Evaluation of Human Robot Collaboration in Masonry Work Using Immersive Virtual Environments

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ABSTRACT: *With the advent of collaborative robots, there is a great potential to improve work performance by human-robot collaboration in engineering tasks. Construction is no exception. Many construction tasks are based on the movement of objects (e.g., material), which are viable candidates for human-robot collaboration. However, due to the physically imposing nature of robot operations and the unstructured environments typical in construction, it is crucial to provide a safe and reliable environment for human workers when performing collaborative work with robots. In this paper, we use Immersive Virtual Environments (IVEs) to evaluate a human response to robots (e.g. perceived safety, trust, and team identification) while performing collaborative construction tasks with robots. By adopting IVEs, various types of robots, interactions, and tasks can be easily tested and evaluated to determine the best HRC practice, without the need to build and evaluate a physical prototype. Several experimental scenarios simulating collaborative masonry tasks were implemented using the Unity3D Game Engine and an Oculus Rift 3D Head-Mounted Display (HMD). The results demonstrate that it is important to take into account work environment of human-robot collaboration in order to understand how humans perceive robots when working with them.*

KEYWORDS: *Human-Robot Collaboration, Immersive Virtual Environment, Masonry, Safety, Trust, Team Identification.*

1. Introduction

Robots have become more and more advanced and collaborative. In recent years, with the development and commercialization of collaborative robotic products such as Universal robots[1], Baxter[2], YuMi[3], robots are increasing the abilities of human workers by taking over repetitive and tedious tasks. These robots therefore have the potential to increase productivity and to provide human workers new flexibility (Fong et al., 2003, De Santis et al., 2008, Beer et al., 2011). Since many construction tasks consist of repetitive physical movement of materials and collaborative work, construction is also a viable candidate for Human-Robot Collaboration (HRC). For now, researchers' interest with respect to HRC has mainly focused on safety issues (De Santis et al., 2008, Bicchi et al., 2008).

Although much of the existing research has demonstrated various ways to develop safe robots, comparatively little attention is given to how to enhance human perception (e.g. trust, technology acceptance, robot as a teammate, etc.) toward robots. Previous studies have been reported that human perception is an essential factor for the use or acceptance of collaborative robot (Ososky et al., 2013, Van Den Brule et al., 2014). Particularly, when a human-robot collaborative task is performed in a challenging and dynamic (e.g. changing over time) environments with a time-critical manner, such as a construction site and a search-and-rescue mission, the importance of human perception is very important because individuals will not accept an untrustworthy robot in such an environment where the consequences of failure can be disastrous (Atkinson and Clark, 2013). Furthermore, in construction, a majority of task includes physically-demanding collaboration among human workers, which can increase individuals' safety concerns so that human perception will become more critical for them to accept robots. Thus, it is necessary to investigate human perception toward robots in construction by seeking answers to the following research questions: How does the dynamic and unstructured environments affect safety perception and trust toward robot while performing construction tasks? Will people perceive their robot co-worker safer and more trustworthy when they collaborate without safeguard? Despite these new and interesting questions, we know very little about this area.

However, in order to answer these questions in HRC, many factors should be evaluated to determine best HRC practices in construction. This is where Immersive Virtual Environments (IVEs) can provide flexibility and

[1] http://www.universal-robots.com/
[2] http://www.rethinkrobotics.com
[3] http://new.abb.com/products/robotics/yumi

functionalities to study the human perception of HRC. By adopting IVEs, various types of robots, interactions, and tasks can be easily tested and evaluated to determine the best HRC practice, without the need to build and evaluate a physical prototype.

To address the abovementioned challenges, this study investigates ways to promote positive perceptions towards the robot in work sites. In this study, we propose to use IVEs as a simulation and experiment environment to study and evaluate human perception of two different conditions of collaborative construction task that involves robot. In particular, the study seeks to examine the impact that the division of work space has on perceived safety, trust, and team identification toward robot in construction work. The results of this study should contribute to designing better robots or better work space/environment for human-robot collaboration in construction site.

2. Need for IVE for Advancing HRC in construction

Human-Robot Collaboration (HRC) has been studied for over a decade (Michael and Alan, 2007, Kazerooni, 1990, Ikeura and Inooka, 1995, Arai et al., 2000, Fong et al., 2003, Murphy, 2004, Dautenhahn, 2007, Reed and Peshkin, 2008). Most research concerned with collaborative robots focus on safety issues. Scholars have developed various technologies of safe robot operation, including an advanced control (Morita et al., 1998, Kosuge and Kazamura, 1997, Vukobratović and Ekalo, 1996, Ikeura and Inooka, 1995, Kosuge et al., 1993), sensor equipment (Sawers and Ting, 2014, Du and Zhang, 2014, Vogel et al., 2013, Vick et al., 2013), and path planning technique (Sanderud et al., 2014). Although these technologies have been developed, a safeguard (e.g., a physical barrier or fence) is widely being deployed in robot applications to avoid any accidents. This safeguard is one of the regulated rules issued by OSHA (Occupational Safety and Health Administration) - Industrial robots and robot system safety (OSHA, 2014), which explicitly states that the most effective means of safeguarding against injury is to shut the robot system off when a human worker invades robot's work cell. Despite their widespread use, these barriers have since become outmoded. With the advent of collaborative robots in manufacturing industry, robots are able to work alongside human worker in an interactive and intuitive manner (Dana and Elizabeth, 2006). Based on these developments of new control schemes, sensors, and a new robot safety standards (e.g. ANSI/RIA R15.06-2012, ISO 10218:2011), collaborative robots can operate in the human-occupied workspace without safety fencing. BMW factory's collaborative door sealing robot is considered as a good example of HRC practice in manufacturing (Knight, 2014).

Although there may be an applicable HRC system in manufacturing, it would be inappropriate to apply the HRC system to construction without recognizing the differences between two work environments and tasks. Firstly, the construction environment is defined by dynamic, unstructured, physically-demanding work conditions (Feng et al., 2013). According to the safeguard system used in industrial robot safety, the safeguard must be installed in a fixed location. However, it is cumbersome to implement the safeguard system in a construction site because the majority of construction tasks take place in mobile, shared, and open spaces. While the safeguard is considered the safest and the most effective way of robot operation, we have no empirical evidence of how work separation really affects human perceptions. Second, construction robots should not only reflect the dynamicity of work environments, but remain a safe and trustworthy workmate for human worker at the same time. Existing research supports the fact that when the human worker has to perform a task in these challenging environments, human perception towards collaborative robots mediates the extent to which he/she will trust the robot as a team-mate. These perceptions are highly correlated with perceived safety and team identification (Hancock et al., 2011, Sanders et al., 2014, Tang et al., 2014, Van Den Brule et al., 2014). Although research in HRC has investigated the impact of robots on various work environment conditions (Katz et al., 2008, Ding et al., 2013, Hayes and Scassellati, 2013, Klamer and Ben Allouch, 2010), they provide a conceptual model or outline of the importance of environment when deploying HRC in the field of domestic and manufacturing robots, rather than investigating empirical knowledge of impact of work environment.

When dealing with many different impacting factors, implementing an experiment that evaluates the human perception of actual robots becomes overwhelming pragmatically and financially (Weistroffer et al., 2013). To mitigate these issues, the use of Immersive Virtual Environments (IVEs) can be a great alternative. IVEs are proven to increase both experimental control and mundane realism, which leads to the enhancement of participants' engagement, thereby increasing experimental impact (Blascovich et al., 2002). Heydarian et al. (2015) also supported the use of IVEs in construction by measuring the sense of presence while each participant performed office-related activities in both IVEs and physical environment. However, very little attention is given to the use of IVEs in HRC. Weistroffer et al. (2013) used virtual environment to evaluate the end-user's perception on robot shape and movement conditions. Inoue et al. (2005) used virtual robots to test the effect of movement. But neither studied the effect of work environment in unstructured environment. In this paper, our goal is to implement immersive interactions between humans and robots where end-user will be able to collaborate within the virtual construction environment with different work scenarios, especially with the existence of a safeguarded or completely open-shared space. Based on these experimental settings, the perception towards the robot in construction can be measured via questionnaires.

3. Methodology

In this section, we are proposing a new methodology that uses Immersive Virtual Environments (IVEs) in the context of Human-Robot Collaboration (HRC) in construction to measure human perception (i.e., to test hypotheses) while performing collaborative construction tasks with robots in a different environment setting. Masonry tasks were selected for this experiment due to its repetitiveness and physically-demanding work pattern. Furthermore, the selection of masonry tasks can be more efficiently supported by a commercially available masonry robot, called SAM100 developed by Construction Robotics[4], which can be used for HRC in construction site.

3.1 Hypotheses

Based on findings from previous research on robot technologies and the impact of work environments, especially the impact of safeguards (separation and shared work condition), we derived the main hypotheses for our experiment;

- H1 –Work area separation will increase perceived safety.
  - H1 was derived from the necessity of safeguard in robot operation. In this experiment, separated work conditions were considered as a benchmark.
- H2 – Work area separation will decrease trust.
  - H2 was derived because there is no empirical background that shows how the changes in environment affect the level of trust toward the robots in construction site.
- H3 – Work area separation will decrease team identification.
  - H3 was derived from the literature to investigate the level of perceived team identification in different work conditions so that we will be able to promote the collaborative robot as a member of the work crew (Reed and Peshkin, 2008, Nikolaidis and Shah, 2013).

3.2 Experimental design

3.2.1 Immersive Virtual Environments (IVEs)

We conducted a between-subjects experiment in a lab-setting using IVEs. A virtual environment was implemented using Unity 3D[5] game engine, which providing various components (e.g. position and orientation, camera, light, renderer, etc.) that can build a virtual scene. Also, Oculus Rift DK2[6] Head-Mounted Display (HMD) was used to provide immersive virtual experience during the experiment. As shown in figure 1, Unity 3D renders two sightly different images shifted horizontally creating illusion of depth to provide stereoscopic views. Also, Oculus Rift DK2 has a tracking system to send an appropriate data to the computer, which determines the user's position and orientation in virtual space. For example, if the user's body moves left and rotates his/her head right-hand side in virtual scene, his/her avatar also moves left and views what is located on right-hand side. Range of position tracking would be limited to 2-3 meters depending upon wired connection of Oculus Rift DK2.

For the proper interaction within the virtual environment, a virtual hand was designed and used to perform basic actions for masonry tasks (e.g. pick up, move, place etc.). The virtual hand was designed to only interact with concrete block rather than every other object in virtual scene. To control the virtual hand, Nintendo Wii MotionPlus controller was used. The controller has a bluetooth connection to the computer. Unlike the other commercial game controllers such as Xbox or PS4, Wii controller requires only one hand to hold and play, which matched our experiment setting.

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[4] http://www.construction-robotics.com
[5] http://www.unity3d.com
[6] https://www.oculus.com/en-us/dk2/

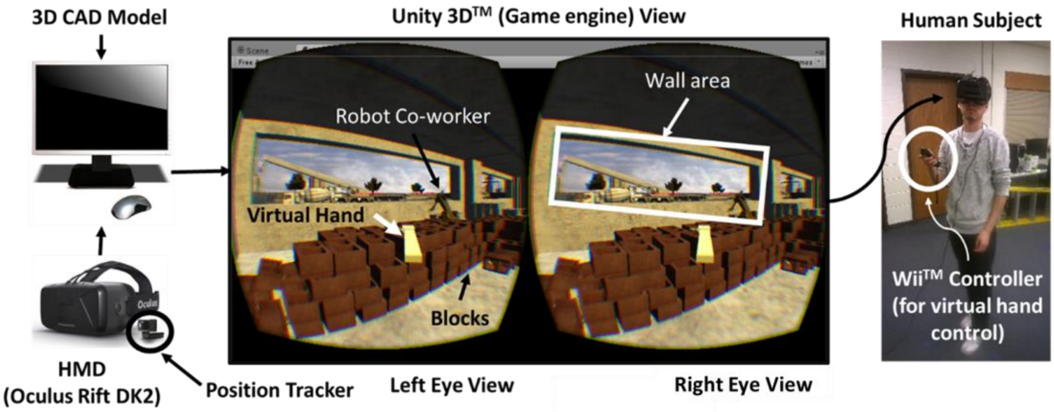

Fig. 1: General settings of immersive virtual environment of masonry work

We manipulated the work environment and task in two experimental conditions: **separate** and **shared** work space (Fig. 2). In the separate work space condition, participants and robots will be working on two separate areas allotted individually which are divided by a partition and a barrier. The wall is also divided into two areas so that participant and robot can have their own task area. The default distance between the human and the robot is 5.5 m for both separation and shared workspace. In shared work space, participants and robots will be working on the same wall without a partition. By comparing the effect of experimental condition we aimed to gain insights into the process that determine a worker's decision to trust a robot agent.

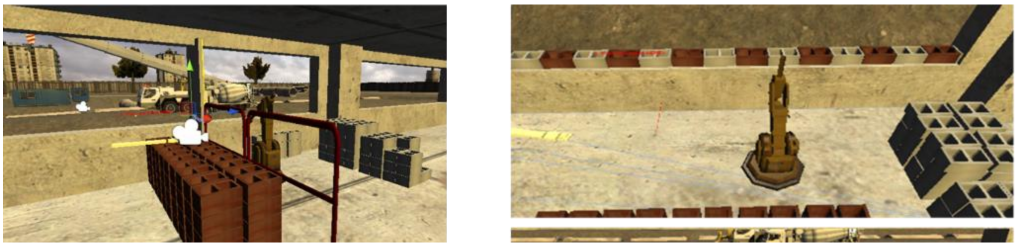

Fig. 2: Separated vs. shared work conditions

3.2.2 Collaboration of masonry task

A simple masonry task was implemented for collaboration between a participant and a robot. In a real world setting, masonry tasks can be difficult for a person who has no experience in construction. Therefore, we wanted the task to be easy and simple enough to allow the participant to naturally see the robot's operation in a construction environment. In this study, masonry work was simplified into a block laying task by excluding a mortar pasting process. A concrete block, which is colored brown, was stored in front of the participant in a separated condition, or on the right hand side in a shared condition. The participant had to take a concrete block by using a virtual hand, and place/drop it onto the wall. If the brick touches on the bottom of the wall (Fig. 3 (a)), the concrete block automatically assembled into the next right position, allowing the participant to perform the masonry task without considering precise alignment of the block laying (Fig. 3 (b)).

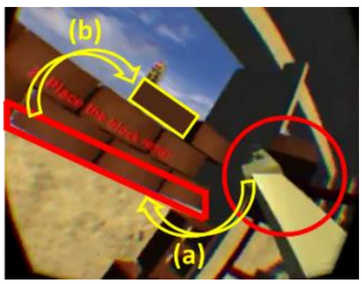

Fig. 3: Simplified masonry task for the experiment

While performing the task, the robot was located in between the block storage and the wall, thereby the robot constantly appeared on the user's field of view to provide better perception toward the robot. The robot was programmed to place a concrete block automatically every 7 seconds.

3.3 Experimental procedure

Prior to recruiting participants for the experiment, the study was approved by the Institutional Review Board (IRB Approval # HUM00098407). The experiment consists of three parts: pre-questionnaire, interaction with robot, and post-questionnaire. Upon arrival, participants were greeted and given a brief description of the study. Once participants consented, they were asked to fill out a short pre-questionnaire using a desktop, which included demographic information such as age and gender and Immersive Tendency Questionnaire (ITQ). Then, they were given instruction on the experimental task using HMD along with a Nintendo Wii Controller. Participants were asked to read the instruction and ask any questions to experimenters before proceeding to the next stage. After the instruction, all participants underwent a calibration of the HMD device and a 2-minute training of performing the experimental task. When a participant reported any physical or mental discomfort, the participant was dismissed immediately from the experiment. In this case, the participants were paid with $2 for showing up. Before proceeding to the experimental task, participants will be randomly assigned to one of two treatment conditions (i.e., shared or separated). The experimental masonry task involved picking up concrete blocks and placing them on a designated area. All participants interacted with the robot in the virtual environment for 7 minutes. Once they finished the experimental task, participants then will fill out the post-questionnaire using the desktop. The post-questionnaire included dependent variables such as perceived safety, trust, and team identification. Once finished, they were debriefed, thanked, paid, and dismissed. All individual participants will be given $10 for completion of the experimental task.

3.4 Measures

3.4.1 Manipulation Check

In order to ensure the effectiveness of manipulation, participants were asked to rate the degree to which they perceive the work area is divided into two separate areas. Perceived workspace division was measured using a 5-point Likert scale ('1' for 'strongly disagree' to '5' for 'strongly agree'). The scale consists of two items including "My work area was separate from robot's work area" (Cronbach's $\alpha = 0.85$).

3.4.2 Team Identification

Team Identification measured the degree to which individuals identify themselves with their human-robot team. The construct was measured using a 5-point Likert scale adapted from (Brown et al., 1986) ('1' for 'strongly disagree' to '5' for 'strongly agree'). The scale consists of six items including "I was happy with being identified as a member of this team" (Cronbach's $\alpha = 0.96$).

3.4.3 Trust toward Robot

Trust toward the robot was measured using an index of twelve items adapted from (Jian et al., 2000), based on 5-point Likert scale ('1' for 'strongly disagree' to '5' for 'strongly agree'). The scale measured the degree to which individuals perceive the robot as trustworthy, reliable, and transparent with its behaviors. Example items were "I was able to trust the robot" and "I was not suspicious of the robot's intent, action or outputs". (Cronbach's $\alpha = 0.88$).

3.4.4 Perceived Safety

Perceived safety measured the degree to which participants perceive physical hazard when working with the robot. The construct is an index of five items adapted from (Bartneck et al., 2009) and (Edmondson, 2004) based on 5-point Likert scale ('1' for 'strongly disagree' to '5' for 'strongly agree'). An example item was "I was directly exposed to physical harm in carrying out the task". (Cronbach's $\alpha = 0.83$).

3.4.5 Control Variables

To control the effects of individual attributes, this study measured Immersive Tendency Questionnaire (ITQ) and participants' age. ITQ measures the degree to which an individual tends to perceive immersion when interacting in virtual environments. The construct was measured using an index of fifteen items adapted from (Witmer and Singer, 1998), based on 5-point Likert scale. The score was calculated by summing the ratings of all items.

Example items were "Do you ever become so involved in a movie that you are not aware of things happening around you?" and "Do you ever become so involved in a video game that it is as if you are inside the game rather than moving a joystick and watching the screen?". (Cronbach's $\alpha = 0.71$)

3.5 Participants

There were 20 participants recruited at University of Michigan. 19 participants were engineering students, and one participant has a degree of literature. Although these participants have no experience of construction work, they have been recruited as a subject for a proof of concept to test the usefulness of the developed IVEs prior to applying it to construction workers. Also please note that, as we addressed in section 3.2.2, a virtual masonry task was designed for a layman so that participants' construction experience and proficiency of masonry work would not be required to make generalizable causal inferences (Shadish et al., 2002). The mean age was 27.20 and 5 were females. Individual participants were randomly assigned to one of two treatments: shared work area and separate work area. There were 9 participants in the separate work area condition while there were 11 participants in the shared work area condition.

4. Results

Data analysis was done employing analysis of covariance (ANCOVA) with Age and ITQ included as covariates in each analysis, except for the manipulation check. A t-test was conducted ensure that the manipulation of work are separation was effective.

Results of t-test showed that the manipulation of this study appears to be effective ($M = 2.40$, $SD = 1.14$). Individuals who were assigned to 'separate work area' perceived more that there is a separation between theirs and robot's work area ($M = 2.89$, $SD = 0.99$), than individuals who were assigned to 'shared work area' ($M = 2.00$, $SD = 1.12$, $t(18) = 1.86$, $p = 0.08$). The result was marginally significant.

H1, posited that work area separation will increase perceived safety, was supported. The result showed that individuals who were assigned to separate work area condition perceived higher level of safety when working with robots ($M = 4.20$, $SD = 0.48$) than those assigned to shared work area condition ($M = 3.27$, $SD = 1.15$, $F(1, 16) = 5.45$, $p = 0.03$, $\eta_p^2 = 0.25$). There were no significant effects of age and ITQ in this analysis.

H2, posited that work area separation will decrease trust, was not supported. However, the result showed that there was a relationship between work area separation and trust toward the robot. Individuals who worked in a separate work area trusted their robot more ($M = 3.69$, $SD = 0.33$) than those worked with their robot in a shared work area ($M = 3.30$, $SD = 0.72$, $F(1, 16) = 8.85$, $p < 0.01$, $\eta_p^2 = 0.36$). There was no main effect of ITQ ($F(1, 16) = 0.83$, $p = 0.78$ $\eta_p^2 = 0.01$), whereas age had a main effect ($F(1, 16) = 8.86$, $p < 0.01$, $\eta_p^2 = 0.36$).

H3, posited that work area separation will decrease team identification, was not supported. However, the result showed a relationship between work area separation and team identification with the robot. Individuals who worked separately with their robot perceived higher level of team identification ($M = 4.09$, $SD = 0.70$) than those working with the robot in a shared work area ($M = 2.92$, $SD = 0.95$, $F(1, 16) = 17.79$, $p < 0.001$, $\eta_p^2 = 0.53$). There was no main effect of ITQ ($F(1, 16) = 2.60$, $p = 0.13$, $\eta_p^2 = 0.14$), whereas age had a main effect ($F(1, 16) = 5.32$, $p < 0.05$, $\eta_p^2 = 0.25$).

5. Discussion

This study examined the impact of work area separation on perception of safety, trust in robot, and team identification in human-robot collaboration for a masonry task. Preliminary results of 20 individuals working with a robot indicated that separation between human's and robot's work areas increased perception of safety, trust, and team identification when working with the robot. Taken together, this study suggests that it is important to take into account work environment of human-robot collaboration in order to understand how humans perceive robots when working with them.

Also, it should be note that individuals' bias and characteristics (e.g. ITQ and age) moderate the effect of perception of HRC, which means that even though a work environment and a collaborative robot are the same, the perception of HRC may depend upon the personality and bias of a user. In other words, for example, even if a co-worker may have enjoyed the robot collaboration, his/her manager or superintendent may have negative perception so that the collaborative robot technology eventually may not be adopted. Thus, prior to implement the HRC in construction, we need to examine a HRC tendency of the various construction work individual and group (e.g. laborer, superintendent, manager, etc.) to fully facilitate the HRC in the field.

This study has several implications for theory. First, the separation of work remains an important consideration to better understand perception of safety in human-robot collaboration. Our results showed that individuals felt less secure when working with the robot in a shared environment. This means that the characteristics of work environment can alter human's subjective perception toward the robot and may facilitate relationship with robots. Although the collaboration without the safeguard decreased the level of perceived safety, the installation of these physical barriers in construction site can be difficult due to many constraints that mentioned in section 2. Given that our results are preliminary, future research should be directed to examine other applicable environment of work area on perceptions of robots in human-robot collaboration for construction work. For example, scholars would build on this study to investigate whether spatial or temporal buffers of work areas (Thiemermann, 2005) and heightened safety perceptions influence behavioral intention to accept robots in construction work. It is likely that individuals would more willingly accept robots in construction sites when they feel it is safe to work with robots.

Second, our results showed that individuals working in shared conditions with their robot trusted the robot less. This means that monitoring a robot that works in a shared work area may not be associated with increases in trust toward the robot. The results may be explained in an alternative way. If working separately, individuals would have perceived the robot as an independent agent within a secured environment. Since much of the current research has supported the fact that the safety perception plays a crucial role in enhancing trust, work separation might make the robot appear more trustworthy due to the increase of safety perception. Thus, to gain more trust, and to facilitate the use of HRC in construction, the collaborative robot must be equipped with intrinsic safety function to make sure the human workers' safety to maintain proper trust toward the robot. In addition to the robot's safety design, it is also necessary to find the appropriate collaborative work interaction and space design which does not sacrificing trustworthiness. For example, instead of using masonry robot, if a delivery robot place a block to a pile of block to supply the materials to a mason in a shared-space without invade work space and interfere on-going masonry task, individuals may have positive trust perception toward the robot because of its assistive manner of interaction and buffer zone of work space (e.g. pile of block).

Third, results of this study indicated that work area sharing negatively influenced team identification. We interpret the results that individuals would have viewed the robot as an independent entity in their team. However, team identification is mainly affected by team performance (e.g. work/error rate, fluency, efficacy, etc.) of co-worker (Chen and Barnes, 2014, Wiltshire and Fiore, 2014, Hoffman and Breazeal, 2007). This study implies that for future research, it is important to examine both work environment and team performance and the interplay between these two constructs.

It is also worth pointing out that the experiment was conducted within the environment that built upon the game engine (Unity 3D), where every interaction could be programmable. Therefore, IVEs will be very useful if a construction task involves complex interaction such as steel erection or pipe installation. Furthermore, in the near future, if the human worker has to collaborate with co-working robot, IVEs can be used as a means of virtual training environment so as to enhance the level of familiarity, which in turn, increases the positive perception toward the robot. However, this experiment also has limitations. It should be noted that results presented in this study is preliminary by having a relatively small sample size, which is 20 individuals. Therefore, some results will lack power, but show a tendency given the sample size. This study is ongoing and will collect more data in order to obtain statistical significance with a decent sample size. Also, a majority of participants were recruited from undergraduate and graduate engineering students who have a higher education level and lack of construction experience. It is possible that construction worker, who will be the actual end-user, might perceive HRC different from students.

6. Conclusion

The process of designing the collaborative robot that can co-exist with a human worker has been focused on the mechanical capability of robot itself. However, individuals' perspectives toward the collaborative robot is also one of the important factors for determining the best HRC practices (Hancock et al., 2011). Based on this idea, we use Immersive Virtual Environments (IVEs) to evaluate a human response to robots (e.g. perceived safety, trust, and team identification) with different work environments while performing a masonry task. In the IVEs, participant can interact with a virtual robot, but it may prove too expensive (e.g. cost and time) to make actual prototype of robot and environment. For quantitatively measuring human perceptions, several psychological metrics were adopted in the survey. As demonstrated, based on the presented approach, participants' perceptions can be easily evaluated prior to implement robot prototyping. They can also contribute to the improvement of work environment and interaction design for HRC by estimating proper environmental design of robot space. Although the current approach has a certain limitations (e.g. majority of student participant and lack of participants) this study was established a proof of concept of HRC in construction domain for facilitating collaborative construction robot technologies. To do this, evaluation of other factors in HRC should also be conducted to guarantee safety and trustworthiness, in turn fostering the acceptable collaboration with the end-user.

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7. References

Arai, H., Takubo, T., Hayashibara, Y. and Tanie, K. Human-robot cooperative manipulation using a virtual nonholonomic constraint. Proceedings ICRA 2000 IEEE International Conference on Robotics and Automation, 2000 San Francisco, California. 4063-4069.

Atkinson, D. J. and Clark, M. H. Autonomous Agents and Human Interpersonal Trust: Can We Engineer a Human-Machine Social Interface for Trust? AAAI Spring Symposium: Trust and Autonomous Systems, 2013 Palo Alto, California.

Bartneck, C., Kulić, D., Croft, E. and Zoghbi, S. (2009), "Measurement Instruments for the Anthropomorphism, Animacy, Likeability, Perceived Intelligence, and Perceived Safety of Robots". *International Journal of Social Robotics*, Vol. 1 No. 1. 71-81.

Beer, J. M., Prakash, A., Mitzner, T. L. and Rogers, W. A. 2011. Understanding robot acceptance. Georgia Institute of Technology.

Bicchi, A., Peshkin, M. A. and Colgate, J. E. 2008. *Safety for physical human–robot interaction*.

Blascovich, J., Loomis, J., Beall, A. C., Swinth, K. R., Hoyt, C. L. and Bailenson, J. N. (2002), "Immersive virtual environment technology as a methodological tool for social psychology". *Psychological Inquiry,* Vol. 13 No. 2. 103-124.

Brown, R., Condor, S., Mathews, A., Wade, G. and Williams, J. (1986), "Explaining intergroup differentiation in an industrial organization". *Journal of Occupational Psychology,* Vol. 59 No. 4. 273-286.

Chen, J. Y. C. and Barnes, M. J. (2014), "Human-Agent Teaming for Multirobot Control: A Review of Human Factors Issues". *Ieee Transactions on Human-Machine Systems,* Vol. 44 No. 1. 13-29.

Dana, K. and Elizabeth, A. C. (2006), "Real-time safety for human–robot interaction". *Robotics and Autonomous Systems,* Vol. 54 No. 1. 112.

Dautenhahn, K. (2007), "Socially intelligent robots: dimensions of human-robot interaction". *Philosophical Transactions of the Royal Society B-Biological Sciences,* Vol. 362 No. 1480. 679-704.

De Santis, A., Siciliano, B., De Luca, A. and Bicchi, A. (2008), "An atlas of physical human-robot interaction". *Mechanism and Machine Theory,* Vol. 43 No. 3. 253-270.

Ding, H., Heyn, J., Matthias, B. and Staab, H. Structured collaborative behavior of industrial robots in mixed human-robot environments. IEEE International Conference on Automation Science and Engineering, 2013. 1101-1106.

Du, G. and Zhang, P. (2014), "Markerless human-robot interface for dual robot manipulators using Kinect sensor". *Robotics and Computer-Integrated Manufacturing,* Vol. 30 No. 2. 150-159.

Edmondson, A. C. (2004), "Learning from failure in health care: frequent opportunities, pervasive barriers". *Quality and Safety in Health Care,* Vol. 13 No. suppl 2. ii3-ii9.

Feng, C., Fredricks, N. and Kamat, V. R. (2013), "Human-robot integration for pose estimation and semiautonomous navigation on unstructured construction sites". *Ann Arbor,* Vol. 1001. 48109.

Fong, T., Nourbakhsh, I. and Dautenhahn, K. (2003), "A survey of socially interactive robots". *Robotics and Autonomous Systems,* Vol. 42 No. 3-4. 143-166.

Hancock, P. A., Billings, D. R., Schaefer, K. E., Chen, J. Y. C., Visser, E. J. D. and Parasuraman, R. (2011), "A Meta-Analysis of Factors Affecting Trust in Human-Robot Interaction". *Human Factors: The Journal of the Human Factors and Ergonomics Society,* Vol. 53 No. 5. 517527.

Hayes, B. and Scassellati, B. Challenges in Shared-Environment Human-Robot Collaboration. ACM/IEEE International Conference on Human-Robot Interaction, 2013.

Heydarian, A., Carneiro, J. P., Gerber, D., Becerik-Gerber, B., Hayes, T. and Wood, W. (2015), "Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations". *Automation in Construction,* Vol. 54. 116-126.

Hoffman, G. and Breazeal, C. 2007. Effects of anticipatory action on human-robot teamwork efficiency, fluency, and perception of team. *Proceedings of the ACM/IEEE international conference on Human-robot interaction.* Arlington, Virginia, USA: ACM.

Ikeura, R. and Inooka, H. Variable impedance control of a robot for cooperation with a human. IEEE International Conference on Robotics and Automation, 21-27 May 1995 Nagoya. IEEE, 3097-3102.

Inoue, K., Nonaka, S., Ujiie, Y., Takubo, T. and Arai, T. Comparison of human psychology for real and virtual mobile manipulators. Robot and Human Interactive Communication, 2005. ROMAN 2005. IEEE International Workshop on, 2005. IEEE, 73-78.

Jian, J.-Y., Bisantz, A. M. and Drury, C. G. (2000), "Foundations for an Empirically Determined Scale of Trust in Automated Systems". *International Journal of Cognitive Ergonomics,* Vol. 4 No. 1. 53-71.

Katz, D., Kenney, J. and Brock, O. How can robots succeed in unstructured environments. In Robotics Science and Systems (RSS) Workshop on Robot Manipulation, 2008.

Kazerooni, H. (1990), "Human-robot interaction via the transfer of power and information signals". *Man and Cybernetics, IEEE Transactions on Systems,* Vol. 20 No. 2. 450-463.

Klamer, T. and Ben Allouch, S. Acceptance and use of a social robot by elderly users in a domestic environment. 4th International Conference on Pervasive Computing Technologies for Healthcare, 22-25 March 2010. 1-8.

Knight, W. 2014. How Human-Robot Teamwork Will Upend Manufacturing. *MIT Technology Review* [Online].

Kosuge, K. and Kazamura, N. Control of a robot handling an object in cooperation with a human. 6th IEEE International Workshop on Robot and Human Communication, 29 Sep-1 Oct 1997. 142-147.

Kosuge, K., Yoshida, H. and Fukuda, T. Dynamic control for robot-human collaboration. 2nd IEEE International Workshop on Robot and Human Communication, 3-5 Nov 1993. 398-401.

Michael, A. G. and Alan, C. S. (2007), "Human-Robot Interaction: A Survey". *Foundations and Trends® in Human-Computer Interaction,* Vol. 1 No. 3. 203275.

Morita, T., Shibuya, K. and Sugano, S. Design and control of mobile manipulation system for human symbiotic humanoid: Hadaly-2. IEEE International Conference on Robotics and Automation, 16-20 May 1998. 1315-1320.

Murphy, R. R. (2004), "Human-robot interaction in rescue robotics". *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on,* Vol. 34 No. 2. 138-153.

Nikolaidis, S. and Shah, J. (2013), "Human-Robot Cross-Training: Computational Formulation, Modeling and Evaluation of a Human Team Training Strategy". *Proceedings of the 8th Acm/Ieee International Conference on Human-Robot Interaction (Hri 2013).* 33-40.

Ososky, S., Schuster, D., Phillips, E. and Jentsch, F. G. Building Appropriate Trust in Human-Robot Teams. AAAI

Spring Symposium Series, 2013.

Reed, K. B. and Peshkin, M. A. (2008), "Physical collaboration of human-human and human-robot teams". *Haptics, IEEE Transactions on,* Vol. 1 No. 2. 108-120.

Sanders, T. L., Wixon, T., Schafer, K. E., Chen, J. Y. C., Hancock, P. A. and Ieee (2014), "The Influence of Modality and Transparency on Trust in Human-Robot Interaction". *2014 Ieee International Inter-Disciplinary Conference on Cognitive Methods in Situation Awareness and Decision Support (Cogsima)*. 156-159.

Sanderud, A. R., Thomessen, T., Hashimoto, H., Osumi, H. and Niitsuma, M. An approach to path planning and real-time redundancy control for human-robot collaboration. IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM, 2014. 1018-1023.

Sawers, A. and Ting, L. H. (2014), "Perspectives on human-human sensorimotor interactions for the design of rehabilitation robots". *Journal of NeuroEngineering and Rehabilitation,* Vol. 11 No. 1.

Shadish, W. R., Cook, T. D. and Campbell, D. T. 2002. *Experimental and quasi-experimental designs for generalized causal inference*, Wadsworth Cengage learning.

Tang, G., Charalambous, G., Webb, P. and Fletcher, S. R. Users' understanding of industrial robot gesture motions and effects on trust. Contemporary Ergonomics and Human Factors, 2014. 116-123.

Thiemermann, S. 2005. *Direkte Mensch-Roboter-Kooperation in der Kleinteilemontage mit einem SCARA-Roboter.* Dokumentenserver der Universität Stuttgart.

Van Den Brule, R., Dotsch, R., Bijlstra, G., Wigboldus, D. J. and Haselager, P. (2014), "Do Robot Performance and Behavioral Style affect Human Trust?". *International Journal of Social Robotics,* Vol. 6 No. 4. 519-531.

Vick, A., Surdilovic, D. and Kruger, J. Safe physical human-robot interaction with industrial dual-arm robots. 9th Workshop on Robot Motion and Control (RoMoCo), 3-5 July 2013 Kuslin. IEEE, 264-269.

Vogel, C., Walter, C. and Elkmann, N. A projection-based sensor system for safe physical human-robot collaboration. IEEE International Conference on Intelligent Robots and Systems, 2013. 5359-5364.

Vukobratović, M. K. and Ekalo, Y. (1996), "New approach to control of robotic manipulators interacting with dynamic environment". *Robotica,* Vol. 14 No. 01. 31-39.

Weistroffer, V., Paljic, A., Callebert, L. and Fuchs, P. A methodology to assess the acceptability of human-robot collaboration using virtual reality. Proceedings of the ACM Symposium on Virtual Reality Software and Technology, VRST, 2013. 39-48.

Wiltshire, T. J. and Fiore, S. M. Social Cognitive and Affective Neuroscience in Human–Machine Systems: A Roadmap for Improving Training, Human–Robot Interaction, and Team Performance. IEEE Transactions on Human-Machine Systems, 2014. IEEE, 779-787.

Witmer, B. G. and Singer, M. J. (1998), "Measuring Presence in Virtual Environments: A Presence Questionnaire". *Presence: Teleoperators and Virtual Environments,* Vol. 7 No. 3. 225-240.