Col-Con: A Collaborative and Configurable VR Platform for Construction — A Pipe Installation Case Study

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Abstract

Virtual reality (VR) has become widely adopted for training, education, and collaboration applications. The construction industry, known for its complex work processes and numerous personnel involved, relies heavily on effective collaboration. Many existing VR research platforms are tailored to specific tasks and offer limited variability. They often demand specialized tools, programming languages, or expertise to enable configurability, thereby restricting accessibility and flexibility. Furthermore, researchers often require diverse settings for conducting user studies, and trainees generally benefit from varied scenarios to enhance training effectiveness. To address these challenges and needs, we introduce Col-Con, a VR platform designed to investigate collaborative behaviors in construction. Col-Con is a configurable, multi-user platform that enables researchers to set up simulations through intuitive and human-readable YAML configuration files. It provides immersive and realistic simulated construction environments, where real-time voice communication, synchronized transformations, animations, sounds, and interactions enhance collaborative experiences. To validate Col-Con's capabilities and investigate user behaviors in a collaborative context, we implemented a realistic and configurable pipe installation task as a case study. A user study demonstrated that pipe installation on Col-Con is highly feasible, with participants reporting a strong sense of immersion and collaboration, making it well-suited for observing collaboration. Thanks to its modular architecture, Col-Con can be easily extended to support additional construction tasks. We envision that Col-Con will facilitate research on exploring virtual reality-based collaborative behaviors in construction and that Col-Con's architecture and implementation can serve as a reference for designing future VR-based multiplayer research platforms. Col-Con is open-sourced at https://github.com/gmu-dcxr/VRC2-System.

Keywords: virtual environment, construction simulation, configurable platform, collaborative behaviors

1 Introduction

Virtual reality (VR) is increasingly utilized as a mechanism for training [1]. While setting up a real-world training environment can be expensive and time-consuming [2], training in VR is relatively low-cost, scalable, and effective in improving human performance [3]. Moreover, VR has been applied to the construction industry for various purposes, including workspace planning [4], safety training [5–8], and building inspection [9]. As VR technologies are still evolving, implementing and maintaining VR systems requires specialized technical skills [10] and is daunting with regards to development costs and the need for specialized expertise [11].

Furthermore, construction workers typically collaborate toward a common goal, making effective collaboration essential. Since setting up a real construction site for research purposes can be expensive and risky, there is a need to develop a construction simulation where workers can virtually work together. Most VR construction simulations are still based on single-user experiences despite the fact that a construction site is a complex environment where various workers, machines, tasks, and events coexist. Current VR construction simulations are typically tailored to specific tasks, resulting in limited flexibility and configurability. Consequently, researchers aiming to explore different experimental conditions must undertake additional design and development efforts. From a training perspective, an effective platform should support the configuration of diverse scenarios to accommodate varying learning objectives and situational complexities.

To address these gaps, we propose Col-Con, a collaborative and configurable virtual reality platform for construction. Col-Con is devised based on a modular and configurable architecture. In addition to supporting specific construction tasks, it provides realistic and immersive simulations of construction site environments. The platform supports multi-user interaction, reflecting the inherently collaborative nature of real-world construction activities. The modularity allows Col-Con to be easily extended to a variety of construction scenarios. For researchers, Col-Con enables the creation of diverse experimental settings through intuitive and human-readable YAML configuration files. Col-Con is also capable of collecting rich user behavioral data, including first-person video, voice communication, and eye-tracking data. From a training point of view, Col-Con allows for the customization of task variations to enhance training effectiveness and learning outcomes.

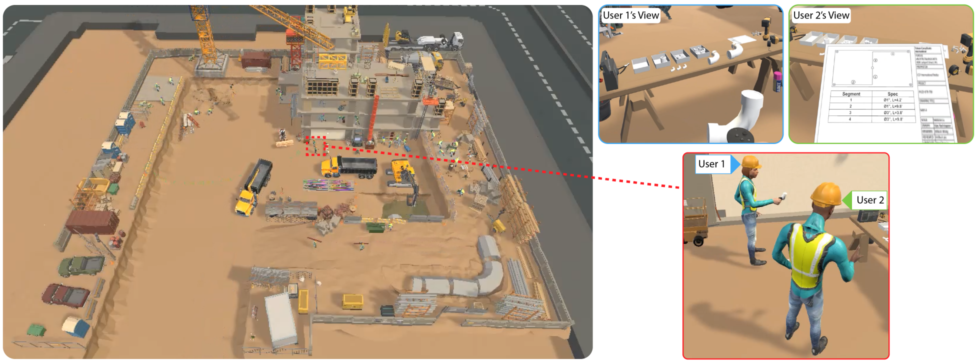


Figure 1 A screenshot of Col-Con. Construction machines, including a tower crane, a crane truck, an excavator, a truck, and a forklift, are in operation. Non-player characters are actively engaged in various tasks. Two users can join this immersive platform to complete tasks collaboratively. We have implemented a realistic pipe installation task where two users (User 1 and User 2) work together to install pipes.

Col-Con stands out from previous VR construction platforms in several key ways. First, it is designed as a versatile platform that is not limited to specific construction tasks, allowing for a wide range of research and training applications. Second, Col-Con offers an immersive and realistic VR construction site where construction machines, events, and scenarios can be easily configured, providing a comprehensive environment for both participants and researchers. Third, as a multi-user simulation platform, Col-Con supports the exploration of collaborative behaviors in VR, with synchronized transformations, animations, sounds, user movements, and interactions enhancing the sense of shared space. Thanks to its modular architecture, construction tasks are independent and can be extended to support additional activities. Finally, Col-Con is configurable and accessible: researchers can easily set up novel simulations using YAML files, eliminating the need for specialized languages, tools, or advanced development expertise.

As an illustration, we implemented a highly realistic pipe installation task in Col-Con, where two participants collaborate to install pipes on the wall in VR. Figure 1 shows an example scene. This task is also fully configurable, allowing researchers to easily adjust task objectives, pipe specifications (such as type, color, diameter, and length), and the distribution of information (defining which types of information are visible to each participant) through a YAML file. Beyond human-human collaboration, we explored futuristic construction scenarios involving human-robot and human-AI

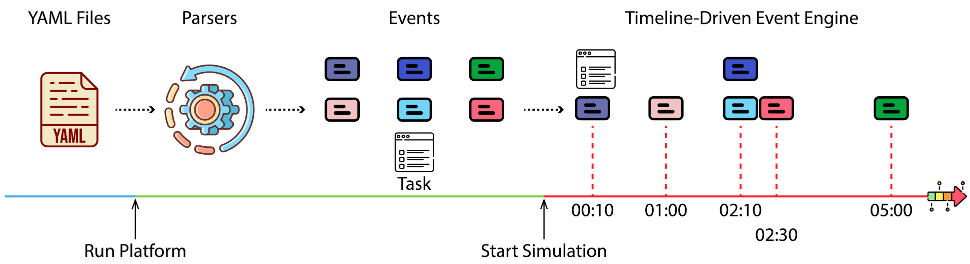


Figure 2 Workflow of Col-Con. Col-Con improves accessibility and maintainability by abstracting away implementation complexity: researchers only need to edit YAML configuration files to define and extend simulations. These files specify scenario settings, task specifications, and associated events. Dedicated parsers interpret the files at initialization, and a timeline-driven event engine schedules and executes the events during simulation. This modular architecture allows efficient reconfiguration of diverse simulations while supporting long-term extensibility.

interactions within this task. Examples include commanding a drone to deliver pipes, directing a robotic dog to process pipes or transport connectors, and instructing a non-player character (NPC) acting as the experimenter to perform refilling operations. These serve as interfaces for human-machine interaction during construction tasks. We conducted a user study to evaluate usability, immersiveness, motion sickness, and task cohesion. In our controlled user study, Col-Con was found highly usable, immersive, and well-suited for collaborative research. Additionally, the study revealed interesting behaviors among participants. Figure 2 shows the workflow of Col-Con.

The major contribution of this work includes:

- Devising a collaborative and configurable multi-user virtual reality platform for construction called Col-Con. It consists of a realistic construction scene, various construction machines, contextual events, and a customized timeline-based event system. It is highly configurable and flexible based on YAML configuration files, enabling researchers to easily build simulations. Col-Con can support collecting multimodal user behavior data encompassing audio, video, and eye-tracking data. Col-Con's design can inform future VR-based multiplayer research platforms.
- Implementing a realistic and configurable pipe installation task on Col-Con to validate Col-Con's capabilities and investigate collaborative behaviors. In our simulations, two users are assigned different roles—the Installer and the Fetcher—to complete pipe installation tasks collaboratively. Furthermore, human-robot and human-AI interactions are implemented to act as the interface of human-machine interactions and to simulate futuristic construction scenarios.
- Conducting a user study involving 14 groups (28 participants) to evaluate the collaborative pipe installation task implemented on the Col-Con platform. The results indicate that (1) Col-Con exhibits strong usability, provides an immersive experience, induces low and tolerable motion sickness, and supports consistent collaboration experiences across users; and (2) Col-Con is well-suited for studying collaborative behaviors in virtual construction environments, offering the potential to yield valuable research insights in a collaborative context.

2 Related Work

2.1 Extended Reality for Construction

Extended reality (XR) has been widely applied in the Architecture, Engineering, and Construction (AEC) industry [12–18]. For example, Johansson and Roupé [19] found that multi-user VR in a construction context can enhance design and constructability review, sequencing, and job planning. Khairadeen Ali et al. [20] proposed iVR, a near real-time construction work inspection system that integrates 3D scanning, extended reality, and visual programming to facilitate interactive onsite inspection for indoor activities and provide numeric data. Azhar et al. [21] investigated the use of XR in building construction courses to enhance the learning experience and engage students in active learning. Bosché et al. [22] developed a mixed reality system for training construction trade workers, which provides realistic and challenging site conditions while mitigating occupational health and safety risks. Balali et al. [23] proposed a VR-based framework for selecting construction interior finish materials, which incorporates visual aesthetics and cost considerations to assist stakeholders in making informed decisions and managing change orders. Additional applications of XR include management [24], building operation and maintenance [25], and visualization and communication [26]. Al-Adhami et al. [27] further explored the feasibility of using Building Information Modeling (BIM) based XR technology for quality control on real construction sites. For more on BIM-based virtual reality applications, please refer to a recent review [28].

Aside from academia, industry has demonstrated real-world applications of XR technology in construction. For example, Industrial Training International offers a VR crane simulator designed for practical training purposes [1].

Unlike previous work, Col-Con is designed as a collaborative construction site simulation platform, allowing for the implementation of various construction tasks. Col-Con offers researchers a foundational immersive construction environment, including construction machines with synchronized events and animations, as well as flexible, pluggable, and configurable features. Researchers can easily set up simulations that support two users. Additionally, we have implemented a realistic pipe installation task on Col-Con and incorporated futuristic human-robot and human-AI interactions.

2.2 Collaborative Virtual Environments

Collaborative Virtual Environments (CVEs) are distributed virtual reality systems that provide graphically realized, potentially infinite digital landscapes [29]. CVEs are shared by participants across a computer network, where they are given graphical embodiments and can interact with the virtual world's contents and communicate with one another using different media [30]. A well-known example of a CVE is the Cave Automatic Virtual Environment (CAVE), a projection-based virtual reality display [31]. CAVE is widely used for educational purposes, as demonstrated in [32, 33].

With advancements in hardware and software, headset-based CVEs are gaining increased attention. For example, Greenhalgh et al. [34] introduced MASSIVE, a virtual reality teleconferencing system that enables multiple users to communicate through

[1] https://www.iti.com/simulations/vr-crane-sim

a combination of audio, graphics, and text media over local and wide area networks. Tseng et al. [35] explored the effects of a 3D vocabulary learning program on English as a Foreign Language (EFL) young learners' vocabulary acquisition, focusing on learner autonomy and collaboration. Similar CVE-based learning research has been conducted [36–38]. Lee et al. [39] developed the Free-roaming Immersive Environment to Support Team-based Analysis (FIESTA), which allows users to position authoring interfaces and visualization artifacts freely within the virtual environment, either on virtual surfaces or suspended in the interaction space. Prabhakaran et al. [40] proposed COFFEE, a collaborative virtual environment for furniture, fixtures, and equipment, enabling concurrent multi-user interaction, communication, and collaboration during the design appraisal of interior furnishings. He et al. [41] introduced CollaboVR, a reconfigurable framework for both co-located and geographically dispersed multi-user communication in VR, combining animated sketching, collaborative scene editing, and real-time multi-user communication. Terkaj et al. [42] introduced a framework for creating virtual learning applications, exemplified by a virtual learning factory application (VLFA). VLFA enables students to engage with a realistic simulation of a manufacturing assembly line, allowing them to learn about manufacturing system design and analysis through interactive tasks and challenges. Additionally, researchers have proposed using CVEs for various purposes, such as learning [43–46], entertainment [47], surgery planning [48], design [49–51], healthcare [52], and human-robot collaboration [53].

Different from previous works, Col-Con is a virtual reality simulation platform specifically designed for construction sites. Furthermore, Col-Con is intended for researchers rather than end users. It serves as a foundational infrastructure for collaboration in construction simulation, allowing researchers to conduct a range of studies, such as construction co-training, collaborative behaviors analysis, and shared situational awareness.

2.3 Configurable Virtual Reality Simulations

Researchers have made significant efforts to develop reconfigurable virtual reality simulations and simulators. For example, Martin et al. [54] presented a reconfigurable architecture for multimodal and collaborative interactions in VEs. The system's reconfigurability is achieved through a modular design and an XML-based configuration file that defines how different input modalities (e.g., 3D tracking, speech, gestures) are interpreted and translated into commands. Alves and Magalhães [55] proposed a generic, reconfigurable VR simulation system for training workers on various machines in industrial settings. The system uses a specification language called VRSimL to describe machines' physical and behavioral characteristics, addressing the inflexibility of traditional simulators.

Cavallo et al. [56] introduced Dataspace, a hybrid reality environment for collaborative information analysis. Its reconfigurability is achieved with 15 high-resolution displays on robotic arms, allowing them to be repositioned to meet different user needs and data contexts. He et al. [41] introduced CollaboVR, a reconfigurable framework for collaborative VR experiences. It incorporates sketching, user layout configurations, and real-time conversion of sketches into 3D models. CollaboVR offers integrated, mirrored, and hybrid user arrangements to enhance collaboration and minimize visual clutter. Gómez and Figueroa presented ProtoColVR [57], a methodology for creating VR training simulators. ProtoColVR integrates tools like Twine and Unity to streamline requirements gathering and support collaborative prototyping. They also developed the Tweenity plugin to integrate Twine and Unity within the ProtoColVR framework.

While prior works achieved some reconfigurability, they exhibit notable limitations. For example, the system by Alves and Magalhães [55] requires users to have expertise in authoring machine specification files using a domain-specific language (VRSimL), and it does not support VR headsets. ProtoColVR [57] similarly demands proficiency in Twine, Unity, and graph-based editing, and its workflow is hindered by inefficiencies resulting from switching between tools (e.g., Twine) and game engines (e.g., Unity). The system by Martin et al. [54] offers limited interaction capabilities due to the need for precise timeout configurations. CollaboVR[41] supports only a single application (Chalktalk) as a proof of concept and lacks broader configurability, with its user study confined to a specific design task. Finally, Dataspace [56] involves a complex and resource-intensive hardware setup, including dynamic high-resolution displays, an interactive projection table, and AR/VR headsets.

Unlike previous works, Col-Con is designed to be configurable through the YAML file, which is more intuitive and human-readable than alternatives such as XML (as used in [54]). This approach enables non-experts to modify simulation parameters without specialized prerequisite knowledge. Col-Con provides fully interactive scenarios and a complete implementation with support for interaction and simulation configuration. Unlike existing platforms that depend on domain-specific languages, proprietary tools, or complex hardware setups, Col-Con minimizes these requirements, reducing the entry barrier for scenario design. Col-Con also integrates comprehensive collaboration features—such as real-time interaction, synchronization, and communication—within a unified environment. By combining configuration and execution in a single platform, Col-Con improves workflow efficiency and eliminates the overhead of switching between multiple tools and game engines. Additionally, it supports the collection of multimodal user behavior data, including voice, gaze, and first-person videos, facilitating in-depth analysis. Col-Con's modular architecture enables easy extension to support additional construction tasks for both research and training purposes. Col-Con is fully functional and openly available as an open-source project.

3 Overview of Col-Con

Figure 3 shows the overview of Col-Con. It follows a bottom-up architecture. Machines serve as the foundation of the simulation, with each machine linked to a series of events. These events collectively form the scenario. When combined with the task, the scenario helps build a session, which consists of a series of scenarios and tasks. The session, along with synchronized transformations, animations, sounds, and interactions creates a simulation environment where participants can join and complete tasks collaboratively. Details are elaborated in the following subsections.

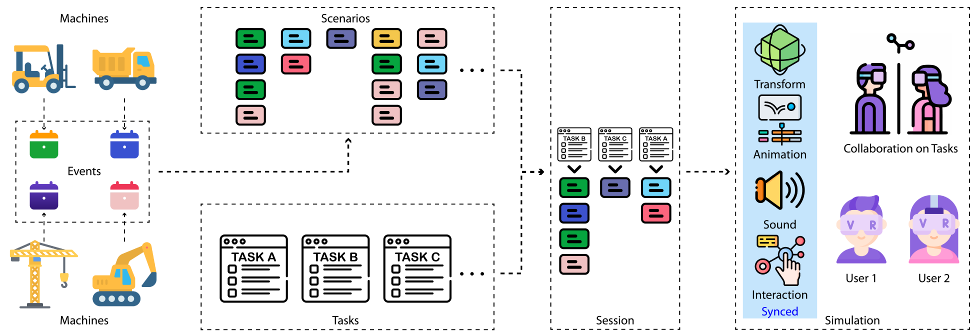


Figure 3 Overview of Col-Con. The platform features construction machines positioned within an immersive construction site. Each machine operates independently from the environment and other machines and is associated with various events. Scenarios are constructed using these events, while construction tasks, with their task-specific interactions and equipment, are independent of the scenarios; thus, scenarios serve as the context in which tasks are executed. A session consists of a combination of scenarios and tasks. Once users join a session, the simulation is prepared to begin. During the simulation, transformations, animations, sounds, and interactions are synchronized as the two users collaborate on tasks.

3.1 Definitions

The terms are defined as follows. **Machines** refer to construction machines. Each machine is associated with a series of **events**, which refer to operations or events. Events are categorized as either *normal* or *accident*, depending on whether they lead to a potential hazard. **Tasks** denote construction activities within this environment that participants are required to complete, with their required interactions and equipment specified for each task. A **scenario** comprises a series of events. A **session** includes both scenarios and tasks. A **simulation** involves two participants joining a session and collaborating on tasks with synchronized transformations, animations, sounds, interactions, and voice communication.

3.2 Configurable Modules

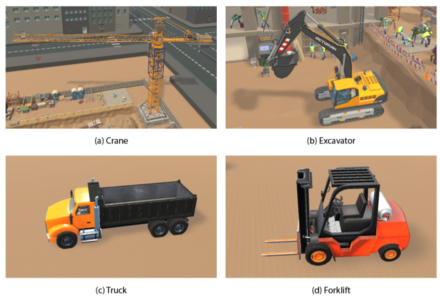


Figure 4 Example construction machines.

As a fundamental component of Col-Con, some construction machines are illustrated in Figure 4. To facilitate researchers, components such as events, scenarios, and tasks are designed to be modular. We have employed YAML files to achieve this configurability.

Listing 1 describes segments from the Crane configuration file. It is a YAML file and is self-explanatory. **Name** represents the configuration file name. **Desc** provides a description of the file. **GameObject** refers to the game object associated with this configuration file. **Events** includes all events related to this machine. **Normals** refers to events that do not pose hazards to users, while **accidents** refers to events that may pose hazards to users. Each event has several attributes. **Id** is the unique identifier for the event. **Condition** defines the type of event, either normal or accident. **Desc** is the description of the event. **Warning** contains the warning content of this event, which is converted to audio and played when the event is triggered.

```
name: "Crane"
desc: "Crane-related events"
gameObject: "Crane"
events:
  normals:
    - id: 1
      condition: "Normal"
      desc: "A load is passing overhead."
      warning: "Warning: A cargo is passing overhead."
    - id: 2
      condition: "Normal"
      desc: "A hook (without a load) is passing overhead in the opposite direction."
  accidents:
    - id: 1
      condition: "Accident"
      desc: "A load with an unpacked pipe is being hoisted and is going to pass above players."
      warning: "Warning: A cargo is going to pass overhead."
    - id: 2
      condition: "Accident"
      desc: "A hook (without a load) is passing overhead in the opposite direction."
```

Listing 1 Crane configuration segments. Please refer to the main text for the explanation.

Table 1 Statistics of implemented events on Col-Con: *Normals* and *Accidents* indicate the number of incidents unlikely and likely to cause hazards, respectively. Note that *Electrocutions*, *ErroneousAI*, and *Irrelevant* do not represent machine but instead refer to abstract categories encompassing various event types.

Class	Crane	CraneTruck	Drone	Forklift	Truck[1]	Electrocutions[2]	ErroneousAI[3]	Irrelevant[4]	Total
Normals	2	3	4	2	2	2	0	0	15
Accidents	9	9	8	0	8	6	4	11	55
Total	11	12	12	2	10	8	4	11	70

[1]The *Truck* class includes events associated with both the excavator (Figure 4(b)) and the truck (Figure 4(c)).

[2]The *Electrocutions* class covers events involving potential electrocution hazards due to water stains.

[3]The *ErroneousAI* class encompasses erroneous events, such as incorrect warnings.

[4]The *Irrelevant* class contains irrelevant events where descriptions and warning content do not match.

Reflection is used to automatically associate the event implementation with the configuration file. For example, in this configuration file, the event **normals (id: 1)** is implemented in the method named *Crane_normals_1* within the *Crane* class. Likewise, the *Crane_accidents_1* method in the *Crane* class implements the event **accidents (id: 1)**. Each implementation stands alone, allowing each one to be referenced individually. Table 1 shows the statistics of the implemented events on Col-Con.

The configuration file for the scenario follows a similar schema to the crane configuration example. This design allows scenarios to be easily constructed by referencing existing events without requiring changes to the implementation. Listing 2 shows an example of the scenario configuration file.

```yaml
# name of the scenario, correspond to the yml filename
name: "Scenario1"
# description of this file
desc: "Scenario definition"
# normal events description in this file
normal: "Normal events: supervising drone, forklift, truck"
# accidents description in this file
accident: "Accident events: crane(in bold type)"
# start timestamp in raw time
start: "0:00"
# end timestamp in raw time
end: "05:40"
# start task
taskStart: 1
# end task
taskEnd: 1
# task config filename under ./Task
task: "Task1.yml"
# all events, including the normal events and accidents
events:
  - id: 1 # the order of the event
    time: "0:30" # start time of this event
    refer: [ "Crane", "accidents", "3" ] # refer to which event in the format of [machine, "normals/accidents", "index"]. It is defined in the Crane.yml file.
```

Listing 2 Scenario YAML file example

For the basic hand menu, please refer to Appendix A.

3.3 Timeline-Driven Event Engine

We developed a customized timeline-driven event engine to manage the sequential triggering of events. This approach provides researchers with the flexibility to specify the timing and content of events by simply creating a scenario configuration file. Additionally, events are synchronized to ensure consistency. When the simulation starts, all events from the session's configured scenarios are parsed and queued, and an internal clock begins. Events are then triggered as the clock reaches their designated times.

Figure 5 depicts an example of the timeline displayed in the Game window. This information is visible to researchers but not to participants, aiding in the supervision of the scenario's progress. From top to bottom, **1:52** indicates the elapsed time since the scenario started. **Timeline of Scenario1** denotes that this timeline pertains to Scenario 1. **0:00 - 05:40** represents the start and end times of the scenario, followed by a three-column table. The columns in the table are as follows. The **1st column** shows the index of events. The **2nd column** displays the trigger time for each event. The **3rd column** lists the names of the events. Colors are used to indicate the status of events: black for passed events, red for current events, and white for upcoming events.

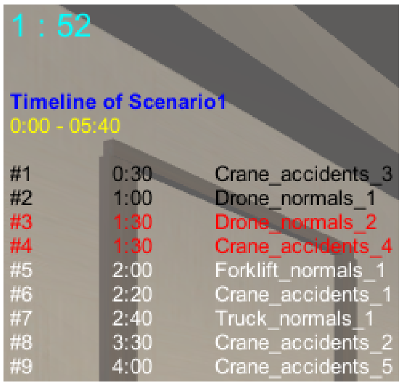


Figure 5 An example of the timeline. Please refer to the main text for the explanation.

Table 2 Eye-tracking data schema

Attribute	real-time	elapse	unix-time	name	tag	rel_x	rel_y	rel_z	rel_dist	x	y	z
Meaning	datetime	seconds after start	Unix timestamp in millisecond	object name	object tag	relative x	relative y	relative z	relative distance	object's x	object's y	object's z
Example	2024-04-08 16:10:45.580	0	1712607045582	RobotDog	Untagged	0.69579	2.11000	5.98508	6.38415	0.69579	2.11000	5.98508

Note: Relative position means from eye to object, i.e., $position(object) - position(eye)$.

3.4 User Behavior Data Collection

Col-Con captures user behavior data throughout the simulation, storing it locally for further analysis. First-person view recordings are saved in MP4 format, while voice communications are saved as WAV files.

Due to privacy restrictions on the Meta Quest headset, raw eye-tracking data is inaccessible. Instead, we collect derived data, including timestamps, object identifiers (name and tag), and both relative and absolute position information. Table 2 shows the eye-tracking data scheme.

3.5 Implementation

We implemented Col-Con on a Windows 11 PC equipped with an NVIDIA RTX 3070 GPU using Unity 2020.3.48. The Meta Quest Pro was employed for both development and user study. We used established multi-user networking frameworks: Photon Fusion for hosting, synchronization, and Remote Procedure Call (RPC) communications, and Photon Voice for real-time voice communication. The Oculus Interaction SDK was used for basic interactions, such as distance grabbing to allow interaction with virtual objects from a distance. Additionally, Meta Movement SDK was used for full-body tracking, and FishNet was utilized to synchronize full-body tracking data. Col-Con is open-sourced at https://github.com/gmu-dcxr/VRC2-System.

3.6 Illustrative Case Study Design

To demonstrate Col-Con's capabilities and provide a concrete context for examining collaborative behaviors, we designed a realistic and configurable pipe installation task within the platform. This task includes essential equipment, such as pipes, connectors, clamps, and glue, and supports key interactions such as pipe-pipe connection, gluing, and clamping.

This task is situated in Col-Con, populated with construction machines and dynamic environmental events. The presence of construction machines not only contributes to the realism of the setting but also serves as a medium for observing how participants respond to environmental events while collaboratively completing the pipe installation task.

4 Case Study: Pipe Installation

Expanding on the construction task introduced in Section 3.6, this section details the implementation of the configurable and highly realistic pipe installation task within

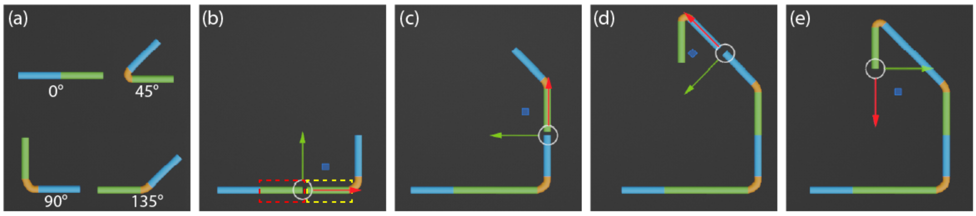


Figure 6 Illustration of the arbitrary pipe connecting algorithm. Each pipe is divided into two or three segments colored blue, green, and orange for illustrative purposes; these colors do not appear in the actual models. (a) shows pipe models with different angles: 0° , 45° , 90° , and 135°. (b) demonstrates how to connect a 0° pipe with a 90° pipe. The 0° pipe is fixed, and the extending direction (depicted by the red arrow) of the contact part (boxed in red) is calculated. The contact part of the 90° pipe (boxed in yellow) will move along with the entire 90° pipe, resulting in a seamless connection. The same rule applies to connecting (c) a 135° pipe and (d) a 45° pipe. (e) This process can be repeated to connect additional pipes at the end.

Col-Con. In this task, two participants are required to install pipes on a wall in virtual reality according to the provided instructions.

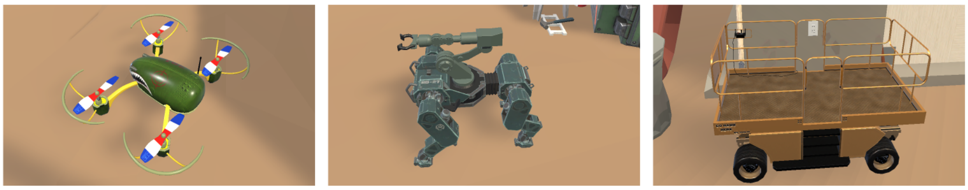
To simulate the pipe installation process, we define two roles: *Installer* and *Fetcher*. The Installer is responsible for installing pipes on the wall and has interactions including grabbing pipes, clamps, and connectors; clamping; gluing; connecting; and operating the scissor lift. The Fetcher supports the installation process and has interactions such as finding and moving pipes from storage, commanding the drone to deliver pipes, commanding the robot dog to cut pipes and/or deliver connectors, and refilling glue and clamps.

Appendix B describes some implementation details for this pipe installation task, such as realistic 3D models B.1, procedural pipe generation approach B.2, pipe and clamp interactions B.3, task-specific hand menu B.4, and assistive equipment interactions B.5.

4.1 Arbitrary Pipe-Pipe Connection

Simulating physics-based interactions in VR presents significant challenges, and pipe connecting is one such complex problem. We address this challenge with a novel combined approach from both the model and algorithmic perspectives. Each pipe (except for the 0° pipe) consists of three segments as shown in Figure 6(a). The x axes of the two ends (blue and green segments) are designed always to point outward. By using the transformation and the x direction of one end of a pipe, we can determine the transformation for the connecting end of the other pipe. This allows us to calculate the complete transformation for the other pipe. A container is created to comprise two pipes, resulting in a connected assembly. Additional pipes can also connect to the container.

Given that approximately 90% of people are right-handed [58], we establish a convention that when connecting two pipes, the pipe held by the right controller (right pipe in short) will move towards the pipe held by the left controller (left pipe in short). Figure 6 illustrates how the connection process works. The green and red



(a) Drone (b) Robot Dog (c) Scissor Lift

Figure 7 Assistive equipment for pipe installation. (a) is a drone for delivering pipes; (b) is a robot dog for carrying pipes for cutting and/or delivering connectors; and (c) is a scissor lift to help with installing pipes that are out of reach.

axes shown are associated with the connecting end of the left pipe. For instance, the axes in Figure 6(b) are associated with the green end of the 0° pipe, while the axes in Figure 6(c) are associated with the blue end of the 90° pipe. The connecting process starts with a fixed 0° pipe and a connecting 90° pipe as shown in Figure 6(b), followed by connections with a 135° pipe and a 45° pipe.

The connector is treated as a special 90° pipe with three fixed-size segments. Consequently, connecting between a pipe and a connector follows the same logic as pipe-to-pipe connecting.

4.2 Assistive Equipment

To enhance the pipe installation task and introduce interfaces for human-machine interaction during construction tasks, we designed assistive equipment as shown in Figure 7.

The scissor lift (Figure 7(c)) assists participants in performing out-of-reach tasks. Participants can enter the lift when they approach it and the **Press X to Enter** hint appears. The hint changes to **Press X to Exit** once they enter. The left-hand joystick is used to move the lift left, right, up, and down.

4.3 Pipe Installation Procedure

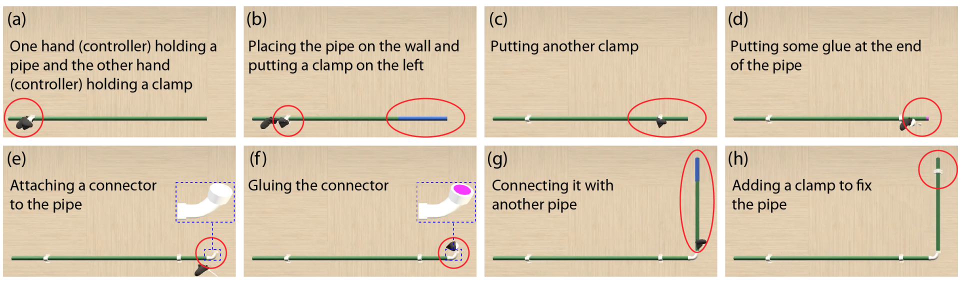


Figure 8 An example of pipe installation. Please refer to the main text for the explanation.

Figure 8 shows a pipe installation example with the following steps:

(a) Grab a pipe and a connector (Figure 8(a));

(b) Place a clamp after experiencing a long vibration (indicating the pipe is horizontal) and release the clamp after a short vibration (Figure 8(b));
(c) Place a clamp on the other end of the pipe and release it after a short vibration (Figure 8(c));
(d) Apply glue (indicated by the purple hint showing its glued status) (Figure 8(d));
(e) Attach a connector of the same size to the glued end (Figure 8(e));
(f) Apply glue to the connector (Figure 8(f));
(g) Position another pipe on top of the connector (Figure 8(g));
(h) Place a clamp on the blue region and release it after a short vibration (Figure 8(h)).

4.4 Configurable Collaborative Tasks

As aforementioned, pipe specifications involve four types of information: type, color, diameter, and angle. For the pipe installation task, we use the type, color, and diameter specifications and add an additional specification: length. To simplify, only straight (0°) pipes are used. The Installer and the Fetcher are given partial information to encourage collaboration. For instance, if the Installer receives information about color and length, the Fetcher will be provided with information about size and type. This division requires them to exchange information to complete the task. Following the design principles of Col-Con and ensuring flexibility and reconfigurability, we use YAML files for configuration. Listing 3 presents the definitions for a training task.

```
name: "Training"
desc: "Training task"
folder: "SheetsTables/training"
image: "training"
P1: [ "color", "type" ]
P2: [ "size", "length" ]
info:
  - id: 1
    segment: 1
    color: green
    type: sewage
    size: 1
    length: 4.2
  - id: 2
    segment: 2
    color: green
    type: sewage
    size: 1
    length: 9.8
  - id: 3
    segment: 3
    color: blue
    type: gas
    size: 3
    length: 3.8
  - id: 4
    segment: 4
    color: blue
    type: gas
    size: 3
    length: 9.8
```

Listing 3 The pipe installation training task's YAML file.

The **Name** field specifies the task name, while the **Desc** field provides a description. The **Folder** and **Image** fields together determine the pipe layout image. The **P1** and **P2** fields define the types of information assigned to P1 and P2 respectively. The **Info** section details the pipe segment specifications, with each item including attributes for **Id**, **Segment**, **Color**, **Type**, **Size**, and **Length**. Here, **Id** denotes the index, **Segment** corresponds to the segment number in the layout image, **Color** specifies the pipe color from *magenta, yellow, green, and blue*, **Type** denotes the pipe type from *sewage, gas, electricity, and water*, **Size** refers to the pipe diameter chosen from *1, 2, 3, and 4*, and **Length** represents the pipe length.

4.5 Implementation

We implemented the pipe installation task within the same environment as Col-Con, reusing fundamental components that Col-Con provides. Additionally, we configured two scenarios to accompany the training and pipe installation tasks. These scenarios include several events that are triggered in sequence at specified times once a session begins. The implementation is open-sourced at https://github.com/gmu-dcxr/VRC2-System.

5 User Study

In a user study, we evaluated our proposed Col-Con platform alongside the pipe installation task implementation. Specifically, we let participants evaluate different aspects such as usability, immersiveness, motion sickness, and team collaboration supported by having them go through collaborative pipe installation tasks on Col-Con. The user study was conducted on two Windows 11 PCs: one equipped with an NVIDIA GTX 1070 GPU and the other with an NVIDIA RTX 2070 GPU. To minimize latency, the Meta Quest Pro headset was connected to the PCs via a cable during the study.

5.1 Questionnaire

We designed a questionnaire to gather participants' responses, covering six aspects:

- **Demographics**: Collecting information including genders, ages, and VR experience.
- **Usability**: Evaluated using the System Usability Scale (SUS) [59], which includes 10 five-point questions.
- **Immersiveness**: Assessed through the Igroup Presence Questionnaire (IPQ) [60], consisting of 14 seven-point questions.
- **Motion Sickness**: Measured with the Simulator Sickness Questionnaire (SSQ) [61], featuring 16 three-point questions.
- **Team Collaboration**: Evaluated using a modified Group Cohesion Questionnaire [62]. We included four task cohesion-related five-point questions: (1) *I feel that we all have a common understanding of the task*; (2) *I feel that group members are very united to achieve our goal on this project*; (3) *I feel that individuals associated with my team have a desire to perform well*; and (4) *I feel that my team is committed to the task.*

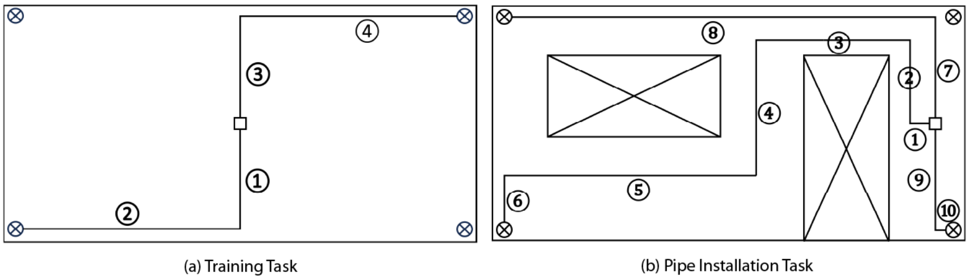


Figure 9 Target pipe layouts. The symbol ⊗ represents the endpoint; the symbol □ indicates the box for disconnected pipes; and circled numbers denote pipe segments. Each perpendicular junction between two pipe segments requires a connector. (a) and (b) depict the layouts for the training and pipe installation tasks, respectively. The corresponding pipe specifications are provided in Table 3.

- **General Feedback**: Collecting participants' opinions on features they liked or disliked and suggestions for improvement.

5.2 Procedure

This user study was conducted in a university laboratory with two separate rooms connected by a door, which remained closed during the study. The experimenter first provided an overview of the user study to the two participants. They then watched two instructional videos: the first from the perspective of the Installer and the second from the perspective of the Fetcher. After viewing the videos, the participants decided who would assume each role.

Two sessions were configured on the Col-Con platform: a training task without events and a pipe installation task with 10 sequential events. The first session lasts 10 minutes, followed by a 30-minute second session. During the pipe installation task, events occurred in a predefined order while the participants worked together to install pipes. Voice communication between the participants was facilitated via the Quest Pro headsets. Figure 9 and Table 3 show the target pipe layouts and their corresponding task specifications, respectively.

Following the role assignment, participants completed the training task to learn basic interactions, including grabbing, clamping, connecting, ordering, and cutting pipes. The experimenter provided guidance as needed.

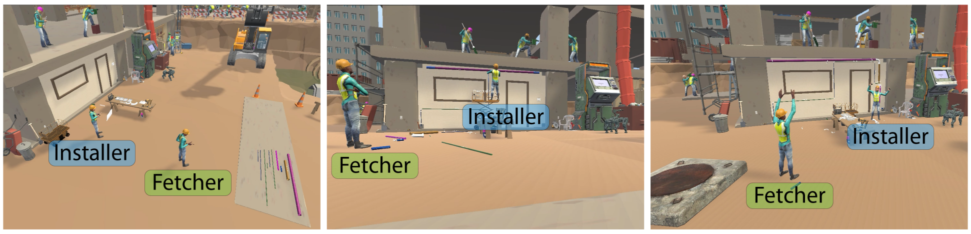
After the training task, participants proceeded to the pipe installation task, where the interactions remained the same but the tasks differed. Participants were asked to complete a questionnaire on the PC after completing the pipe installation task.

5.3 Participants

The university's Institutional Review Board approved this study. We recruited participants via emails and social platforms. A total of 28 participants (self-reported: 11 males and 17 females, aged 21-38, M = 26.36, SD = 4.26) were recruited. 16 participants reported no VR experience, while 12 participants reported having years of VR

Table 3 Task specifications for pipe layouts in Figure 9. Note that the Installer and the Fetcher are provided with different types of information to prompt collaboration between them.

Session	Training Task				Pipe Installation Task			
Role	Installer		Fetcher		Installer		Fetcher	
Segment	Color	Type	Size	Length	Color	Length	Size	Type
1	green	sewage	1	4.2	green	gas	1	1
2	green	sewage	1	9.8	blue	gas	1	3.5
3	blue	gas	3	3.8	green	gas	1	7.5
4	blue	gas	3	9.8	blue	gas	1	6
5	-	-	-	-	green	gas	1	10
6	-	-	-	-	blue	gas	1	2.5
7	-	-	-	-	yellow	electricity	4	3.5
8	-	-	-	-	magenta	electricity	4	18.5
9	-	-	-	-	magenta	water	2	4
10	-	-	-	-	blue	water	2	0.5



(a) Just Started (b) In Progress (c) Just Finished

Figure 10 An example of the pipe installation task observed in the user study. In (a), the task had just started; the Fetcher was examining the instruction sheet, while the Installer was checking the storage area where some pipes were placed. In (b), the installation was in progress; the Installer was working on the installation while the Fetcher observed. In (c), the installation was complete, and the users waved to each other to celebrate.

experience (M = 2.75, SD = 1.66). 7 participants had VR gaming experience; 7 participants experienced VR in research/course projects; 1 participant experienced VR in attractions; and 1 participant tried VR in movies. Each user study session comprised a team of two participants who collaborated to complete tasks.

5.4 Results

In the user study, we found that users could collaborate effectively. Additionally, users felt that the simulation and the pipe installation task were realistic and engaging. Figure 10 shows an example of the progress made by participants during the pipe installation task.

5.4.1 Usability

We calculated the SUS score based on the process devised by John Brooke [59]. The overall average of SUS scores is 77.59 with an SD of 13.67. Table 4 shows the SUS scores distribution. According to the approximations of the adjectives specified by Bangor et al. [63], 77.59 is regarded as "good". Specifically, the number of "excellent" ratings is 9 (32%), the number of "good" ratings is 9 (32%), and the number of "ok" ratings is 10 (36%).

Table 4 SUS scores distribution by role.

Range	Installer	Fetcher
50–59	1	0
60–69	4	3
70–79	2	3
80–89	2	3
90–100	3	5

We performed a one-sample t-test, hypothesizing a significant difference between the SUS scores and the good standard (72.5), specifically that the SUS scores mean was greater than the good standard. The one-tailed analysis result is $t = 1.97$ and $p < 0.05$, supporting the hypothesis.

Moreover, we found a statistically significant difference between the Installer and the Fetcher ($t = -2.73$, $p < 0.05$). This is reasonable, as the Installer's task requires more interactions, such as picking, gluing, connecting, putting, clamping, aligning, and operating the lift, compared to the Fetcher's task.

According to the general feedback, the lower SUS ratings (scores below 70) from Installers were primarily associated with specific interaction challenges, such as operating the lift (G5-I, G10-I), the absence of start/end point markers (G4-I), difficulties in pipe alignment (G6-I), returning pipes to their original position (G9-I), and uncertainty about task initiation (G2-I). Similarly, lower ratings from Fetchers were associated with interactions involving object targeting (G5-F), numeric input (G8-F), and occasional inconsistencies in auditory feedback (G3-F). These insights highlight targeted opportunities to further enhance the intuitiveness and consistency of the interaction design.

5.4.2 Presence

Per Usoh et al. [60], we first calculated the spatial presence, involvement, and experienced realism. Then, we calculated their characteristic scores. Table 5 shows the results. As the IPQ questionnaire uses a 7-point Likert scale, we can conclude that the scores for spatial presence, involvement, and experienced realism are moderate. This means that Col-Con makes the user feel present, engaged, and realistic to some extent.

We did not find statistically significant differences between the Installer and the Fetcher in all four aspects: General Presence (GP, $t = 0.64$, $p = 0.53$), Spatial Presence (SP, $t = 1.39$, $p = 0.19$), Involvement (INV, $t = 0.77$, $p = 0.46$), and Experienced Realism (REAL, $t = 0.50$, $p = 0.63$).

These results indicate that the presence experienced in Col-Con is role-independent, meaning participants within the group have the same immersive experience.

Table 5 Results of the IPQ questionnaire. Scores for GP, SP, INV, and REAL are averaged across all 28 participants.

Metrics	GP	SP	INV	REAL
Mean	6.11	4.38	4.59	4.42
SD	1.13	0.65	0.72	1.21

Table 6 Results of the SSQ questionnaire. Metrics are calculated based on all 28 participants' ratings.

Metrics	N	O	D	TS
Mean	11.93	17.60	12.43	13.22
SD	17.92	19.69	16.66	15.05

5.4.3 Motion Sickness

Per Kennedy et al. [61], we calculated the mean and standard deviation of Nausea, Oculomotor, Disorientation, and Total Score from SSQ responses. Table 6 shows the results. Compared to a previous study that used the same SSQ questionnaire to evaluate motion sickness [64], the total score of Col-Con is 13.22, which is lower than the 19.77 reported in their work. Furthermore, the average scores for Nausea, Oculomotor, and Disorientation in Col-Con are lower, indicating that the level of sickness caused by Col-Con is acceptable and may not significantly impact participants' comfort.

We did not find statistically significant differences between the Installer and the Fetcher in all four aspects: Nausea (N, $t = 0.45$, $p = 0.66$), Oculomotor (O, $t = 0.19$, $p = 0.85$), Disorientation (D, $t = 0.84$, $p = 0.42$), and Total Score (TS, $t = 0.53$, $p = 0.60$).

Col-Con incorporates several design strategies to minimize motion sickness, including the use of full-body tracking in place of locomotion. While these measures were generally effective, one participant (G11-I) reported dizziness associated with the use of the lift. This feedback suggests that the lift interaction could be further refined to enhance user comfort.

5.4.4 Collaboration

Based on all 28 participants' ratings, the overall task cohesion ratings are as follows: Mean = 4.75, and SD = 0.35. As these four questions use the 5-Points-Likert scale, we conclude that collaboration is high and effective.

We did not find statistically significant differences between the Installer and the Fetcher in collaboration ratings ($t = 0.43$, $p = 0.67$), which indicates that both participants within a group have similar perceptions of collaboration.

5.4.5 Role Differences

Table 7 presents the means for each metric across the four evaluated dimensions. The results indicate that Fetchers perceived the system as significantly more usable than Installers ($p < 0.05$), while Installers reported a stronger sense of presence. Fetchers also experienced less motion sickness, and both roles gave similar ratings for collaboration. These findings align with participants' general feedback: the Installer role involved more complex interactions—such as picking, gluing, connecting, putting, clamping, aligning, and operating the lift—which likely contributed to greater task demands. Increased interaction complexities may result in reduced perceived usability, heightened immersion, and a higher likelihood of motion sickness. Despite the differences in task

Table 7 Metric means by role. ↑ denotes that higher values are preferable, whereas ↓ denotes that lower values are preferable. * indicates a statistically significant difference ($p < 0.05$). The winner of each metric is shown in bold.

Dimension	Usability ↑	Presence ↑				Motion Sickness ↓				Collaboration ↑
Metrics	SUS*	GP	SP	INV	REAL	N	O	D	TS	GCQ
Installer	73.39	**6.21**	**4.54**	**4.68**	**4.55**	13.63	18.41	14.91	14.96	**4.77**
Fetcher	**81.79**	6.00	4.21	4.50	4.29	**10.22**	**16.78**	**9.94**	**11.49**	4.73

demands, both roles worked towards a shared goal, which likely contributed to similar perceptions of collaboration.

5.4.6 General Feedback

At the end of the questionnaire, we asked the participants four questions and summarized their responses as follows. We use the abbreviation *Group number-Role* to denote the participant within a given group. For example, G1-I and G1-F refer to the Installer and Fetcher in Group 1, respectively.

Summary

Participants praised the immersiveness of the simulated environments, realistic tasks, intuitive interactions, and collaborative features like voice communication. Positive feedback also highlighted the robot assistants, pipe interactions, and clear instructions.

Common issues included difficulties with pipe alignment, targeting, numeric input, and scissor lift-induced dizziness. Suggestions for improvements focused on more intuitive controls and clearer visual cues.

Overall, the feedback was positive, with participants finding the experience engaging and educational. They also offered actionable suggestions to enhance usability and comfort. We include detailed feedback as follows.

Q1: What features do you like?

Participants expressed their preferences for various features in the following ways. Several participants, including G1-F, G8-F, G10-F, G12-F, and G14-F, complimented the drone and robot dog, with G10-F noting, "The robot dog was a nice idea." The immersive environment was praised by G1-I, G7-I, and G9-F, with G1-I commenting, "The virtual world is an excellent replica of reality." Environmental sound was valued by G2-F and G3-F, while G7-F found the task was realistic.

Participants G6-F, G6-I, G8-I, G8-F, and G10-I appreciated the pipe interactions. Clear instructions were favored by G4-I and G13-F. The intuitive and realistic interactions were noted positively by G9-I, G9-F, G11-I, and G13-I. Vibration feedback was appreciated by G11-I and G14-I, and the scissor lift feature was liked by G5-I and G10-I. Real-time voice communication was valued by G9-F and G13-F, and G4-I found collaboration in VR beneficial.

Additionally, G4-F enjoyed "learning while playing," while G13-I highlighted their appreciation for "the realistic way of fixing pipes on the wall, including the glue."

Q2: What features don't you like?

Some participants expressed their dislikes regarding various aspects of the experience. G1-F found it confusing to order multiple different pipes simultaneously, particularly when they were of the same type but different colors. G4-F reported discomfort due to a simulated truck nearly hitting her and suggested incorporating additional safety features. G5-F and G8-F experienced issues with the accuracy of targeting and inputting numbers. Both G8-I and G11-I disliked riding the scissor lift, with G11-I noting that the movement up and down made her feel somewhat dizzy. G6-I and G12-I were dissatisfied with the need to carefully align pipes on the wall sometimes. G9-F mentioned that the process became somewhat disorganized after ordering connectors and clamps multiple times. G10-I commented, "I wasn't able to see the full view when I got too close to the wall." Besides, G4-I stated, "I liked everything."

Q3: Any suggestions to improve it?

Some participants provided suggestions for improvement. G1-F suggested two participants could have the full information, which might defeat the purpose of a collaborative simulation but could speed up the process. Suggestions for enhancing interactions included improvements to grabbing (G1-I), targeting (G5-F), and putting items back (G9-I). Participants also recommended design revisions, such as adding tips (G7-F), displaying connector sizes (G12-I), reorganizing refilled clamps (G9-F), and ensuring consistent environment sizes (G8-I). G10-F preferred movement using a joystick.

Some participants expressed positive feedback. G4-F commented, "I really had a very great experience!" G5-I described the experience as "great", and G13-I stated, "It was a good experience."

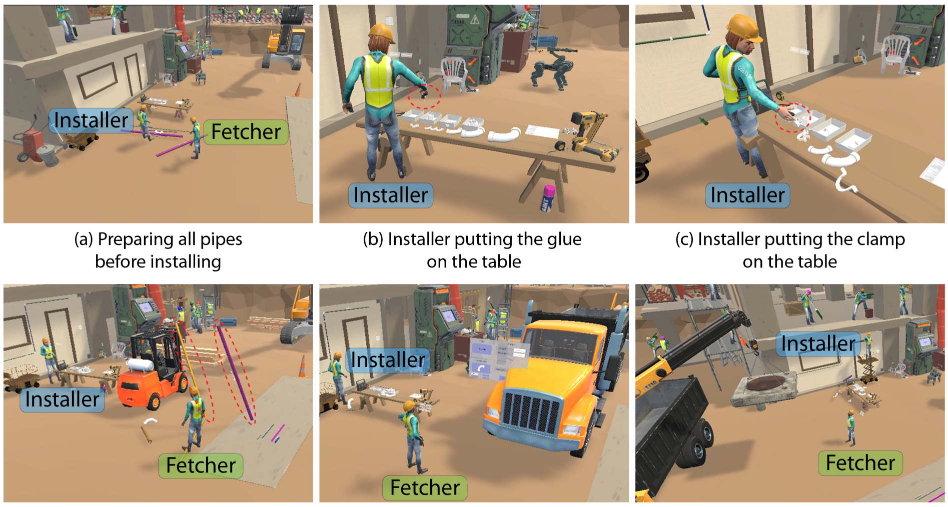
Q4: Anything else you want to tell us?

Participants expressed their favor in response to the question. G1-F commented, "Good work." G1-I remarked, "It is good to see people coming up with unique solutions for the problems we face in the world. Keep up the excellent work and continue your amazing efforts." G4-F praised the effort with, "Great job! Good luck with your team's future endeavors." G4-I found the VR experience particularly valuable, noting, "It's really interesting to build in VR. As a CS graduate with limited knowledge of the construction field, I learned a lot through this VR experience. Thanks for designing this, and kudos to your team." G9-F described the work as "Nice." G10-I found the game "interesting", while G13-I described it as a "fun experience."

6 Discussion

6.1 Role Determination

After watching two introductory videos, the two participants within each group needed to decide on their roles, specifically who would be the Installer and who would be the Fetcher. Most groups reached a decision following a brief verbal discussion. However, there was one notable exception: G13 chose to use "flipping a coin with Siri" to determine the roles. This method is particularly interesting as it mirrors real-life



(a) Preparing all pipes before installing
(b) Installer putting the glue on the table
(c) Installer putting the clamp on the table
(d) The forklift colliding with pipes
(e) Fetcher waiting for the truck to leave
(f) Fetcher being distracted by the unloading crane truck

Figure 11 Interesting moments captured from the user study. (a) Some participants preferred to prepare all pipes before beginning the installation process. (b) The Installer often placed the glue on the table after use, despite not being instructed to do so. (c) The Installer would place the clamp on the table if it did not fit the pipe properly. (d) A passing forklift collided with pipes prepared by the Fetcher, causing the pipes to bounce. (e) The truck obstructed a portion of the UI, causing the Fetcher to wait for the truck to leave. It is worth noting that the Fetcher could move to the left, triggering the UI to follow and become fully visible. (f) The Fetcher was distracted by the crane truck that was unloading cargo while the Installer was working on tasks.

scenarios where decision-making can sometimes rely on randomization, such as using *"Rock Paper Scissors"* in situations where making a decision is challenging.

6.2 Task Completion Guidance

The only rule communicated to participants was that they should install pipes from left to right as specified in the instruction sheet. Beyond this, they had the freedom to decide on various aspects, such as the installation order, the use of existing pipes, ordering new pipes, and cutting pipes. This level of autonomy led to some interesting observations. For instance, most groups alternated between preparing and installing pipes—preparing a pipe and then installing it. However, some groups preferred to prepare all the pipes before starting the installation process (Figure 11(a)). Additionally, it was noted that some groups continuously ordered and cut pipes, but did not use those pipes, leaving them in the storage area.

Another interesting observation was that some participants, particularly Installers, placed the glue (Figure 11(b)) or the clamp (Figure 11(c)) back on the tabletop, even though this was not specified in the instructions. This behavior suggests that some participants preferred to maintain an organized workspace, while others did not exhibit the same inclination.

6.3 Unexpected Situations

We designed events in Col-Con to simulate real-world scenarios that participants might encounter during pipe installation. For instance, if pipes were placed in the path of a truck or forklift, collisions could occur, causing the pipes to be displaced due to physics. In such cases, participants needed to reorder and/or cut pipes again.

For example, Figure 11(d) illustrates a forklift colliding with pipes, while Figure 11(e) shows the Fetcher waiting for the truck to clear the area. It is important to note that the user interface (UI) moves with the participants, ensuring that it remains in their view. As a result, the Fetcher has the option to move left to maintain visibility of the UI. Additionally, some participants proactively reminded their partners about incoming machines. We also observed that some participants were occasionally distracted by environmental events. For instance, the Fetcher was drawn away by the unloading crane truck, as illustrated in Figure 11(f).

6.4 Motion Sickness

After each user study session and before participants completed the questionnaire, we verbally asked about their feelings. Some Installers reported feeling comfortable at all times, while others experienced motion sickness when manipulating and moving with the lift. The lift was introduced: 1) to simulate the scale of a real construction site, accommodating large wall dimensions (width and height); 2) to circumvent the limited space available for the user study; and 3) to address user experience considerations as the cable connecting the PC and headset was of limited length. The lift was intended to extend the range accessible by the Installer.

One participant (P11-I) found a workaround to mitigate motion sickness by *closing her eyes while the lift was moving until it became stationary.*

7 Limitations and Future Work

Currently, Col-Con supports two-user collaboration in the construction site. Given that construction sites naturally involve multiple workers, expanding the system to support more users would enhance its realism. The current implementation of Col-Con is based on Photon Fusion, which, due to its design regarding input authority and state authority, limits interaction flexibility between users. For future work, we plan to transition to Unity Multiplayer Networking, as its distributed authority model is better suited for complex multi-user interactions. Additionally, based on feedback from group collaboration questions, Col-Con has proven to be an effective platform for multi-user collaboration in a simulated construction environment. Moving forward, we aim to explore and incorporate a wider range of collaborative construction tasks.

In the simulated pipe installation task, we defined two distinct roles: Installer and Fetcher. Each role is responsible for different tasks, as reflected in their respective menus and interactions. For example, the Installer cannot access the AI Drone and RobotDog menus, limiting their ability to order or cut pipes. Additionally, information about pipe specifications is distributed between the roles, necessitating communication and information exchange to complete the tasks. As noted by G1-F, *"Two participants* *could have the full information, which might defeat the purpose of a collaborative simulation but could speed up the process."* This feedback suggests the need to explore a more realistic and balanced setting, where two users can collaborate both naturally and efficiently.

However, the effectiveness of such collaboration may also depend on the realism of the simulation. While Col-Con includes partial physics (e.g., gravity and collision), it does not simulate mass-based behavior, allowing users to carry unrealistically long pipes. This limitation may impact immersion and contribute to a suspension of disbelief, highlighting an opportunity for future research to enhance physical plausibility.

From a user experience perspective, Col-Con currently requires a cable connection between the headset and the PC, meaning it is not a standalone application. This setup limits the range within which users can move and affects the user experience, as they need to manage the risk of the cable becoming tangled. While we attempted to run Col-Con wirelessly using Air Link, the performance did not meet our expectations compared to the wired connection. For future work, we plan to enable Col-Con to operate wirelessly without compromising the user experience. Moreover, although the current case study focuses on a stand-only pipe installation task, other construction tasks that involve navigation, locomotion, or frequent shifts between egocentric and exocentric views may introduce a higher risk of VR-based motion sickness. We plan to integrate mitigation techniques, such as dynamic FOV reduction or teleport-based locomotion, to alleviate motion sickness.

8 Conclusion

We introduce Col-Con, a collaborative and configurable virtual reality platform in construction. Col-Con offers a highly immersive experience, enabling researchers to configure scenarios easily using human-readable YAML files. The platform ensures synchronized transformations, animations, sounds, interactions, and real-time voice communication, allowing users to share a fully immersive environment. Additionally, Col-Con can collect user behavior data, such as first-person videos, voice communication, and eye-tracking data for further in-depth analysis.

Beyond supporting specific collaborative tasks, Col-Con's design goals were also validated. The YAML-based configuration system allowed rapid prototyping of diverse simulation setups without modifying the core system, demonstrating accessibility for non-programmers and facilitating reuse across studies. Its modular architecture enabled the integration of human and robot within dynamic construction scenarios. Furthermore, the platform's ability to collect synchronized multimodal data further positions it as a versatile platform for studying collaboration in VR. These capabilities affirm Col-Con's broader value as a flexible, extensible, and researcher-friendly platform for studying human-human and human-AI collaboration in virtual construction environments.

As a case study, we implemented a realistic and configurable pipe installation task to validate Col-Con's capabilities and to investigate user behaviors in a collaborative context. A user study with 14 groups (28 participants) was conducted to evaluate both the Col-Con platform and the simulated construction task. The combined qualitative and quantitative findings suggest that (1) Col-Con demonstrates strong usability, provides an immersive experience, induces low and tolerable motion sickness, and supports consistent collaboration experiences across users; and (2) Col-Con is well-suited for studying collaborative behaviors in virtual construction environments, offering the potential to yield valuable research insights.

We envision Col-Con as a multi-user simulation platform that can facilitate research in virtual reality-based collaborative behavior exploration in the construction context, such as co-training, behavior analysis, and shared situational awareness. Moreover, Col-Con's design can inform future VR-based multiplayer research platforms. Both Col-Con and the pipe installation task are open-sourced at https://github.com/gmu-dcxr/VRC2-System.

Supplementary Information. A brief elaboration of Col-Con is shown in the main video (Online Resource 1, https://youtu.be/olM4iUC9Zwc). The arbitrary pipe connection and the Fetcher's and the Installer's interactions are shown in the additional material (Online Resource 2, https://youtu.be/dBhycHHC9OY).

Author Contributions. L.Y.: writing, system architecture design, leading implementation, user study, and analysis; C.C.: conceptualization, scenario design, and testing; W.R.: implementation; J.D.: implementation; M.S.: implementation; H.H.: advising; S.H.: scenario design; B.E.: writing, advising, and project supervision; Lap-Fai Y.: writing, advising, and project supervision.

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Data Availability. Col-Con is openly available in a GitHub repository (Liuchuan Yu et al.) (https://github.com/gmu-dcxr/VRC2-System). The authors confirm that the data, tools, and documentation supporting the findings of this study are available within the article and through the links provided in the manuscript.

Declarations

Conflict of interest. The authors declare no conflict of competing for financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A Col-Con's Basic Hand Menu

We implemented a simple menu for Col-Con that always follows the user's movements, staying within easy reach at all times. This menu is configurable via a configuration file. For illustration purposes, two menu items, *Supervisor* and *Safety Manager*, are included in Figure B6. Both items function as cascades, as shown in Figure A1 and log a record when their leaf nodes are clicked.

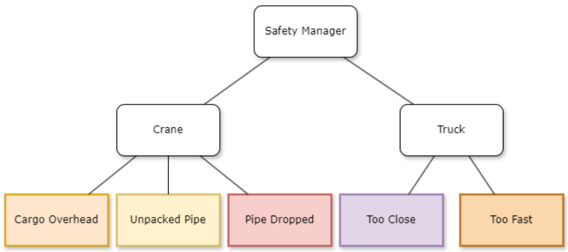


Figure A1 An example of the cascade structure of the Col-Con menu for the *Safety Manager* and *Supervisor*. When the leaf nodes (shown in color) are clicked, a record is written to the log.

As for the **Supervisor** button, it will trigger a cascade menu to report something unusual to the supervisor. So will the **Safety Manager**, which will report to the safety manager. Their implementations are based on a YAML configuration file, which achieves the flexible and extendible goal. Listing 4 shows an example. It will write down a record in the log file. Note that the top four menu items in Figure B6(b) are related to the pipe installation task, which will be detailed later.

```
name: "SupervisorMenu"
desc: "Supervisor Menu in the hierarchy mode"
menu:
  id: 0
  level: 0
  text: "Supervisor"
  desc: "level 0 menu, supervisor button itself"
  menu:
    - id: 1
      level: 1
      text: "Wrong Task"
      desc: "The task is wrong."
    - id: 2
      level: 1
      text: "Material"
      desc: "material submenu"
      menu:
        - id: 1
          level: 2
          text: "Need More Material"
          desc: "More material is needed."
        - id: 2
          level: 2
          text: "Wrong Material"
          desc: "The material is wrong."
```

Listing 4 Supervisor menu YAML file

Appendix B Pipe Installation Implementations

B.1 3D Models

The basic materials for pipe installation primarily involve pipes, clamps, glue, and connectors. Pipes may vary in diameter. Based on these requirements, we created the 3D models as shown in Figure B2.

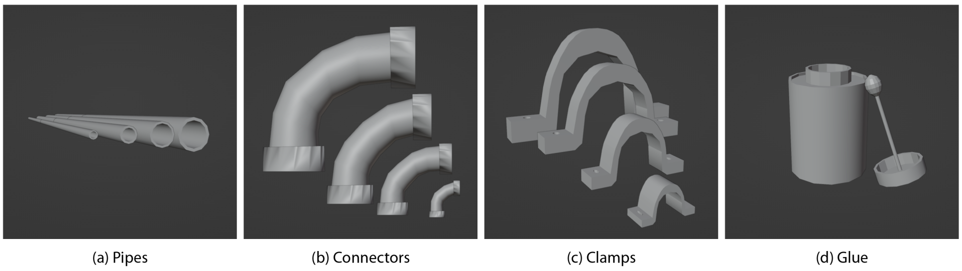


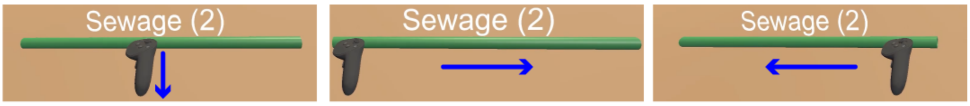
Figure B2 3D models for the pipe installation task. Connectors, clamps, and glue are directly used in the task, while pipes are procedurally processed to apply materials and textures. Note that for generality, we also modeled pipes with various angles (45° , 90° , and 135°).

B.2 Procedural Pipe Generation

In the construction industry, pipes exhibit a variety of characteristics, including types, diameters, and colors. To accommodate this diversity, we employ procedural techniques to generate different pipe models. In our setup, pipes are specified by four attributes: **type** (sewage, water, gas, and electricity), **color** (magenta, green, blue, and yellow), **diameter** (1, 2, 3, and 4 inches), and **angle** (0°, 45°, 90°, and 135°). Given that the fundamental shape of the pipe models is similar, we use procedural modeling techniques to render variations. We created models for four diameters and four angles, resulting in 16 distinct pipe models without material or texture. To accommodate variations in pipe length, each model, except for the straight pipe, consists of three segments. As illustrated in Figure 6(a), the green and blue segments can be scaled to adjust the length of the pipes. The type and color attributes are applied through materials during runtime according to specific requirements. Note that the sizes of the pipes are not to scale with real-world dimensions; they are intended for demonstration purposes.

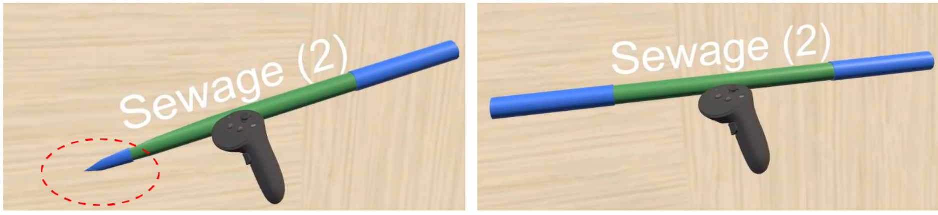
B.3 Pipe and Clamp Interactions

Clamps are necessary to fix the pipe on the wall. We use blue hints to mark the areas that require clamping, as shown in Figure B4(b). The holding point of the pipe is positioned in the middle, which can make it difficult for participants to reach the blue region and place a clamp if the pipe is too long. To address this issue, we introduce



(a) Joystick pressed (original) (b) Joystick pushed to right (c) Joystick pushed to left

Figure B3 Pipe holding point control. (a) By default, the pipe is held in the middle when the pipe is grabbed or when the joystick is pressed to reset; (b) When the joystick is pushed to the right, the pipe moves to the right and the holding point is on the left, and (c) vice versa.



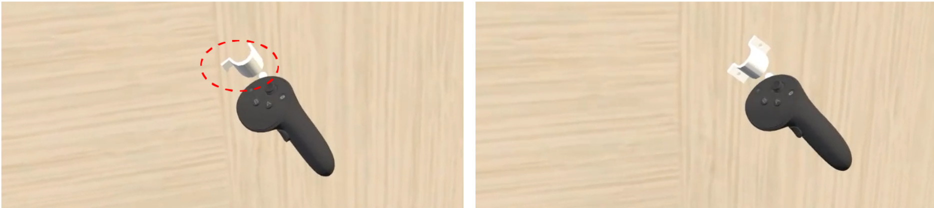
(a) Pipe penetrating the wall (b) Pipe on the wall surface

Figure B4 Compensation for holding a pipe. Due to the interaction SDK in use, the held pipe follows the controller's movement, resulting in an unrealistic wall penetration artifact. To address this issue, we developed a compensation algorithm that adheres the pipe to the wall surface. (a) and (b) show the effect before and after applying the compensation algorithm respectively. The blue regions indicate where clamps should be placed. These blue regions appear when the pipe touches the wall and disappear either when the pipe is removed from the wall, or when a correctly-sized clamp is placed on the blue region and the pipe is fixed to the wall. Note that when the pipe is nearly horizontal or vertical after compensation, it will be snapped to be perfectly horizontal or vertical, followed by a long vibration signal to inform the user about the snapping.

an interaction mechanism. Participants can move the pipe left or right by pushing the controller joystick left (Figure B3(c)) or right (Figure B3(b)), and can reset by pressing the controller joystick (Figure B3(a)).

Due to the interaction SDK being utilized, when objects such as pipes and clamps are grabbed, they follow the movement of the controller. This can result in the objects passing through the wall, which diverges from real-world experience. To address this issue, we developed a compensation algorithm and provided haptic feedback to participants. The compensation algorithm projects the pipe's transformation onto the wall surface, ensuring that the object adheres to and remains perpendicular to the surface. The effect of applying the compensation algorithm to the pipe is illustrated in Figure B4(a) and Figure B4(b). Similarly, the effect on the clamp is shown in Figure B5(a) and Figure B5(b).

When the pipe is nearly horizontal or vertical after compensation, it will be snapped to precisely align horizontally or vertically, accompanied by a long vibration to indicate its orientation. Similarly, after compensating the clamp, a short vibration will signal the participant that they can release the clamp.

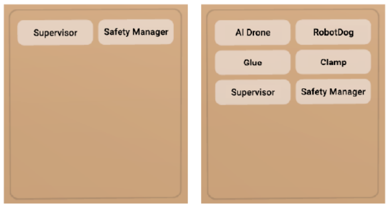


(a) Clamp penetrating the wall (b) Clamp on the wall surface

Figure B5 Compensation for holding a clamp. A similar wall penetration artifact appears when a clamp is held and moved with the controller. To address this issue, we developed a separate compensation algorithm. (a) and (b) show the effect before and after applying this algorithm, respectively. Note that a short vibration will be triggered when the clamp has been compensated, which informs the participant that he can release the clamp.

B.4 Task-Specific Hand Menu

Figure B7 The Drone UI for ordering pipes: This interface appears after the Fecther presses the *AI Drone* menu button (Figure B6(b)). After specifying the pipe type, color, diameter, and quantity, the drone (Figure 7(a)) will deliver the requested pipes.



(a) Installer Menu (b) Fetcher Menu

Figure B6 Hand menu for pipe installation.

Installer and *Fetcher* have distinct menus as shown in Figure B6. This menu remains in front of the user's Field of View (FOV). The Installer and the Fetcher share two menu items: *Supervisor* and *Safety Manager*, derived from the Col-Con. The Fetcher has four unique menu items: *AI Drone*, *RobotDog*, *Glue*, and *Clamp*. The Fetcher supports the installation process and has interactions such as finding and moving pipes from storage, commanding the drone to deliver pipes (by pressing the **AI Drone** button in Figure B6(b), which opens the window shown in Figure B7), commanding the robot dog to cut pipes and/or deliver connectors (by pressing the **RobotDog** button in

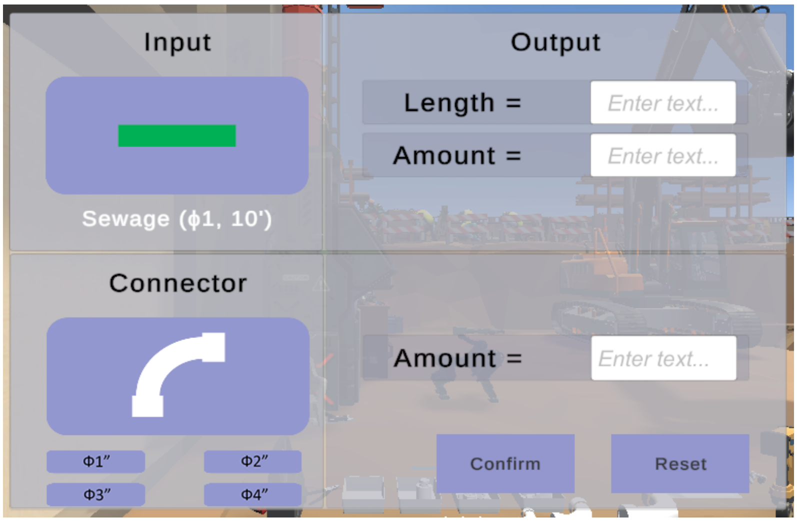


Figure B8 The robot dog UI for cutting pipes and delivering connectors: This interface appears after the Fetcher clicks the *RobotDog* menu button (Figure B6(b)). After the requirements such as the pipe length, quantity, and connector size are specified, the robot dog (Figure 7(b)) will carry out the requested tasks.

Figure B6(b), which opens the window shown in Figure B8), and refilling glue (by pressing the **Glue** button) and clamps (by pressing the **Clamp** button).

B.5 Assistive Equipment Interactions

The drone (Figure 7(a)) assists with delivering pipes. It is activated by clicking the *AI Drone* button in Figure B6(b) and clicking the *Confirm* button in Figure B7. The robot dog (Figure 7(b)) aids in carrying pipes for cutting and/or delivering connectors. It is triggered by clicking the *RobotDog* button in Figure B6(b) and clicking the *Confirm* button in Figure B8.

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