lines were identified through deliberations of the authors involving brainstorming, scientific imagination, and reasonable inference informed by review of several Virtual Reality usability literature resources (e.g., *Virtual Reality*, *International Journal of Virtual Reality*, *Journal of Virtual Reality and Broadcasting*, etc.) Each influencing line has been based on a rationalized example. For example, working environment influences the selection of tracking technology in the case that an indoor task and operation cannot exploit GPS because the GPS signal would be obstructed.

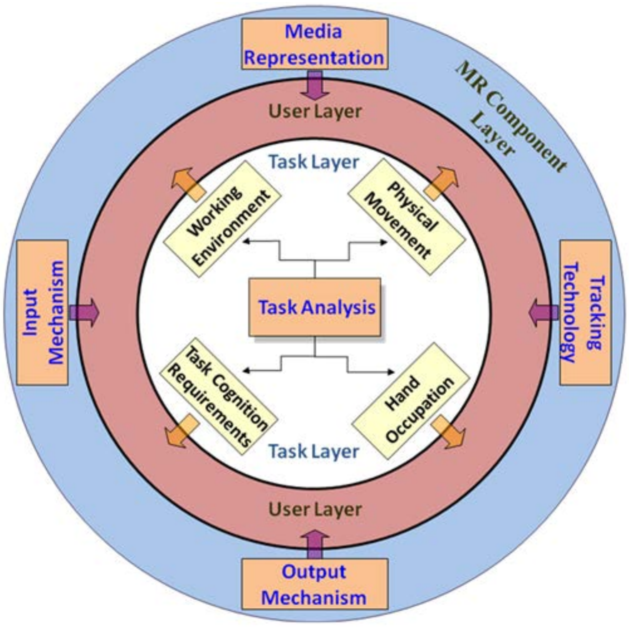

FIG. 1: User-Centered Framework of Layer Interactions

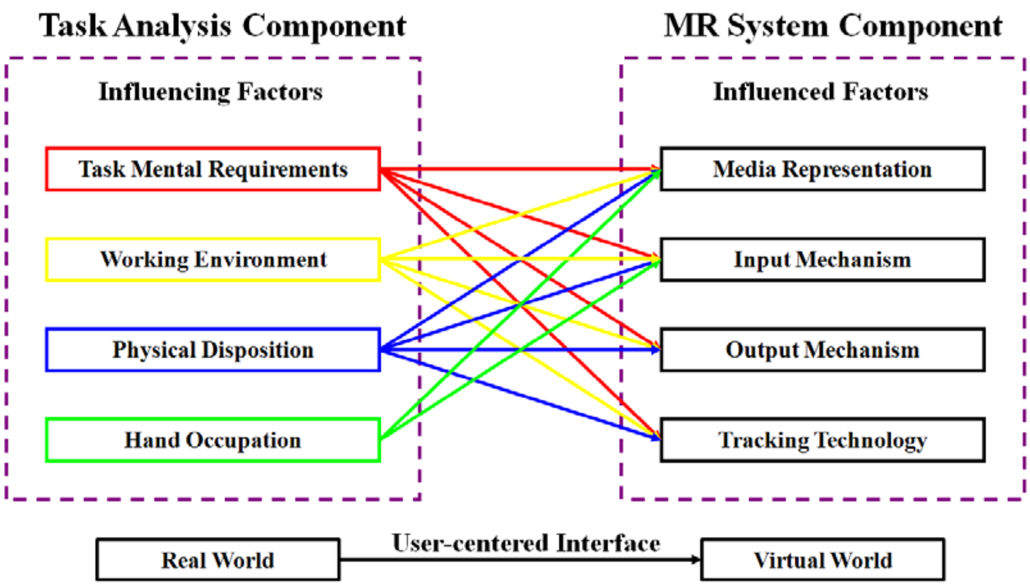

FIG. 2: Influencing Relationships between Task Requirements and MR System Design

3.1 Methodology for Technology-Task Mapping

An overall procedure has been developed for mapping the appropriate MR technology component onto the specific task. The procedure consists of two serial phases: analyze task, and choose MR technology component. Figure 3 illustrates the overall procedure and the details for each step are elaborated as follows:

Step 1 – Analyze task: First, the task of interest should be analyzed through techniques such as site observation, interview with experts, etc., in order to obtain an understanding of the current parameters of performing the task. Then the task should be broken down to the composite level. At the composite task level, in addition to identifying the sequence of motor tasks which may be involved in the activity, the hypothetical information processing model can be formulated where associated perceptual and cognitive tasks are identified. Based on the analysis of those tasks, potential augmentations from the MR tool can be conceptualized. Also, from the information processing model (Wang 2005), the mental requirement associated with the process, which AR is envisioned to meet can be recognized. Task analysis can also yield facts about working environment, physical disposition, and hand occupation, which are essential in the second step.

Step 2 – Choose the MR technology component(s): Specifications and guidelines for mapping the appropriate technology to tasks have been developed and illustrated in Tables 1, 2, 3, and 4. The task analysis—described in the aspects of mental requirements, working environment, physical disposition, and hand occupation—then can be plugged into the specification and guidelines to arrive at the suggested MR technology component. This step can configure an MR tool prototype for the task of interest, but still needs to be evaluated for system usability improvement.

Step 3 - Usability evaluation: This last step is to improve the prototype system from the second step to a usable and effective system. User-based evaluation is an essential component of developing any interactive application, and is especially important for applications as complex and innovative as MR environments. Usability evaluation, in this context, is a process that aims to identify problems with how well a user interface design satisfies requirements for ease of application for specified tasks (Mack and Nielsen 1994; Bowman et al. 2004). Identified problems are then used to make recommendations for improving the interface design. Three kinds of usability evaluation are identified as particularly appropriate: heuristic evaluation, formative evaluation, and summative evaluation. The method presented herein uses a combination of heuristic evaluation and formative usability evaluation. While the concept of combining heuristic evaluation and formative user testing is not necessarily new, applying these methods to an MR-based user interface is novel. Best guesses about an interaction design are substantiated or refuted by many tight, short cycles of heuristic and formative evaluation. Heuristic evaluation (Gabbard 1999) is a type of analytical evaluation in which a particular user interface is assessed by determining what usability design guidelines it violates and supports. Then, based on these findings, especially the violations, recommendations for changes to improve the design are made. Formative evaluation (Del Galdo et al. 1986) is a type of empirical, observational assessment with users that begins in the earliest phases of user interaction design and continues throughout the entire life cycle, with the purpose of iteratively and quantifiably assessing and improving the user interaction design. Even though the whole usability evaluation framework involves the heuristic and formative evaluation, formative evaluation is not going to be implemented here due to the research scope which was established.

As mentioned above, the knowledge of how to evaluate usability is formalized to the extent that such generalized concepts as heuristic, formative, and summative exist. However, the details of how such evaluations are conducted depends upon the specifics of the technology in question and such knowledge is accumulated through numerous experiences with numerous prototypes, each one adding to the corpus of knowledge about that technology's usability aspects. That is why our tables have blank spaces in the "Example" and "Reference" columns; the knowledge is developed gradually through aggregation across this area of inquiry. The attributes of the technology and its application dictate the appropriate considerations in the usability evaluation. In this article, we put forward just such an approach that we try to demonstrate as being appropriate for applying MR technology, in general, to the general class of AEC tasks. As such, the usability evaluation and the related MR system specification guidelines are to be tested by application against the present and future prototypes that are developed for research and industry. In this article, we intend only to present and illustrate the formal approach for that purpose.

3.2 Design Guidelines and Example Illustrations

The approach to develop AR design specifications and guidelines is to recognize the influencing relationship between certain task components and MR components and to collect and synthesize information from many different sources including experience and documentation regarding Virtual Environments (VEs), Augmented Reality, human-computer interaction, known technology limitations, etc. This latter task is still requires such a search for information because MR research is still relatively new and the corpus of knowledge regarding best practices for MR system design is still far from being fully developed. Future years of research and development may lead to a more refined set of system specification fundamentals. The remainder of this section walks the reader through the steps to be executed and is guided by reference to the whole procedure and influencing relationships in Figure 3.

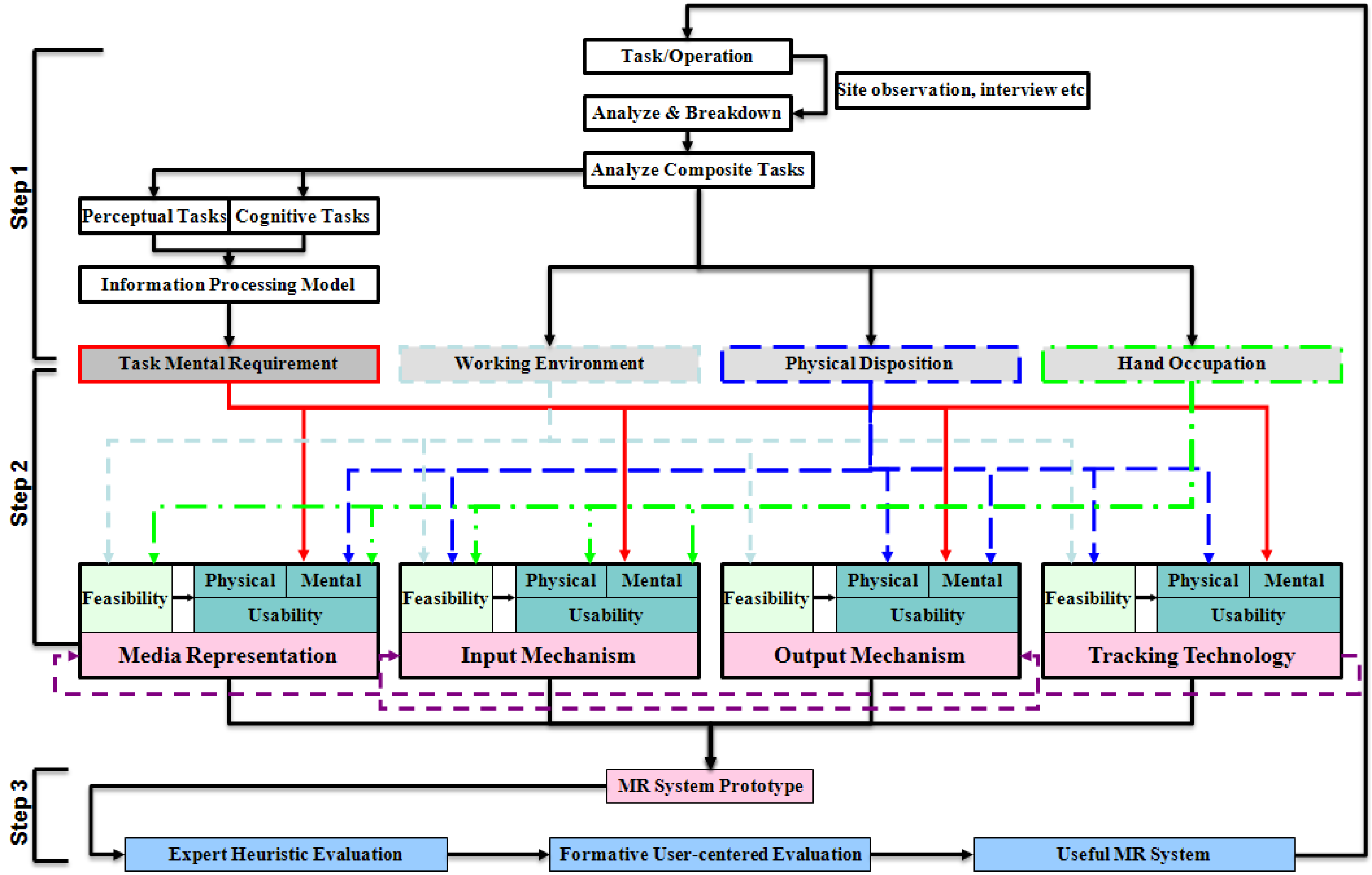

Fig. 3. Procedure for MR System Development Cycle

The guidelines, developed from the considerations derived from various sources as described above, have been condensed and categorized as described below. Usability issues can be considered through two serial steps: feasibility analysis and ergonomics analysis. Feasibility analysis should be implemented first because the selected technology components must be validated as fundamentally viable before time is spent on investigating features to enhance performance. Only once the selected technology is determined feasible for at least not obstructing the task at hand, there is a necessity to think about the ergonomics issues for more effective augmentation. In the specification options tables (1 through 4), feasibility analysis and ergonomics issues are elaborated separately. In the ergonomics analysis, two related ergonomics properties, physical comfort and cognitive load, are considered separately. For discussion convenience, the following notations are used in the specification tables that indicate the influencing factors from the task: Task Mental requirement = M; Working environment = W; Physical disposition = P; Hand occupation = H.

3.2.1 Selection of Media Representation

Selecting the type of media representation is referring to the efficiency of conveying information in a certain context by different media representation format. In general, clear, simple, relevant, and consistent information is desired, but these criteria are not always attainable or strictly desired. Also, if hands will be occupied for performing certain task while paying attention to the virtual information, line of sight to the real object(s) should not be obstructed by the solid virtual objects. Although 3D solid models provide high fidelity, realistic information for the user, there is a possibility that the 3D virtual objects may be unsuitable for the work at hand, providing too much detail or cluttering the user's view of the work. However, solid object will block the view of other virtual information, or real environment background behind it. More specification options and associated examples can be found in Table 1.

TABLE 1. Guideline and Suggestions of Media Representation

	Media Representation		
Aspect	**Suggestions and Consideration**	**Example**	**Reference**
Feasibility	If the task is to be performed under potentially dangerous conditions, use of solid virtual object, large amounts of text and large size image should be avoided. (W)	In such conditions, workers need to keep high situational awareness and update the surroundings in real time. Use of these representations may occupy too much space of the worker's real world view.	
	3D solid virtual object should not be used when the corresponding to-be-manipulated real object needs to be in line of sight. (H)	Solid object will block the view of other virtual information, or real environment background. Also the real task in the user's hand will also be affected with the user's line of sight being blocked.	(Gabbard 1997)
Physical Usability	None		
Mental Usability	In tasks such as assembly, repair, or maintenance where the virtual information needs to be registered to the real objects and also the real objects and the task in hand needs to be directly viewed by the users, the wireframe format is the appropriate one for such contexts because of its see-through features with cues for 3D shape. (H)		
	One method of providing a high-fidelity media representation uses sequences of video clips. This method appears to be well-suited for mixed environments (MEs) where people in the worksite perform tasks such as receiving training for procedure guidance and construction methods with minimal interaction. (P)		(Gabbard 1997)
	Simple, informative media representation that actually facilitates real work may provide much more utility for serving the purpose of certain applications than high fidelity, true-to-life virtual media representation. (M)	In annotation applications, text and 3-D wireframe drawings might suffice.	(Gabbard 1997)

In some cases, real-world, high-fidelity physical and behavioral representations may be desirable in applications, which attempt to provide a high degree of realism, such as in simulation, training, architecture design and planning etc. (M)		(Ishizaki 1996)
The high fidelity representation may indirectly lead to usability issues associated with lag and low frame rates because of limited computing resources. (M)		(Gabbard 1997)
The presence of directional cues, such as on-screen compass or, a navigational grid and/or a navigational map may have a positive effect on users' abilities to perform navigational tasks. (M)		(Darken and Sibert 1995)
Components of the media representation conveying virtual information may suggest activity as well, via real-world metaphor of functionality. This use of metaphor may also decrease the cognitive load associated with translating user intentions to user actions. (M)	Users can expect that a virtual flashlight will provide lighting, a virtual clock will provide the current time, and a virtual phone will provide voice communications.	(Neale and Carroll 1997)
Text is suitable to be used in descriptive, instructional and procedural tasks, where users need much explanatory information from a database rather than geometrical information. (M)	The function description can be attached to each button on the control panel of a heavy equipment in order to help novice operators to recall what each button is supposed to do without referring back to the manual or asking other workers.	(Gabbard 1997)
Indicators are more likely used in highlighting the to-be identified object or feature, and pointing out operation direction or sequence. (M)	Wearing a head-mounted display (HMD), the project manager can have a virtual route plan for heavy equipment moving direction overlaid onto his real view of the equipment. Such a route can be analyzed later for potentials of productivity improvement.	(Gabbard 1997)
3D data is appropriate for visualizing the data sets specifically in engineering analysis and design. (M)	The heat distribution or water flow speed in mechanical piping can be visualized using a color spectrum and certain visualization techniques.	
3D grouped uni-object is appropriate in a visualization-only task, however, 3D ungrouped objects enable a user to manipulate any sub-object for more editing functions. (M)		

3.2.2 Selection of Input Mechanism

Rekimoto and Nagao (1995) point out that AR systems can acquire implicit (passive) contextual input (i.e., signals from the environment) that can reduce the complexity of the human-computer interaction. Nevertheless, cognitive load and robustness of these input sensors remain a lightly explored focus of AR research. For this discussion, the characteristics of interest regarding the input mechanism include control-display gain, user-centered interaction (“naturalness” and “intuitiveness” of interaction), weight, comfort, mobility, portability and cost. As a general rule, Mixed Environments (MEs) should avoid non-intuitive, unnatural, or poorly-mapped input devices. Specification options and associated examples are illustrated in Table 2.

TABLE 2. Guideline and Suggestions of Input Mechanism

Aspect	Input mechanism Suggestions and Consideration	Examples	Reference
Feasibility	For MEs involving little or no manipulation, sitting users, or limited facility space, tracking by hand may be more appropriate and comfortable for extended use. (P)	Workers in a limited working volume such as an HVAC duct tunnel or special equipment may need hand-based input mechanism to interact with the virtual information presented in front of the real scene view.	(Templeman 1996)
	For tasks involving a relatively large movement area, the input devices such as keyboard with short cables or tethering that are not portable may not be suitable. Wireless device or tangible devices may be better choices (P).		
	Noisy environments make speech input unidentifiable by the computer, which may cause confusion for the worker. (W)		
	If both of the user's hands must be dedicated to the task, then the interaction with virtual information can be realized by a tangible, body-centered input mechanism and a speech input mechanism rather than keyboard, gestural, and hand-based techniques, etc. (H)		
Physical Usability	If the input mechanism requires hands occupation, then the weight, size, and form of the input mechanism needs to be considered for the magnitude of fatigue. (H)	Gestural, hand-based input mechanism may not be too heavy. However, for tangible input mechanism, fatigue may be a problem in MEs that include moderately weighted real props.	(Gabbard 1997)
Mental Usability	If hands are required to perform work tasks and to interact with virtual information simultaneously, mental transformation involved in switching between those two tasks should be considered. The less the mismatch between the task object and input mechanism, the less mental transformation is required. Metaphors which have a number of mismatches (semantic differences between real and virtual worlds) may leave users confused about available functionality and mappings. (M) (H)	If the virtual object used for tangible input is seamlessly attached to the tool or object in the manual task, then what you see virtually is what you actually perform. If hands are only required for the input mechanism, the selection of input mechanism should be based on naturalness or intuitiveness, which is discussed in the following.	(Mapes and Moshell 1995)
	It is important that interface metaphors intuitively match user task as well as allow for concurrent real world task execution. Moderately or large sized props may occlude virtual objects or the entire virtual display. (M)		(Stoakley et al. 1995)
	Whether the input device is to be worn, held, or stood upon, etc. designers should strive for natural interaction between user and device. (M)		
	In cases where virtual model interaction implies some physical implement, real-world physical props may be used as opposed to virtual tools coupled with synthetic force-feedback. (M)	A scalpel implies surgery and a flight stick may imply a flight simulator.	(Gabbard 1997)
	Avoid integrating traditional input devices, such as a keyboard or 2D mouse in combination with 3D, free-space input devices. Instead, designers should consider adding input capability via voice or gesture input. (M)	A worker may have a difficult time switching between a keyboard and 3D mouse, especially when immersed in an HMD-based environment.	(Hinckley et al. 1994)

	An advantage of desk-mounted imitated devices is that they are typically not worn, thus facilitating ease of device integration into working, desktop environments. Therefore the isometric devices are suitable for desktop environments such as design detailing processes or control panels for operating equipment. (M)	A CAD environment may need six DOF imitated devices for better design detailing over the keyboard.	(Gabbard 1997)
	Multimodal interaction reinforces cognitive perception during manipulation tasks by providing alternate sensory input. ME developers should use speech recognition and natural language input as a complement to multimodal interfaces, as opposed to stand-alone mechanisms. (M)	Studies have shown that the addition of aural, haptic, and force feedback cues to otherwise visual-only systems improve user perception, manipulation, and performance (Brooks et al. 1990).	(Wickens and Baker 1995)
	Verbal annotation is useful for applications areas, such as visualization, simulation, and training VEs, where preserving contextual information is important. (M)	Users of an ME designed for scientific visualization may wish to capture analysis remarks related to specific data sets. Likewise, verbal annotation to simulations provides additional context when the simulation is played back (e.g., for the purposes of training or evaluation).	(Harmon et al. 1996)

3.2.3 Selection of Output Mechanism

The display devices used in AR may have less stringent requirements for implementation than VE systems demand because AR does not involve replacing the real world in which the user is operating with a virtual world. Optical see-through HMDs with a small field-of-view may be satisfactory because the user can still see the real world with his peripheral vision; the see-through HMD does not shut off the user's normal field-of-view. A system's content presentation component(s) may have an effect on a user's cognitive processes (among many others), and subsequently, usability. Mapping user scenarios and tasks to appropriate display types and characteristics is essential for the development of truly useful and usable visual displays. Specification options and associated examples are illustrated in Table 3.

TABLE 3. Guideline and Suggestions of Output Mechanism

	Output Mechanism (Display)	
Aspect	**Suggestions and Consideration**	**Reference**
Feasibility	In a noisy working environment, the audio display is useless because the worker cannot distinguish the voice of the display from the ambient noise. (W)	
Physical Usability	Compounding HMD weight is the fact that HMDs are typically tethered by audio and video cabling, limiting user mobility to cable length and support mechanisms. (P)	(Gabbard 1997)
	If the task is performed by stationary worker (sitting or standing), standalone monitor is appropriate without need to carry any output device. On the other hand, if the task requires continuous movement, weight and comfort of the output device should be the most important consideration for the physical usability analysis. (P)	
Mental Usability	Compared with video-based ST HMD, the optical ST HMD can provide a better awareness of the surrounding objects and the task at hand, giving the user more sense of presence, which influences the performance in tasks which require continuous movement. (P)	(Wang and Dunston 2006a)
	Selection of visual output mechanism has much to do with presence and centricity requirements. Tasks requiring an exocentric frame of reference (navigation information, location of self and other entities) need exocentric displays such as standalone and hand-held monitor, and projections etc. Tasks requiring an egocentric frame of reference (object identification, location and distance estimation) may need an egocentric display such as an HMD (M).	(Wang and Dunston 2006a)
	An egocentric point of view is useful when users need to experience a strong sense of presence. Situations where users benefit from an exocentric view include ones in which detailed relative position and motion between the user and other objects are desired, e.g., orienting oneself in a large environment by externally viewing one’s location and heading in the context of the environment (M).	(Wang and Dunston 2006a)
	Stereoscopic displays are beneficial in enhancing perception and task performance in the situations when	(Davis and

	information is presented in an egocentric view rather than an exocentric (M).	Hodges 1995)
	An acoustic display is specifically beneficial for safety and alarm by catching the user's attention and caution via audible warning.	(Gabbard 1997)
	Individual modalities may be superfluous and therefore careful consideration is needed in the use of a variety of modal channels.	(Haniff et al. 1999)

3.2.4 Selection of Tracking Technology

In general, when assessing tracking technology relative to user tasks, one should consider working volume, desired range of motion, required accuracy and precision, and likelihood of tracker occlusion. Developers and evaluators can consider the Applewhite (1991) framework (advantages and disadvantages and other parameters such as accuracy, range etc.) when assessing the suitability of tracking technologies with respect to representative user tasks. Specification options and associated examples are summarized in Table 4.

TABLE 4. Guideline and Suggestions of Tracking Technology

Aspect	Suggestions and Consideration	Tracking Technology Examples	Reference
Feasibility	GPS tracking is suitable for outdoor use but achievable accuracies should be compared to task requirements. (W)		
	User movements can occlude tracking during task performance, generating spurious data. (W)	If the construction or working site is occupied by many vertical erections or many personnel, ultrasonic, optical, and infrared tracking systems are susceptible to object and body interference since line-of-sight is required.	(Strickland et al. 1994).
	For VEs that require large user-roaming areas, sophisticated ultrasonic tracking systems may be used to increase user range. (W)		(Applewhite 1991)
	Magnetic trackers are typically limited to a range of a few meters, yet do not require line-of-sight and thus are suitable for MEs with small working volumes and minimum electromagnetic interference. Body-mounted magnetic transmitters are powered through small cables, resulting in some user tethering. (P)		(Applewhite 1991)
	Ultrasonic, optical, and infrared tracking systems avoid tethering and thus allow greater freedom of motion. However, a possible tradeoff is the fact that these systems are susceptible to body interference since line-of-sight is required. In this case, the movement by the users might occlude tracking while conducting tasks. This might generate spurious data. (P)		(Strickland et al. 1994)
Physical Usability	The weight, portability, and robustness of tracking technology should be the primary consideration for the physical usability analysis. (P)	Mechanical tracking has many cables to tether the movement of the user. Therefore, if a task requires standing and moving in a small volume, mechanical tracking will exert much burden on the worker.	(Applewhite 1991)
Mental Usability	Mental requirements have a lot to do with the accuracy of the tracking technology. (M)	Less accurate tracking technology such as GPS may register the virtual information to the real environment several feet away from the target position, which has a large negative influence on the human's perceptual process. User need spend much cognitive efforts to try to offset the difference and imagine the correct combination. Such superfluential mental transformation may damage the performance of the worker.	(Applewhite 1991)

3.3 Influences between MR Components

In addition to the correspondence between task characteristics and MR technology components, there are also important relationships between MR components. That is, one MR component can influence the selection of another MR component. Two such relations are of note: 1) between tracking technology and media representation and 2) between input and output mechanisms. These relationships are indicated in Figure 3.

Tracking technology and media representation are related via the registration requirements of the supporting visualization. The tracking technology can be described in terms of granularity or accuracy. Finely grained systems are accurate with regard to how well they estimate the correct location of an object. Coarsely grained systems such as GPS offer less accurate positioning data. The granularity of the system influences the nature and quality of the representation used on the interface. For example, realistically rendered virtual objects are appropriate for accurate systems that allow them to be tightly coupled with real objects. This example also may be considered as a case of media representation determining tracking technology. For less accurate systems, any desire for tightly coupling virtual images to the real world may not be satisfactorily achieved. Presently, vision-based systems provide the single best results regarding accuracy and flexibility.

The relationship between input and output reveals a congruence issue, which has been elaborated by Milgram et al. (1999). They addressed the influence of a mismatch between the actions made possible by the input (control) device and the response observable via the output (display) device. Depending on the means provided and the circumstances, a user can effect changes in the observed scene which are either congruent or, to varying degrees, incongruent with respect to the form, position and orientation of the device(s) provided. Ordinarily, a highly congruent control-display relationship will correspond with a natural, or intuitive, control scheme, whereas an incongruent relationship will compel the user to perform a number of mental transformations in order to predict the outcome of an input action. A simple vehicle simulator example was given by Milgram et al. for illustrating high congruence of input and output mechanisms. The vehicle simulator has an egocentric (out-the-window) display of a roadway, showing real data and a standard steering wheel, in addition to an accelerator and brake pedals as the control devices. The egocentric display together with the control device create a highly congruent input-output mapping in the sense that a leftward control input will cause the simulated vehicle to turn to the left (as the visual display rotates to the right). Such a setup is very effective for local guidance, since it enables the operator/driver readily to follow an established trajectory to get from one point to another. The reader is referred to discussion provided by Milgram et al. for greater detail.

4. CASE ILLUSTRATION

A case illustration is implemented in this section using the above methodology on a prototype Mixed Reality Collaborative Virtual Environment (MRCVE) system. The intent of the case illustration is to demonstrate the feasibility and potentials of this methodology to guide new MR-based system design as well as to help evaluate existing systems.

MR techniques should be very promising for collaborative design review. MR can provide an alternative medium that allows groups of people to share the same work and communications space. Additionally, discussing ideas in a collaboration meeting need not be limited to the conventional 2D design medium. Technology mapping to review collaboration task for realizing an MRCVE (Wang and Dunston 2005) was implemented using the methodology described above. Technology mapping was implemented and the procedure is depicted Figure 4. The explanatory details are elaborated in terms of the two primary steps as described below.

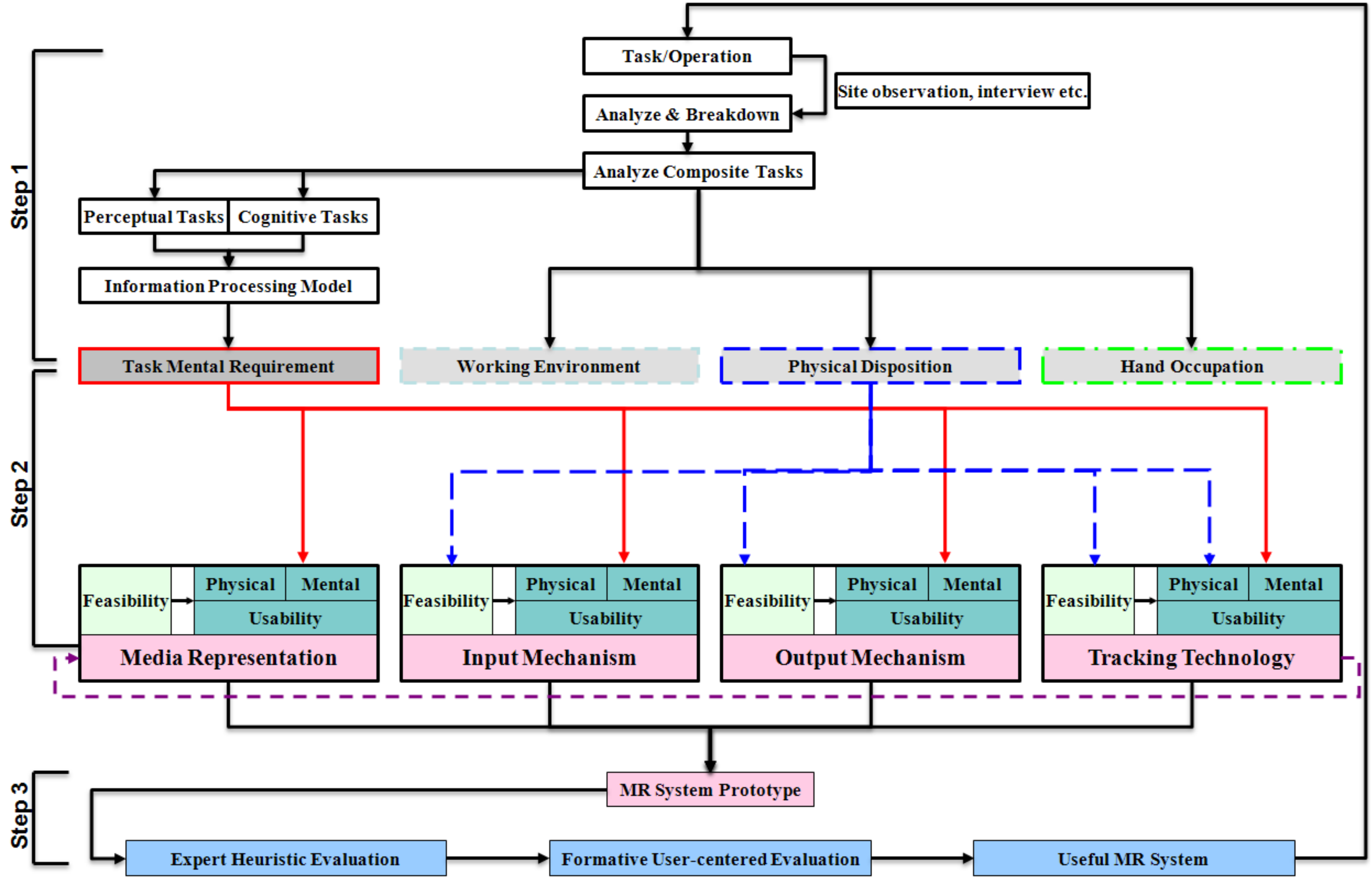

FIG. 4: Implementation of Specifying Methodology for MRCVE and Considerations of Influencing Relationships

4.1 Step 1 — Analyze the Design Review Task for Mechanical Detailing:

The design review task can be broken down as illustrated in Figure 5. Figure 5 depicts the hierarchical break-down of the design review task. Understanding the relationship between an upper level task and its subtasks may help MR designers identify potential user goals and tasks. For a more complete understanding, it is useful to consider the implications of combining tasks, in particular, how lower level tasks combine to form higher-level tasks. Performance of all member tasks (in some hierarchical order) represents performance of a single higher-level task. The hierarchy of low-level tasks during performance of a high-level task may be dependent on the nature of the high-level task as well as relationships among low-level tasks. For instance as shown in Figure 5, "eye travel and move" is one subtask of "examine", which in turn forms the critical upper level task such as "architecture design review"

The breakdown can yield the major composite tasks involved and then the hypothetical information processing model can be developed with the associated perceptual and cognitive tasks identified (see Figure 6). An information-processing account of task performance provides a description of the encoding of perceptual information, how different codes are used within internal psychological subsystems, and the organization of these subsystems. The information flow for particular tasks can be captured by diagrams of hypothesized processing subsystems (Proctor and Van Zandt 1994). These diagrams assist in identifying the mental operations that take place in the processing of various types of information from input to output. The information-processing approach provides a basis for analyzing the task components in terms of their demands on perceptual, cognitive, and motor processes. MR systems should strive for benefiting human working memory limits and attention allocation. By analyzing the hypothesized information processing model, we can craft the MR system to minimize working memory load by exploiting different working memory codes. The MR system should be plugged into the information processing model where it can play a role in maximizing the efficiency of attention allocation. Figure 6 presents the hypothesized human information processing model involved in design review task. In a typical design review task, the designers typically must first observe, inspect and identify the design from the perceptual task level. Then the designers must encode, estimate, compare, analyze, plan the details of the design from the cognitive aspect. Finally, they might need to write down or annotate on the design.

This task breakdown and the developed information processing model reveal that spatial cognition and comprehension should be the major research issue. The lessons learned and the research results can be applied to other MR systems that involve similar parameters. Upon studying face-to-face design review collaboration with respect to the four influencing factors, it was found that only mental requirements and physical disposition are the significant factors. Each of the influencing lines depicted in Figure 4 are discussed as follows.

- *Mental requirements*: The composite task level involves major tasks including navigation, examining, and annotating. These composite tasks can be divided into sub-tasks for developing a hypothetical information processing model (see Fig. 6). From this simplified model, the perceptual tasks such as object inspection, identification and location, and cognitive tasks such as distance and orientation estimation, refer to local situation awareness (egocentric frame of reference). Also the cognitive need for performing mental tasks demands the design modeling to be rich enough to reach a high degree of realism.
- *Physical disposition*: Collaborators may move around the table and either stand or sit. Even though the working space is predominantly around a table, roaming space and working volume should not be restricted.
- *Working environments*: The environment is indoors and quiet.
- *Hand occupation*: Hands are used to interact with digital content primarily and for paper-based annotating.

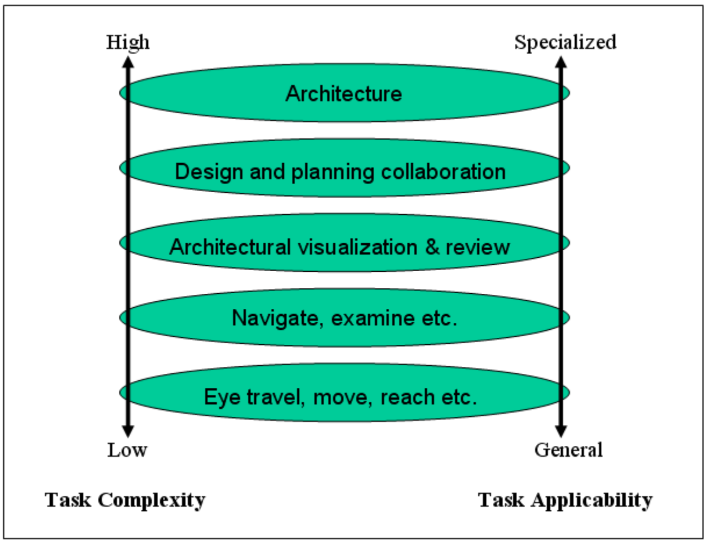

FIG. 5. Task Hierarchical Breakdown of Design Review Collaboration

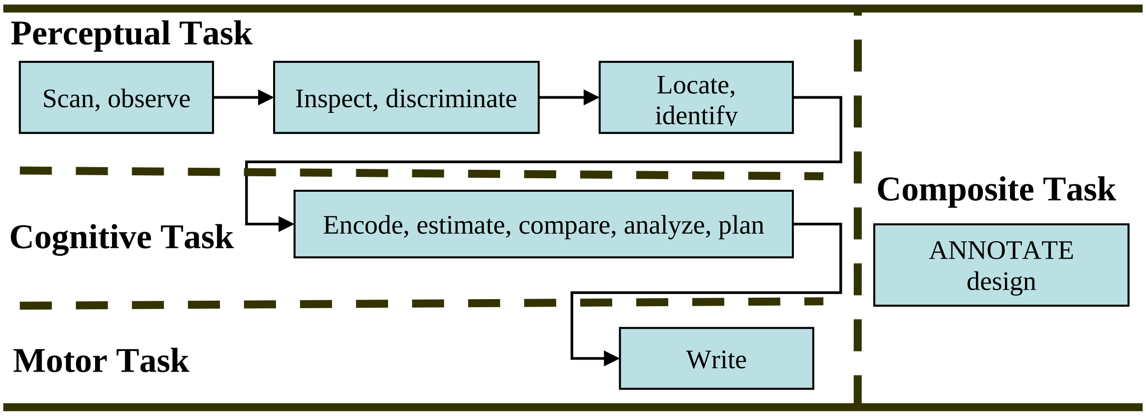

FIG. 6: Hypothetical Information Processing Model for MRCVE Representative Task

4.2 Step 2 — Map the Technology to Task

Figure 4 shows the complete mapping process. The influencing relationships were revealed and applied in mapping technology to task as explained below.

Media representation: Design visualization and review requires a high degree of realism that embraces many features (e.g., geometry, materials, color, etc.) to be rendered and reviewed. High-fidelity representations (physical and behavioral properties) are desirable in such an application. Also, navigation tasks inherent in reviewing designs require the presence of directional cues, such as an on-screen compass or a navigational grid and/or a navigational map. Such features may have a positive effect on the users' ability to perform navigational tasks. A hybrid representation of 3D virtual object (design) and 2D digital image (navigational map) should be used for enhancing the user's comprehension of the design models. However, the high fidelity scene may trigger usability problems associated with lag and low image regeneration frame rate simply because computing power is limited. The additional computing power required ensures rapid and smooth regeneration of a high-fidelity image may be either infeasible or undesirable. Specifically, many constructors utilize personal computers to run their everyday software applications and might be reluctant to invest in specialized brand of high-end graphics computers only for the purpose of supporting Mixed Reality visualization.

Input device: The virtual model is rendered in 3D space, which eliminates the use of 2D-based input devices because of the spatial mismatch. Also, collaborators should be able to move around the meeting table, which implies that input devices either should have long cables or be wireless. In order to strive for natural interaction between user and device, tangible input devices should be the most appropriate. Tangible input devices (or tangible user interfaces) are physical artifacts used as representations and controls for directly manipulating their corresponding digital associations. For example, a real pen tracked positionally in 3D space may be used to point to or select virtual objects or write annotations in the digital space. Also speech recognition and natural language input might be incorporated to create multimodal interfaces as opposed to single-channel input mechanisms. Such features enable verbal annotation that is useful for review note-taking in MEs, where preserving contextual information is important.

Output device: Selection of the visual output mechanism (display type and features) has much to do with presence and centricity requirements. Design review involves much examining of design details, implying that an egocentric point of view is useful to provide a strong sense of presence. An HMD can satisfy this requirement. Compared with a monoscopic video-based see-through head mounted display (ST HMD), an optical ST HMD can provide a better awareness of the surrounding objects and the task at hand, giving the user a stronger sense of presence (connection with the virtual objects). However, the optical ST HMD can not work with the pattern recognition tracker typically used with video-based ST HMDs, but is feasible with other optical trackers. Therefore the selection of the output device requires the consideration of the tracking technology. Stereoscopic video-based ST displays are beneficial in enhancing perception and task performance in situations when information is presented in an egocentric view rather than an exocentric view. Therefore, stereoscopic video-based ST HMDs are determined to be the most appropriate for the MRCVE.

Tracking technology: In MRCVE, if a user wants to see the other side of a virtual object, he must physically move himself and the HMD he wears, an action requiring medium-to-long-range position and orientation tracking. AR requires a highly accurate tracking system because even small tracker errors cause noticeable mis-registrations between real and virtual objects, which may compromise the user's comprehension of the model. One option for accurate tracking by pattern recognition over a larger scale is the use of multiple markers (see Figure 7). The drawback is the requirement that the user's view must always include at least one marker in order to maintain display of the virtual object(s). Ultrasonic, optical, and infrared tracking systems avoid tethering and thus allow greater freedom of motion, but are susceptible to interferences.

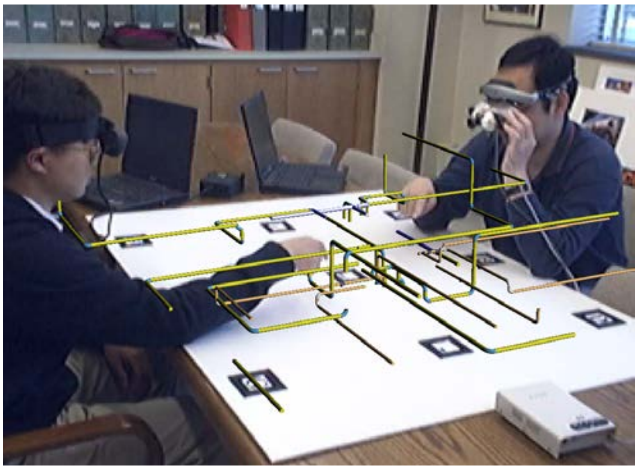

FIG. 7: MRCVE Face-to-face Collaboration Scenario

5. FUTURE DIRECTIONS

Although the foregoing approach has been formulated and presented to specify AR systems for specific tasks, the authors acknowledge that the existing technologies are still prohibitively limited with regard to versatility. Therefore, two areas of development are noted for further research to produce improved capabilities in MR or AR systems.

Hybrid approaches: Technological components in future MR systems may be developed as hybrids, because combining approaches can cover weaknesses. The hybrid media representation can be used because different representations can meet different perceptual and cognitive demands of users with different work requirements. Current trackcing and registration strategies generally focus on a single strategy. Future systems may be more robust if multiple techniques are combined. Almost all work in AR has focused on the visual sense.

Augmentation might apply to other senses as well, especially aural, so multimodal input and display can be applied.

Perceptual and cognitive studies: Mixed Reality is an area ripe for psychological studies. Experimental research can yield valuable knowledge regarding how and where MR truly augments a persons's ability to perform tasks in specific environments and situations. Jannick Rolland, Frank Biocca and their students conducted a study of the effect caused by eye displacements in video see-through HMDs (Rolland 1995). They found that users partially adapted to the eye displacement, but they also had negative after effects after removing the HMD. Steve Ellis' group at NASA Ames has conducted work on perceived depth in a see-through HMD (Ellis 1994). A study conducted by the authors compared the 3D CAD and Augmented Reality in the efficiency of detecting design errors, revealing that the interactive nature of an AR environment can considerably enhance human's perception and comprehension of a design model over that facilitated by a non-intuitive CAD environment (Wang and Dunston 2006b) A subsequent experiment (Wang and Dunston 2006b) was designed and implemented to quantify the perceptual incompatibility by comparing two types of display devices used in an MR environment. The results revealed that using the HMD yielded shorter completion time, reduced orientation displacement, and incurred less task work load for a spatial orientation task that requires local situation awareness. Such studies are key to further developing the specification guidelines presented in Tables 1-3 for media representation, control, and display aspects.

SUMMARY AND CONCLUSIONS

This paper has presented a methodology for analyzing a work task for the purpose of mapping appropriate Mixed Reality technological components to that task, to increase the likelihood of success in technology transfer. Also, a technology selection process is identified to choose appropriate technology characteristics including information representations, interaction methods and, tracking technology for a specific task category. Such a thorough mapping methodology can be used to guide new MR-based system design as well as to help evaluate existing systems. Each task or simple operation can be mapped to a collection of suitable technology strategies.

The AR design specifications and guidelines for mapping appropriate Mixed Reality technological components onto the characteristics of operations are developed from the considerations derived from various sources. While developing those guidelines, usability issues are one of the major things considered through two serial steps: feasibility analysis and ergonomics analysis. The approach to develop these AR design specifications and guidelines is to recognize the influencing relationship between certain task components and MR components and to collect and synthesize information from many different sources including experience and documentation regarding Virtual Environments (VEs), Augmented Reality, human-computer interaction, known technology limitations, etc. This latter task still requires such a search for information because MR research is still relatively new and the corpus of knowledge regarding best practices for MR system design is still far from being fully developed. The main findings and conclusions are as follows:

- As for the selection of media representation, in general, clear, simple, relevant, and consistent information is desired, but these criteria are not always attainable or strictly desired
- As for the selection of input mechanism, Mixed Environments should avoid non-intuitive, unnatural, or poorly-mapped input devices.
- A system's content presentation component(s) may have an effect on a user's cognitive processes (among many others), and subsequently, usability. Mapping user scenarios and tasks to appropriate display types and characteristics is essential for the development of truly useful and usable visual displays.
- In general, when assessing tracking technology relative to user tasks, one should consider working volume, desired range of motion, required accuracy and precision, and likelihood of tracker occlusion.

A case illustration was implemented using this methodology on a prototype Mixed Reality Collaborative Virtual Environment system. The influencing relationships were revealed and applied in a detailed mapping of technology to task. The case illustration demonstrates the feasibility and potentials of this methodology to guide new MR-based system design as well as to help evaluate existing systems. Implementation of this approach is straightforward and effective, but further development of MR technological options and user cognition studies are still needed to establish a complete base of knowledge for specification guidelines.

The validity of the presented methodology will be evaluated in future work. However, a complete evaluation of the methodology will involve long-term attention to its applicability. The reliable validation of the methodology will need much repetitive, comparative experimentation of different configurations.

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