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A HIERARCHICAL TAXONOMY OF AEC OPERATIONS FOR MIXED REALITY APPLICATIONS

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SUMMARY: *Mixed Reality (MR), or more specifically Augmented Reality (AR) technology, is frequently mentioned as a solution to human performance problems of degraded perception and cognition. There have been few attempts to develop lab-based MR prototypes for architecture, engineering, and construction (AEC) operations and thus no commercial MR applications can be found in the industry today. It is envisioned that useful MR systems will support the execution of information-intensive tasks, and identification of opportunities for MR requires analysis of AEC tasks at the appropriate level of detail. This paper develops an AEC task taxonomy and task analysis method for understanding the nature of a given task from a user-centered perspective. The composite and primitive levels are deemed appropriate levels for MR mapping to technology. The paper also identifies a set of influencing factors that should be analyzed and considered while selecting from among the MR technological component alternatives. Until construction product and process design become more highly integrated, MR technology applications can only occur at the lower level task, constrained to very limited application areas.*

KEYWORDS: *Augmented Reality; cognitive load; Mixed Reality; taxonomy, interactive systems*

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1. INTRODUCTION

While machines generally excel at physically-intensive tasks that require speed, strength, repetitive motions, and operation in hostile environments, humans are generally more cost-effective at mentally-intensive tasks that require judgment, sensing, and adaptability (Everett and Slocum 1994). Thus one vital role for automation is to augment rather than replace human capabilities. Mixed Reality (MR) technology can seamlessly delivers digitally based information to an individual within the operational context of their real world environment, thus making it a suitable solution for problems of degraded perception and cognition occurring in mentally-intensive tasks of appropriating information for decision-making. Virtually all construction activities require performance of some mental tasks (information seeking, assessment, and decision-making), which may also be embedded into a larger physically-intensive task. As the performance of the mental tasks improves, the overall productivity and quality should increase accordingly. MR can augment human ability in accessing data and information, which can enhance the decision-making cycle. There have been few attempts to develop lab-based MR prototypes for architecture, engineering, and construction (AEC) operations (Kensek et al. 2000, Dunston et al. 2002, Webster et al. 1996, Navab et al. 2002, Donath et al. 2001, Roberts et al. 2002, Hammad et al. 2002; Berlo et al. 2009; Wang and Dunston 2006; Schall 2009; Shin and Dunston 2009), and thus no practical commercial applications exist for the industry today. Science-based technology development constructs should be formulated to optimize the adoption of MR technology into AEC arenas if this option for portable human-computer interfacing is to be widely embraced.

Most of the identified MR research applications are prototypes that were implemented for special applications and typically for a narrow range of function. However, MR applications must be flexibly designed, in order to enable easy adaptation to different tasks and thereby facilitate technology adoption. Thus there is a need to develop an analytical approach for aligning MR technology tools to the daily work of AEC practitioners. In order to address this critical issue, this paper presents a framework for specifying effective MR systems, especially those classified as Augmented Reality (AR), for AEC work tasks. The overall framework incorporates critical human factors considerations which also underscore opportunities for valuable research that can further refine the specification framework. This paper presents the approach of using an AEC task taxonomy to describe AEC operations and tasks at an analyzable mental task level. Also a set of influencing factors for selection of appropriate MR technological components is identified to increase the likelihood of successful application of MR technology in AEC arenas.

The developed AEC task taxonomy can be the starting point for formulating fundamental propositions regarding flexibility, extendibility, and popularity of MR systems. The benefits of the results of this paper can help to successfully design effective MR-based systems for the AEC arena, to help technology designers and researchers to understand the user's goals and task requirements, and the circumstances under which users must work, how users as groups collaborate to accomplish a goal, and so on. The major emphasis of this paper is on task analysis before actual design of the MR system begins.

2. RELATED WORK

The authors' approach for mapping technology to task draws upon similar approaches developed for identifying appropriate uses of mechanical automation or robotics. While mechanical automation is appropriate for physically intensive tasks, MR technology is suitable for information-intensive tasks or more specifically, for enhancing human cognitive processes. Several important studies have attempted to identify which types of construction work are best suited to automation. Warszawski (1990) suggested that four generic or multipurpose robots could perform 10 "basic activities" (positioning, connecting, attaching, finishing, coating, concreting, building, inlaying, covering, and jointing) common in building work. Tucker (1988) computed the "automated potentials" of 17 "distinct areas." Kangari and Halpin (1989) ranked 33 "processes" according to need, technology, and economics, to arrive at a "robotics feasibility" score. Everett and Slocum (1994) hierarchically classified construction field operations into seven categories (project, division, activity, basic task, elemental motion, orthopedics, and cell), in order to explore the appropriate level where construction automation and robotics should be applied. These previous classification methods were developed mainly for construction phase activities and with robotics in mind. A unique set of considerations is appropriate to devise a specific AEC taxonomy which is geared towards the application suitability of MR technologies. None of the previous classification could be directly used in this context because the objective for MR implementations is to augment human mental capabilities rather than to substitute for their physical capabilities. Therefore, the objective of this paper is to offer an explanation of how AEC operations may be categorized and organized from a human-centered perspective. Key tasks are therefore human ability related and information intensive. A taxonomy was developed and geared towards the ergonomic analysis of a task of interest and such analysis can further serve a methodology for mapping technology to task.

3. HUMAN FACTORS IN MR SYSTEMS

MR systems may be regarded as a type of machine interface to a digital environment or to digital information, which means that the theory in human-machine interfaces applies to the research of human-MR system interfaces. Figure 1 depicts the interaction cycle. Humans obtain information through perceptual processing of the output (i.e., display) from the MR system. The mental cognition is activated in the brain to process the data and information, which may then be followed by a determined motor action. The action may apply to the work task at hand or to further interaction with the MR system. The latter action is typically conducted via input devices of the MR system. Computing components in the MR system then process the input command and display feedback as new output. Human factors issues involved in the use of MR-based technology vary according to the application domain. The real consideration here is that introducing an MR system involves presenting a user with a new information medium and tool that, if not properly designed, can be more of a burden than a help. Therefore, the actual impact on how humans obtain and function with information should be understood and addressed. The design of the MR system should exploit perception and cognition abilities without hampering the physical response action for performing the real world task. Therefore, the perceptual and cognitive issues are explored here with regard to major MR system technological components — media representation, input mechanism, output mechanism, and position/orientation tracker.

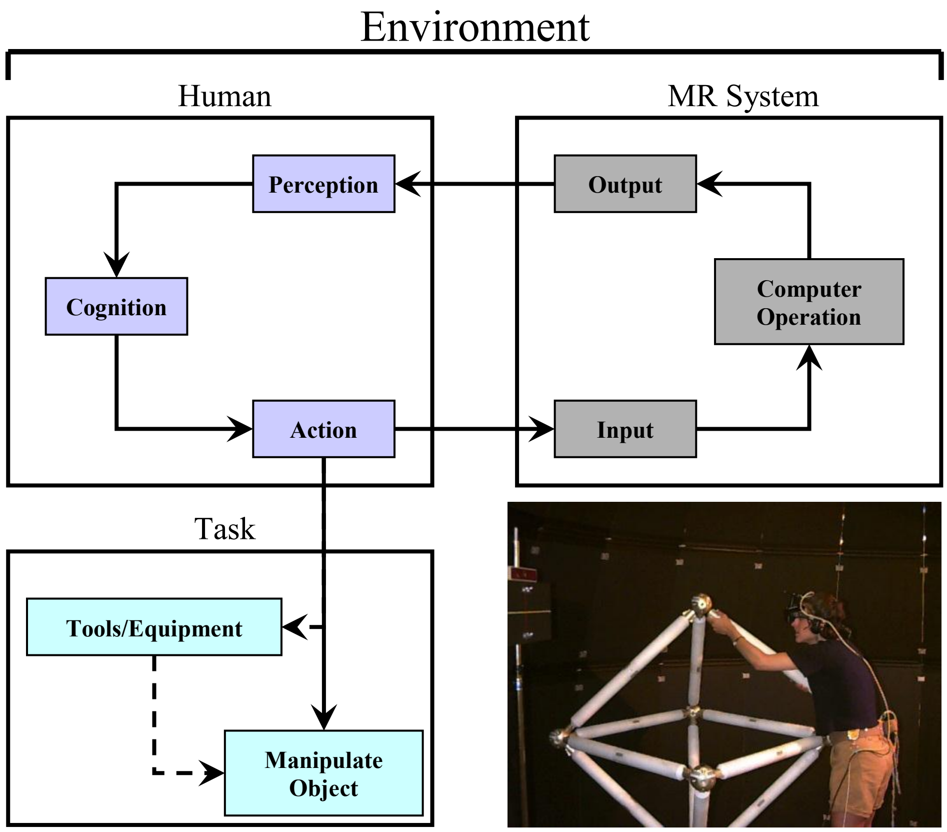

FIG. 1: Interface Model in MR Environment for Task Performance (Adapted from Proctor 1994); the example photo on lower right of AR being used to construct a space frame is from the "Augmented Reality for Construction" website (http://graphics.cs.columbia.edu/projects/arc/arc.html; accessed August 2008)

4. ANALYZING AEC TASKS

In order to map appropriate MR technology to tasks, it is necessary to analyze AEC tasks according to common functional aspects. One approach to characterizing tasks, activities, or operations involved in AEC is to examine general, fundamental tasks which serve as common denominators for analysis of more complex activities. As noted earlier, Everett and Slocum (1994) revealed that automated mechanical systems are suitable for physical tasks while humans are still more effective at decision making tasks. MR-based technology is suitable for such information-intensive tasks, which in the AEC industry, often deal with the information translation usually between a paper-based source and the work. MR can augment a human's ability to access information and documentation in the course of performing the work and enhance the individual's decision-making ability. All construction activities require performance of some information-intensive basic tasks and those tasks are the key focus in the following taxonomy which builds upon Everett and Slocum's.

4.1 Taxonomy for Categorizing AEC Tasks

The concept of a hierarchical taxonomy breaks architecture, engineering, and especially construction field operations down to low-level subtasks. In this context, there are three major benefits from establishing an AEC task taxonomy: (1) opportunities are more readily identified for exploiting Mixed Reality at appropriate task complexity levels; (2) an analytical methodology may be developed for mapping technology to the essential mental and physical tasks; and (3) enumeration of fundamental tasks enables the MR system designer to make use of previous MR system designs and evaluations. For a certain task, choosing the appropriate task complexity level will be important for discussing technology suitability.

Everett and Slocum (1994) presented a hierarchical taxonomy for construction field operations breaking down operations from the most general perspective into seven levels of increasing refinement: project, division, activity, basic task, elemental motion, orthopedics, and cell. Following the pattern of Everett and Slocum's hierarchy, a new classification of AEC tasks into five categories is shown in Figure 2 and examples are provided in Table 1. The composite and primitive levels are the ones where MR-based technology should be applied because the mental tasks involved at these levels are where human information processing models can be formulated for the respective task(s). The models can then be analyzed to reveal the issues to be addressed in research and development. Such mental activity analysis can assist in choosing an appropriate MR-based technology — media representation, interaction mechanisms (input and output), and even tracking technology. The levels of the task taxonomy are defined next.

TABLE 1. Hierarchical Taxonomy of AEC Tasks and Operations

Level	Description	Examples
1	Application Domains	Architecture, engineering, construction, inspection, maintenance, training and education
2	Application-Specific Operation	Safety and disaster response situation, maintenance, repair, build, dismantle, testing, fabrication, inspection, construction planning, conceptual planning, individual design, design and planning coordination and collaboration etc.
3	Operation-Specific Activities	Assembly, examining working flow or sequence, factory layout, architecture visualization or planning, equipment path planning, monitoring, tele-operation, tele-robotics, etc.
4	Composite Tasks	Measure, connect, navigate, organize, obtain, select, align, connect, record, annotate, report etc.
5	Primitive Tasks	Reach, grasp, eye travel, move

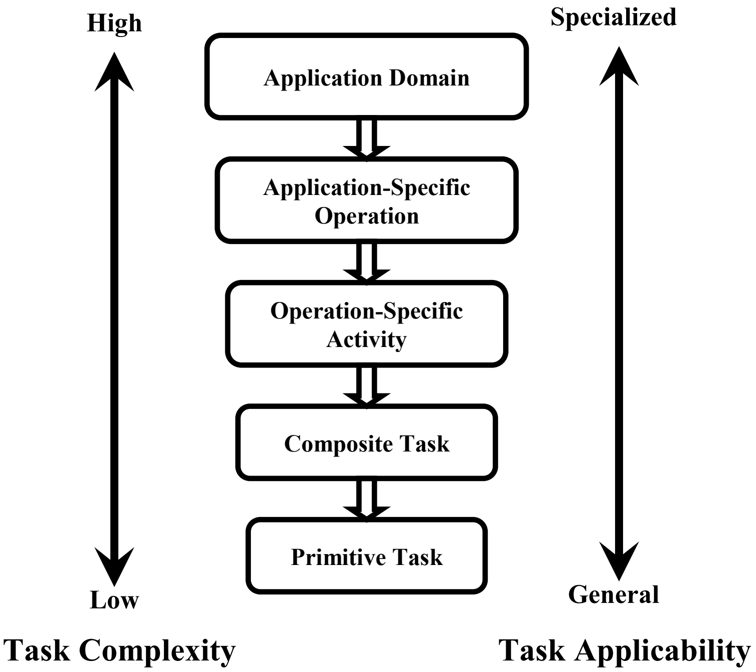

Fig. 2: Hierarchical Taxonomy of AEC Tasks and Operations

Application Domain: Architecture, engineering, construction, inspection, maintenance, training and education are the coarsely-classified areas where MR-based technology can be promisingly applied.
Application-Specific Operation: This category includes the specific operations in the identified application domains. A specialized operation such as field testing is termed as an application-specific operation, or a collection of application-specific operations characterizes a particular application domain.

Operation-Specific Activity: This level breaks the application-specific operations further down into specific units of work or activities such as construction work planning, factory layout, etc. Activities represent all undertakings that either coordinate or support work for or produce a recognizable, completed unit of work with spatial limits and/or dimensions.

Composite Task: Composite tasks are the fundamental building blocks of construction field work, with each representing one in a series of steps that comprise an activity. Any productive activities performed in the field can be categorized into one or more composite tasks. All the composite tasks can be performed by human craftspeople, but some can be accomplished by machines. The composite task is the highest level appropriate for exploring MR suitability because it actually consists of the three serial steps or tasks noted from Proctor and Van Zandt (1994): perceptual, cognitive, and motor tasks. The first two types of tasks are primarily mental processes, which typically precede the motor response, and they are important for developing an information processing model. Table 2 illustrates some examples of these serial tasks.

Primitive Task: Primitive tasks refer to elemental motion such as reaching, grasping, moving, eye travel, etc. In this research, the level of primitive task is the lowest valuable level to be analyzed.

TABLE 2. Breakdown of Composite Tasks

Breakdown of Composite Tasks		
1	Perceptual Tasks	detect, receive, inspect, scan, observe, survey, read, discriminate, locate, identify, etc.
2	Cognitive Tasks	calculate, interpolate, categorize, itemize, compute, tabulate, encode, transfer, analyze, estimate, choose, predict, compare, plan, etc.
3	Motor Tasks	activate, lower, close, move, connect, press, disconnect, raise, hold, set join, align, track, regulate, transport, synchronize, etc.

4.2 Implications of AEC Task Taxonomy

The relationships between the different levels in the task taxonomy follow the fundamental class-subclass structure. This structure results in organization which is indicated in Figure 3. Multiple elements at one level make up individual elements at the next higher level. Thus task complexity increases in the upward direction through the hierarchy. At the same time, lower level elements can generally be incorporated in various higher level elements. Therefore, the lower level elements have more generalized applicability while the higher level elements apply to more specialized purposes.

The more general the applicability of the task, the more frequently it can occur in higher-level tasks. For example, a primitive-level task such as hand reach, can occur as part of composite tasks such as measure, connect, align, select, etc., as well as the operation-specific activities such as assembly, factory layout, etc. Another example is that the operation-specific activity of design visualization can appear in the architecture domain for presenting the product to the owner, in the engineering domain for structural analysis, in the construction phase for work planning and even on-site scheduling visualization, in the inspection phase for comparing the as-built structure against design, or even in a training session. The implication for MR systems is that by enumerating the lower-level tasks within higher-level tasks, a designer can make use of previous MR system designs and evaluations of such lower level tasks. That is, a previously designed MR system or feature can have upward applicability in the hierarchy. This concept establishes a reusable-resource for future designs of MR systems.

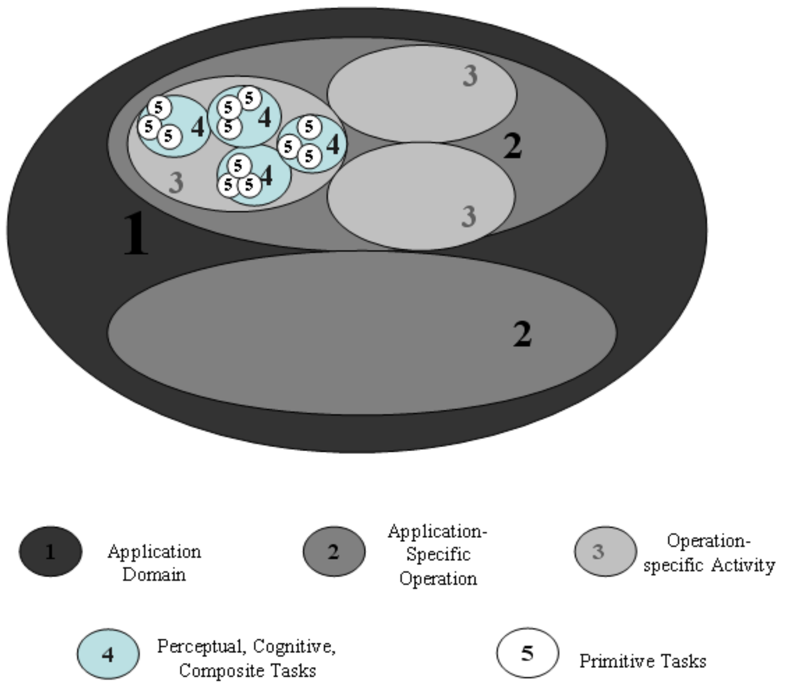

FIG. 3: Relationships of Task Levels

5. INFLUENCING FACTORS IN SELECTION OF MR TECHNOLOGY

By combining considerations from the major technological components of MR systems, the human-MR environment interface model illustrated in Figure 1, and knowledge regarding mental and physical human factors, the authors identified four significant factors that should at least be considered in the design of AR systems. These features can act as a starting point for designing an MR system. These four influencing factors are task mental requirements, working environment, physical disposition, and hands occupation, and each of these can influence the feasibility and usability of the four MR technological components (media representation, input mechanism, output mechanism, and tracking technology). Implications of these four factors are described in the following sections.

5.1 Task Mental Requirements

Task mental requirements have to do with perceptual and cognitive tasks mentioned above. Examples of perceptual, cognitive, and motor tasks were given in Table 2, some of which are adapted from Berliner's (1964) processing classification of 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.

5.2 Working Environments

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 dangerous conditions, where workers need to maintain high situational awareness and continually update knowledge of their surroundings in real time, 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.

5.3 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.

5.4 Hands 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 (see Figure 1). 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 MR 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.

6. CASE ILLUSTRATION

To illustrate how the analysis of mental task requirements complements the contemplation of an MR system and how the three objectives of using the AEC hierarchical taxonomy can be fulfilled in a real case, a simplified process of architectural wall panel installation can be described by the hypothesized human information processing model in Figure 4. In this situation, multiple sizes of panels have been specified with unique finishes such that they must be specifically arranged. The craftsperson typically must first plan the layout of the work. Once that is done, the craftsperson must identify the to-be-installed wall panel B and inspect it with reference to the design drawings to confirm it is the correct one. He also needs to visually (perceptually) locate the position of the existing in-place wall panel A, against which the wall panel B should be positioned. All of these simplified tasks are perceptual tasks. After confirming the to-be-positioned wall panel B and target position (next to wall panel A), the next thing the craftsman needs to think about is how to physically move the wall panel B next to wall panel A. While handling the panel, the cognitive tasks then begin, involving a more cognitively intense mental cycle of estimating, comparing, and adjusting to the target position until wall panel A and B are properly aligned and fulfilling the design requirements. Then the latter panel is secured to the supporting wall structure. The cycle of identify, inspect, locate, estimate, compare, align, and connect repeats over and over. MR can help the craftsman to identify the exact to-be-positioned wall panel easily and accurately by displaying the features of a virtual wall such as composition, shape, and finish design. It can show the virtual version of wall panel B in the target position precisely adjoined to the real wall panel A. Therefore the final layout is displayed in the real view of the craftsperson to augment the performance of position estimating and comparison. Since the wall assembly is a highly repetitive task, more cycles yields more time saving benefits from the MR tool.

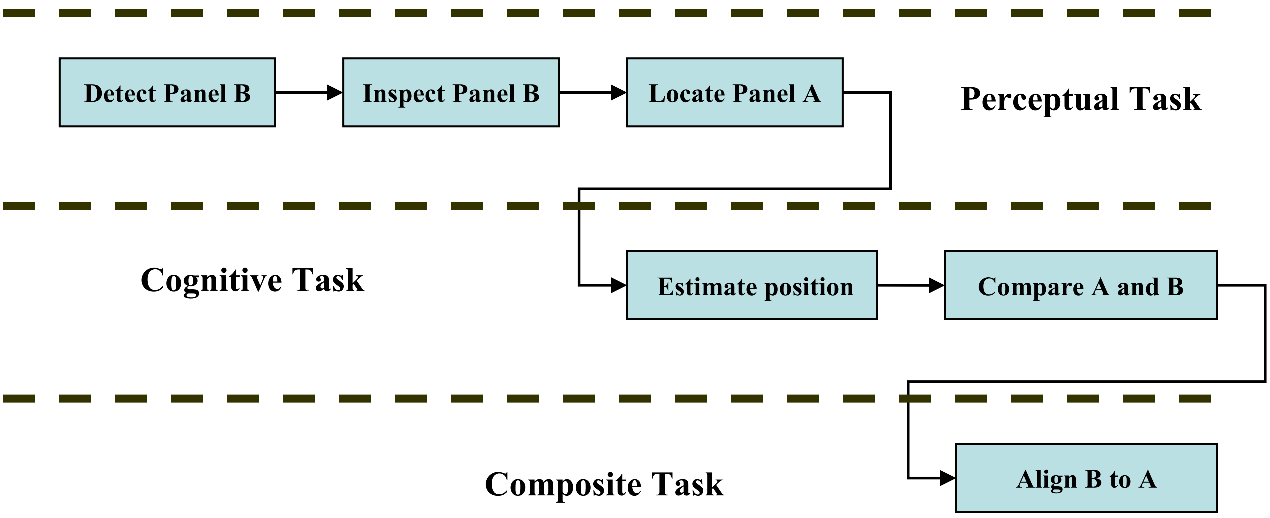

FIG. 4: A Simplified Hypothesized Human's Information Processing Model in Architectural Wall Panel Assembly

The three objectives (from Section 4.1) of using AEC hierarchical taxonomy for wall panel illustration are fulfilled as follows:

Objective 1: Identification of opportunities for exploiting Mixed Reality at appropriate task complexity levels. Referring to Fig. 2, assembling or placing the wall panels can be regarded as architecture visualization and planning at the level of an operation-specific activity and as an application specific operation “build.”
Objective 2: Development of an analytical methodology for mapping technology to the essential mental and physical tasks. The identified mental requirements combined with analysis of working environments, physical disposition and hands-occupation can be used to determine appropriate technological components of MR. For example, the large roaming area and frequent motion of personnel excludes mechanical trackers because of reach limitations. Magnetic trackers are challenged by transmittal interferences due to the presence of metal tools equipment and materials. Optical trackers tend to have line-of-sight occlusions, but innovative setups or hybrid technology strategies might enable a user to get beyond this barrier.
Objective 3: Enumeration of fundamental tasks enables the MR system designer to make use of previous designs and evaluations. Furthermore, any usability concerns associated with these tasks are brought to light for consideration. For example, the usability experience with different depth-judgment strategies (e.g., pointers, indicators, stereo image, etc.) gained in the task of installing wall panels can also be applied to other tasks where depth perception is critical. The experience with trackers used in the task of installing wall panels can also be drawn upon for other tasks performed in similar working environments and physical dispositions.

7. IMPLICATIONS FOR MR TECHNOLOGY IN AEC

Using familiar manufacturing terminology, Everett and Slocum (1994) articulated that project delivery goes through stages of product design, process (construction methods) design, and fabrication. The design-bid-build project delivery life cycle is graphically illustrated in these terms in Figure 5. In construction, product design and process design are relatively independent of each other. Product design is performed by architects and engineers who design the constructed facility down to the level of detail that enables definition of activities, but who otherwise do not get involved in the building process other than inspecting the finished work for conformance to their specifications. Contractors have control over process design and fabrication but generally have little or no input into product design. A construction process planner may be required to complete the architect's product design as part of the construction process design. With so-called performance specifications, the process designers and fabricators may have significant input into product design. *Fabrication*, in this model, refers to any physical labor by the prime contractor, subcontractors, or supplier to produce a physical component of the designed facility. Sections 7.1 – 7.4 briefly describe key implications for implementing MR based systems within this context.

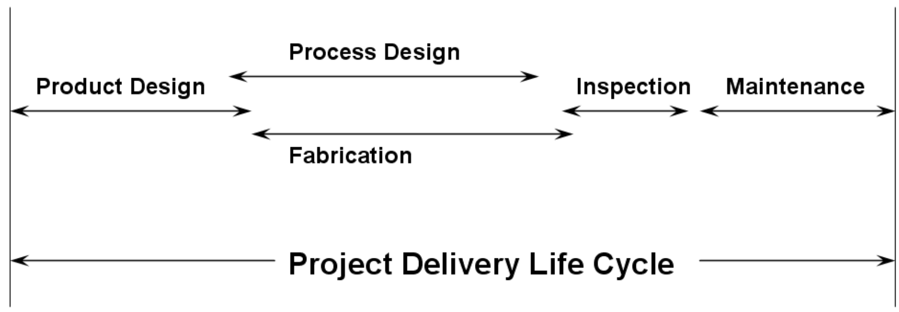

FIG. 5: Project Delivery Life Cycle (adapted from Everett and Slocum 1994)

7.1 Database/Information Availability for MR Systems

The success of MR as a tool for AEC relies heavily on whether all phases in the project life cycle are integrated to provide an accessible database which can be used readily by MR systems. As stated above, product designers provide design information only to a level of detail which useful down to the activity level of the process design. Generally speaking, there has been no historical need or incentive for architects and engineers to concern themselves with the intricacies of the work in the field, so finer levels of detail have not been incorporated into design. Just as Everett and Slocum (1994) noted for construction automation, there is a gap between the finest level of product design detail and the most suitable general level of MR technology application. More specifically, projects currently lack a compiled database of supporting information that could be readily exploited by MR technology due to the fact that no design and construction parties are required to provide such an information source. In addition to facility design information, MR systems may require access to a detailed database of the environment. For example, the architectural application of "seeing into the walls" assumes that the system has a database of where all the pipes, wires and other hidden objects are within the building. Such a database may not be readily available, and even if it is, it may not be in a format that is easily usable. Drawings are still more often than not in two dimensions, are otherwise too abstract, or may not be grouped to segregate the parts of the model that, for example, represent wires from the parts that represent pipes.

To make MR technology feasible at the composite level and therefore broadly useful, the gap between the level of detail of construction product design and the information requirements of MR technology must be closed. It is noted that more research is in progress regarding new production philosophy, emphasizing coordination or integration of production design and process design. Designers of the final product help determine the processes to be used to create the product, and process designers contribute to the final product design. This can happen by extending design details to the level where MR systems can have enough information to be effectively utilized. In the envisioned project environment, rich design information organized around a 3D object design model that is produced and assembled in earlier stages is available in digital format for use in later stages by multiple project parties.

7.2 MR System Flexibility

Most MR research applications are prototypes that were implemented for special applications, however, MR applications must be flexibly designed, in order to enable easy adaptation to different tasks. More research needs to be implemented to address flexibility issues of MR systems. To be cost effective, sustainable, and popularized, MR system must be designed to be flexible enough to be transferable from project to project or among different levels of tasks. It is envisioned that the developed AEC task taxonomy can be the starting point for formulating fundamental propositions regarding flexibility, extendibility, and popularity of MR systems.

7.3 Technology Application Levels

The MR technology transfer can happen in all kinds of levels, depending on the level of detail of information provided by architecture and engineering. The more detailed information from product design can enable lower-level tasks to be augmented by MR systems. Compared with automation and robotics which are conceptualized to be appropriate for the basic-task level (e.g., connect, cut, dig, place, etc.) (Everett and Slocum 1994), advances in task augmentation by MR-based technology should occur at the composite task level within the hierarchical taxonomy scheme presented in Figure 2 for the AEC industry. Also, the perceptual and cognitive components involved in composite tasks should be the important research focus for developing the hypothetical information processing model which can be used to identify where MR can improve and augment performance of a specific task.

8. LIMITATIONS

To develop the MR system prototype designs, there are some limitations regarding MR technology that need to be addressed. The next three sections (8.1-8.3) describe these limitations.

8.1 Lack of Accurate Tracking Technology

Accurate registration and positioning of virtual objects in the real environment requires accurate tracking of the user's head and sensing of the locations of other objects in the environment. AR imposes much stricter requirements on the tracking system than virtual-environment applications require. AR requires highly accurate trackers because even tiny tracking errors result in noticeable registration errors (misalignment) between real and virtual objects. The greatest obstacle to building effective AR systems is the requirement of accurate, long-range sensors and trackers that report the locations of the user and the surrounding objects in the environment. Azuma (2001) noted a lack of trackers that provide high accuracy at long ranges in real time. Since that assessment, the authors note only the refinement of pre-existing strategies that are still limited in range. For example, although the most advanced commercial systems (e.g., IS-1200 VisTracker) are extendable to larger areas, the goal is achieved by simply repeating the infrastructure (tracking markers) for a short range solution to cover the larger area, an option generally not attractive to users in construction industry settings.

8.2 Lack of Motivation for Technology Transfer

It is well-known that construction practitioners are generally reluctant to make dramatic changes in their use and adoption of new technology. Without all the technology components fully developed for industry applications, whether AR is truly a cost-effective solution in its proposed applications has yet to be determined. Much research should therefore be aimed at proving first the feasibility and then the profitability of implementing MR systems for information intensive tasks.

8.3 Social issues

Social concerns should not be ignored during attempts to move AR out of the research lab and into the hands of real users (Azuma 1997). For example, if workers perceive lasers to be a health risk, they may refuse to use an MR system with lasers as the tracker, even if those lasers are eye safe. Another important factor is whether or not the technology is perceived as a threat to jobs, as a replacement for workers. This factor should not be a significant challenge for MR implementation because the technology is intended as a support tool to more thoroughly equip the user to perform work rather than as an automated system to replace the human worker.

9. SUMMARY

This paper has presented a hierarchical AEC taxonomy that may be used to identify opportunities for Mixed Reality implementation as well as to develop an analytical methodology for mapping MR technology to AEC industry tasks. The taxonomy classifies normal AEC operations into the following levels: Application Domain, Application-Specific Operation, Operation-Specific Activity, Composite Task, and Primitive Task. AEC operations should be broken down to these level for analysis of mapping from Mixed Reality technologies. It was found that the composite and primitive levels of AEC operations are deemed appropriate for MR mapping to technology. Until construction product and process design become more highly integrated, MR technology applications can only occur at the lower level task (composite and primitive levels), constrained to very limited application areas. Associated visions, case studies and examples have been provided for a context-driven discussion. The implications of MR technology applications in AEC arenas and technological have been discussed at a comprehensive level. In order to make MR technology feasible at the composite level and therefore broadly useful, the gap between the level of detail of construction product design and the information requirements of MR technology must be closed. In order to be cost effective, sustainable, and popularized, MR system must be designed to be flexible enough to be transferable from project to project or among different levels of tasks. The perceptual and cognitive components involved in composite tasks should be the important research focus for developing the hypothetical information processing model which can be used to identify where MR can improve and augment performance of a specific task. The main limitations include the lack of accurate tracking technologies, the lack of motivation of technology transfer in AEC and certain social issues. The developed AEC task taxonomy in this paper can be the starting point for formulating fundamental propositions regarding flexibility, extendibility, and popularity of MR systems.

10. ACKNOWLEDGMENT

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11. REFERENCES

Azuma, R. T. (1997) “A Survey of Augmented Reality.” *In Presence: Teleoperators and Virtual Environments*, MIT Press, *6* (4), 355-385.

Azuma, R. T., Baillot, Y., Behringer, R., Feiner, S., Julier, S., MacIntyre, B. (2001). “Recent Advances in Augmented Reality.” *IEEE Computer Graphics and Applications,* 21 (6), 34-47.

Berliner, C., Angell, D., and Shearer, J. (1964). “Behaviors, Measures and Instruments for Performance Evaluation in Simulated Environments.” *Proceedings of Symposium and Workshop on Qualification of Human Performance*, Albuquerque, NM.Berlo, L., Helmholt, K., Hoekstra, W. (2009). “C2B: Augmented Reality on the Construction Site.” *Proceedings of the 9th International Conference on Construction Applications of Virtual Reality (CONVR 2009*) Xiangyu Wang and Ning Gu, editors, Nov 5-6, Sydney, Australia, 295-304.

Donath, D., Beetz, J., Grether, K., Kruijff, E., Petzold, F., Seichter, H. (2001) “Cooling Factory, a Concrete Project to Test New Architectural Applications for Augmented Reality.” *Proceedings of International Conference on Augmented, Virtual Environments and Three-Dimensional Imaging*, Venetia Giagourta, Michael G. Strintzis (ed.), 14-17.

Dunston, P. S., Wang, X., Billinghurst, M., and Hampson, B. (2002). “Mixed Reality Benefits for Design Perception.” *Proceedings of 19th International Symposium on Automation and Robotics in Construction (ISARC 2002)*, William Stone, editor, NIST Special Publication 989, Washington D.C., Sep. 23-25, 2002, 191-196.

Everett, J. G., Slocum, A. H. (1994). “Automation and Robotics Opportunities: Construction Versus Manufacturing.” *Journal of Construction Engineering and Management*, 120 (2), 443-452.

Hammad, A., Garrett, J. H., and Karimi, H. A. (2002). “Potential of Mobile Augmented Reality for Infrastructure Field Tasks.” *Proceedings of the 7th Int’l Conference on Applications of Advanced Technology in Transportation*, August 5-7, Boston Marriot, Cambridge, MA, 425-432.

Kangari, R., and Halpin, D. W. (1989). “Potential robotics utilization in construction.” Journal of Construction Engineering and Management, ASCE, 115 (1), 126-143.

Kensek, K., Noble, D., Schiler, M., and Tripathi, A. (2000). “Augmented Reality: An Application for Architecture.” *Proceedings of 8th International Conference on Computing in Civil and Building Engineering*, Stanford, CA, August 14-16, 294-301.

Navab, N. et al. (1999). “Scene Augmentation via the Fusion of Industrial Drawings and Uncalibrated Images with a View to Markerless Calibration.” *Proceedings of 2nd Int’l Workshop Augmented Reality (IWAR 99),* Los Alamitos, Calif., 125-133.

Proctor, R. and Van Zandt, H. (1994). *Human Factors in Simple and Complex Systems*. Allyn & Bacon.

Roberts, G. W., Evans, A., Dodson, A., Denby, B., Cooper, S., and Hollands, R. (2002). “Look Beneath the Surface with Augmented Reality.” *GPS World*, February, Internet Article, 14-20. URL: http://www.gpsworld.com/gpsworld/.

Schall, G. (2009). “Handheld Augmented Reality in Civil Engineering.” *4th Conference on Computer Image Processing and its Application in Slovenia 2009 (ROSUS 2009)*, Maribor, Slovenia, March 19, 19-25.

Shin, D. and Dunston, P. S. (2009). “Evaluation of Augmented Reality in Steel Column Inspection.” *Automation in Construction*, Elseveir, 18(2), 118-129.

Tucker, R. (1988). “High payoff areas for automation applications.” Proceeding, 5th International Symposium on Automation and Robotics in Construction, Japan Industrial Robot Association, Tokyo, 9-16.

Wang, X. and Dunston, P. S. (2006). "Usability Evaluation of a Mixed Reality Collaborative Tool for Design Review," *International Conference on Computer Graphics, Imaging and Visualisation (CGIV'06)*, IEEE, Sydney, Australia, July 26-28, 448-451.

Wang, X., Dunston, P. S., Skibniewski, M. (2004). “Mixed Reality Technology Applications in Construction Equipment Operator Training.” *Proceedings of the 21st International Symposium on Automation and Robotics in Construction (ISARC 2004),* September 21-25, Jeju, Korea, 393-400.

Waszawski, A. (1990). Industrialization and robotics in building. Harper and Row, New York, N.Y.

Webster, A., Feiner, S., MacIntyre B., Massie, W., Krueger, T. (1996). “Augmented Reality in Architectural Construction, Inspection, and Renovation.” *Proceedings of ASCE Computing* in Civil Engineering, Anaheim, California, June 17-19, 913-919.