Mixed Reality: Are Two Hands Better Than One?

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ABSTRACT
For simulating hands-on tasks, the ease of enabling two-handed interaction with virtual objects gives Mixed Reality (MR) an expected advantage over Virtual Reality (VR). A user study examined whether two-handed interaction is critical for simulating hands-on tasks in MR. The study explored the effect of one- and two-handed interaction on task performance in a MR assembly task. When presented with a MR system, most users chose to interact with two hands. This choice was not affected by a user's past VR experience or the quantity and complexity of the real objects with which users interacted. Although two-handed interaction did not yield a significant performance improvement, two hands allowed subjects to perform the virtual assembly task similarly to the real-world task. Subjects using only one hand performed the task fundamentally differently, showing that affording two-handed interaction is critical for training systems.

Categories and Subject Descriptors
I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Interaction styles;

General Terms
Experimentation, Human Factors.

Keywords
Mixed Reality, Virtual Reality, Two-handed Interaction

1. INTRODUCTION
Hands-on tasks, such as engineering design and assembly, require an interface that balances natural and intuitive interaction with precision [6]. A two-handed interface is expected to provide advantages in all areas. Mixed Reality (MR) is a technology that can easily afford two-handed interaction. For this work, we define MR systems as those in which physical correlates are handled to manipulate co-located virtual objects. Because interaction relies on real objects, the usual MR interface is one's hands (and the objects themselves). This paper explores the performance advantages, for conducting MR engineering assembly, provided by a two-handed interface.

MR's ability to provide *natural*, *intuitive*, and *precise* interaction should benefit simulating engineering design. *Natural* interaction is defined by [2] as manipulating virtual objects as if the objects were actually there, as if the interface was transparent. MR interaction is similar to the real-world: users manipulate real objects with two hands, and the real objects provide haptic feedback and physical constraints. An *intuitive* interface requires that the set of perceived affordances is equal to the set of real affordances – one's hands are such an interface. VR systems require users to train to use an interface. However, the intuitive interface of MR should allow users to train directly to perform a task. *Precision* is especially important to engineering design tasks. Zachmann [6] gives the example of performing automotive assembly verification: the virtual interaction must simulate the interaction between the engineer's hands and the real car as completely and correctly as possible. Interaction between the real objects of MR provides constraints on movement, which allow for more precise interaction than with purely virtual objects.

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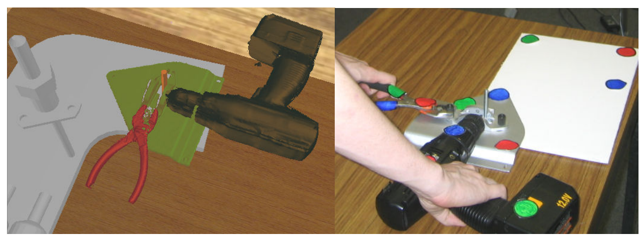

Figure 1. Handling real objects makes MR interactions more similar to the real-world task.

1.1. Applying MR to Engineering Design
MR appears to be an excellent platform for investigating engineering design tasks. However, few MR systems have been applied to engineering design: [4] presents a two-handed gloved and haptic MR system, which provides tracked simple objects for generic manipulation and assembly tasks. [7] uses MR to provide step-by-step instructions during a furniture assembly task. [5] allows users to manipulate real objects and simple physical correlates, while viewing high fidelity scanned models and CAD models of not yet manufactured parts, with the goal of verifying engineering design.

1.2. Interacting with Two Hands in VR
In VR, two-handed interaction techniques can provide increased task performance over one-handed interaction. In [3], participants aligned two virtual objects by handling two props (a dolls head and cutting plane). Expectedly, using two hands provided increased accuracy. On the responsive workbench, users perform best by using two hands (one glove and one stylus) [1]. In [3] two-handed interaction allowed subjects to more easily explore alternative problem solving strategies.

Although explored for VR systems, the advantages of two-handed interaction in MR have not yet been presented. The goal of this work is to identify the performance advantages (if any) of using two hands in MR, and to determine if two-handed interaction is critical to performing engineering design tasks in MR.

2. STUDY DESCRIPTION

2.1. Overview

The MR system presented in [5] was used to evaluate task performance for a hands-on assembly task. The MR system used 8 webcams to track colored markers placed on four real objects (3 pipe objects and a hand-tracking watch worn on the user's wrist). For the user's dominant hand a simple transparent sphere was provided as an avatar. Users wore a Virtual Research V8 HMD which was tracked by a WorldViz PPT and an Intersense InertiaCube2.

Hypothesis: on the following metrics, participants using two hands will perform better than those using only one hand:

- The time required to complete the task. Two hands will allow for more efficient rotation, and will let users handle two objects at once.
- The number of mistakes and collisions. Two hands will give users better control over objects which might be unwieldy with only one hand.

2.1.1 Procedure

The study was conducted at the IEEE Virtual Reality 2006 conference, with subjects taken from volunteering attendees. It was repeated at the University of Florida, with participants from a graduate-level advanced graphics course ("LAB" population). Participants were first asked to perform a tutorial task. This consisted of placing a PVC pipe object into a specified position and orientation in a connector-array (the four-by-four array of cylindrical receptacles in Figure 2). Both the pipes and the connector-array were real objects. A virtual box covered the connector-array. The solution was presented as a "proposed design sheet," a picture of the finished construction shown from a different perspective and without the enclosing box. The proposed design sheet was placed next to the connector-array on the virtual table (*Figure 2c)*.

Participants were next asked to complete a timed task with three, more complex pipe shapes (Figure 2). Participants were instructed to perform the task as quickly as possible and to minimize mistakes (collisions and misplacing pipes). Participants were informed when they misplaced pipes in the connector-array, but were not instructed how to fix the mistake.

2.2. Performance Metrics

Participants' performance was determined by the following metrics:

Speed: Completion time & Number of rotations performed.
Errors: Number of collisions & Misplacements of pipes.

2.2.1. Time Metrics

Completion time was measured, by stopwatch and timestamp, from the instructed start time until the time the investigator informed the participant that he or she had correctly completed the task. The *number of rotations* was determined by reviewing video of the task performance. Only rotations over 45 degrees were counted (rotations > 360 degrees counted twice). A minimum of three rotations was required to bring the pipes from their initial orientation to the correct orientation for placement into the connector-array.

2.2.2. Error Metrics

By highlighting colliding triangles in red, collisions were made visible to the participant. The *number of collisions* was measured through reviewing both virtual and real video of the task. Although pipe-box collisions were also displayed to subjects, only pipe-to-pipe collisions are analyzed in this paper. Collisions caused by tracking errors were not counted. *Misplacement of pipes* was the counted number of instances that a participant placed a pipe into the wrong position or orientation in the connector-array. Misplacements were counted by observing video of the task

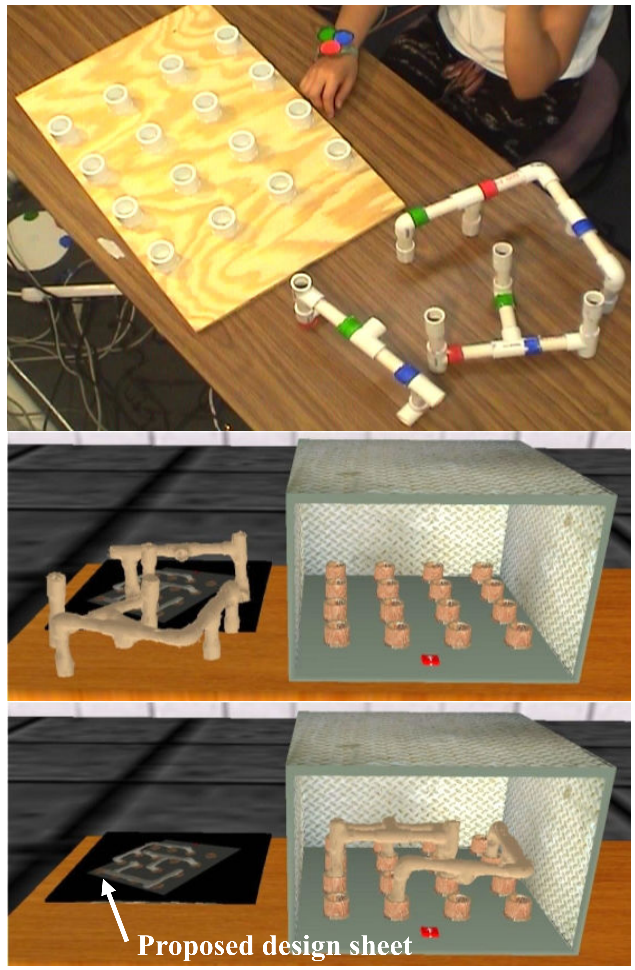

Figure 2. The starting state of the task (top: real, middle: virtual) and the finished assembly (bottom).

2.3. Classification of Interaction

Participants were not pre-assigned to one- or two-handed groups. Instead, conditions were determined *post priori* through observing video of their interactions. Users were classified into two groups by their use of hands in the pipe layout task:

- ***Class 1H*** (n = 6, 2 in LAB, 4 in VR2006): Participants used only the hand on which they wore the tracking watch.
- ***Class 2H***: Two-handed (n = 12, 5 in LAB, 7 in VR2006).

3. DISCUSSION

In terms of ability, the populations were similar: because all participants work in the computer graphics field, both populations were expected to have similar spatial abilities. However, VR2006 participants were also experienced with using VR systems, while LAB participants universally had no experience with VR. Section 3.1 explores participants' choice in hand use. The performance of each class is shown in Figure 5, with analysis given in Section 3.2. No significant performance differences were found between 1H and 2H conditions. This is partly a result of compensating actions taken by the 1H participants (Section 3.3).

3.1. Making a Choice in Hand Use

Because participants were neither assigned to a hand-use class, nor informed that they could use either one or two hands, participants' *choice* in hand use can be examined:

- When presented with a MR system, what percentage of users will choose to interact with two hands?
- Does this choice correlate to the user's level of experience with (predominantly one-handed) VR systems?
- By presenting the user with multiple real objects, does MR invite the user to interact with two hands?

3.1.1. Choosing to Use Two Hands

The majority of participants (~70%) chose to interact using two hands. The large percentage is surprising: participants were not informed that they could use two hands, and an avatar was provided for only one hand. Additionally, the choice of many participants in the 1H condition may have been due to being uncomfortable with the HMD. Although instructed to adjust the HMD to fit before beginning the tutorial task, 50% of participants in 1H (both VR2006 and LAB) were observed using their non-active hand to steady the HMD. This suggests that the percentage of participants who *wanted* to use two hands may be even higher than the amount that did.

3.1.2. Effects of Experience on Hand Choice

It was hypothesized that participants with VR experience (VR2006 population) will assume that MR places similar restrictions on interaction with the virtual world, and choose to use only one hand to complete the task. Only slightly more than one-third (36%) of VR2006 participants interacted with only one hand, while 64% used two hands. The less experienced LAB population was expected to naively use two hands. Slightly less than one-third (29%) of LAB participants used one hand, while 71% used two hands to interact.

The slight difference between VR2006 and LAB populations is not significant for the sample size. The majority of users will choose to interact with a MR system using two hands, *regardless of past experience* with one-handed VR systems.

3.1.3. Effects of Real Objects on Hand Choice

We believe that by presenting real objects to the user, MR invites real-world interaction – i.e. use of two hands. The effect of the *quantity* and *complexity* of the real objects on hand choice was evaluated: neither the quantity nor the complexity of the real objects influenced the participants' choice of using one or two hands.

Quantity: All LAB participants used the same number of hands to perform the tutorial task (1 pipe) as for the timed task (3 pipes). Two VR2006 participants (18%) used one hand for the tutorial task and switched to two hands for the timed task, but this was due to getting comfortable with the HMD, as these participants used their free hand during the tutorial task to steady the HMD.

Complexity: The complexity of the real objects was also observed to have no effect on hand choice. The complexity of an object is defined as the number of rotations required for correct placement. One of the pipes was clearly less complex than the others. It required no rotations to bring it into the correct orientation for placement. Only a single participant (out of 12) in the 2H group used one hand to manipulate the less complex pipe. All other participants handled all pipes with two hands.

Why do users choose to interact with two hands in MR? It can not be concluded that the choice is dependent on the quantity or complexity of real objects. We believe that it is simply the presence of real objects: Inexperienced users naively assume real objects imply that real-world interaction is possible. Experienced VR users interpret the real objects as a less restrictive interface, and interact in MR *as they want to interact* in VR.

3.2. Evaluating Performance

To explore the performance differences of one- and two-handed interaction, a two-tailed t-test compared 1H and 2H:

- Completion time
    - For the LAB population, 1H had a faster average completion time (154 sec) than 2H (166.8 sec), but the difference was not significant ($p = 0.66$).
    - For the VR2006 population, 1H was also faster than 2H (mean of 176 sec to 222.9 sec), but the difference was not significant ($p = 0.46$ VR2006).
- Rotations performed
    - For the LAB population, the difference was less than one rotation (1H = 6.5, 2H = 7.0), and was not significant ($p = 0.49$).
    - For the VR2006 population, 1H participants performed 1.3 more rotations on average than 2H participants (8.0 to 6.7), but the difference was not significant ($p = 0.61$).
- Collisions
    - For the LAB population, 1H averaged 1.0 pipe-pipe collisions to 2.6 for 2H. This was not significant ($p = 0.32$).
    - For the VR2006 population 1H averaged 4.3 (here the median of 2.5 provides a better indicator of performance) to 2.9 for 2H. Again, the difference is not significant ($p = 0.64$).
- Pipe misplacements
    - For the LAB population, 1H participants averaged 1.0 misplacements to 0.4 for 2H, but the difference was not significant ($p = 0.66$).
    - For the VR2006 population, 1H participants averaged less misplacements than 2H (mean of 0.25 to 1.43), but the difference was not significant ($p = 0.15$).

Using two hands for the pipe layout task did not provide any significant benefits in speed or errors committed. 1H participants employed compensating actions (Section 3.3) that contributed to a similar level of performance.

LAB (n=7)	Time	Rotations	Collision	Misplaced	VR2006(n=11)	Time	Rotations	Collision	Misplaced
1H(n=2) Mean	154.0	6.50	1.00	1.00	1H(n=4) Mean	176.0	8.00	4.25	0.25
StdDev	14.14	0.71	1.41	1.41	StdDev	99.81	4.32	5.32	0.50
2H (n=5) Mean	166.8	7.00	2.60	0.40	2H (n=7) Mean	222.9	6.71	2.86	1.43
StdDev	57.12	0.71	1.14	0.55	StdDev	85.06	1.98	1.57	1.81

Figure 3. For LAB (top) and VR2006 (bottom) populations: performance metric mean and std. dev.

3.3. Compensating for Using One Hand

For one vs. two hands, performing the pipe layout task was *fundamentally different*. While gross scores were similar (including completion time and errors), the performance of the task is semantically different.

In VR [1] observed that participants using only one hand employed an inefficient ratcheting motion to rotate objects. In MR, ratcheting takes the form of incrementally spinning the pipe about one of its legs pinched between two fingers and the thumb. Surprisingly, we observed ratcheting in only 25% of the 1H class. 75% of 1H participants instead cleared space on the table to put down a pipe, and then rotated the pipe while it rested on the table (Figure 8). Additionally, 25% of 1H participants placed one leg of a pipe into its matching connector, and used it as a pivot to correctly position the pipe.

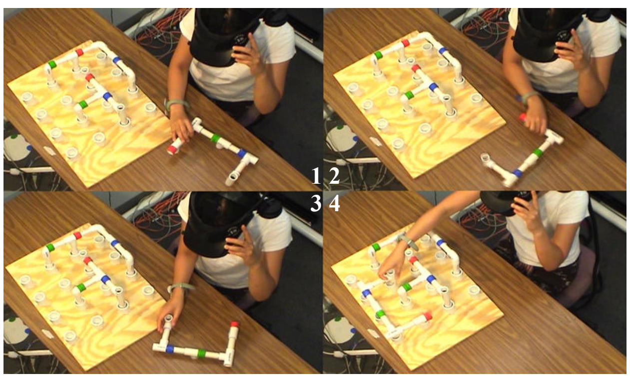

Figure 4. Participants compensated for one-handedness by rotating pipes into the desired orientation on the table surface.

4. CONCLUSIONS

Using two hands to perform an assembly task in MR did not provide a performance advantage over using one hand. However, *only by using two hands* were participants able to complete the task in a way similar to performing the real-world assembly.

4.1.1 Observations

- The majority of users, independent of prior VR experience, choose to interact with two hands.
- While it is expected that the presence of real objects in MR invites two-handed interaction, the quantity and complexity of the real objects did not affect participants' choice of one or two handed interaction.
- Using two hands did not reduce the time required to complete the task. 1H participants found new ways of rotating the pipes without ratcheting. They achieved the same performance as the 2H participants, but through different actions.
- Two-handed interaction did not reduce the number of collisions or pipe misplacements.

Although the majority of MR users chose to interact similarly to reality by using two hands, no performance advantage was gained by this choice. Users in the one-hand condition were able to overcome their disadvantage by exploring creative techniques of rotating and placing the pipes. These techniques represent a *fundamentally different* set of interactions than those exhibited by the two-handed condition.

The goal of MR systems for engineering design is to train or explore assembly. For such systems, it is necessary for users to interact in MR *as similarly as possible* as they would when presented with the real assembly. If compensating techniques (such as those demonstrated by the 1H subjects) are used to overcome the limitations of a system interface, users will not be properly trained and may suffer from negative training transfer. Thus for training engineering design tasks such as assembly and design verification, we believe that affording two-handed interaction is critical.

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