VISIBILITY ENHANCEMENT OF CRANE OPERATORS USING BIM-BASED DIMINISHED REALITY

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ABSTRACT: *The limited visibility experienced by crane operators in construction sites poses significant challenges, leading to reduced performance and safety concerns. Obstructive elements, such as existing buildings, construction elements, or vehicles, can block the crane operator's field of view, hindering their ability to execute lifting operations with precision and confidence. To address this issue, this study presents a novel approach using Building Information Modelling (BIM)-based diminished reality (DR) to enhance visibility by dynamically removing obstructive objects from the crane operator's perspective in real-time. The research employs a marker-based registration system that effectively aligns BIM data with the physical environment, ensuring realistic and precise DR visualization. Additionally, a semi-automatic selection method that involves minimal intervention from the user is employed to select desired objects. To generate the background, the system utilizes real-time observation data from occluded areas. A validation through a case study demonstrates the practical applicability of the developed system in real-life construction scenarios.*

KEYWORDS: *Diminished Reality (DR), Augmented Reality (AR), Mixed Reality (MR), Crane, Visibility, Building Information Modelling (BIM), HoloLens, Construction industry.*

1. INTRODUCTION

Construction sites are inherently hazardous environments due to the presence of heavy machinery and large equipment. Among these, cranes play a vital role in the construction process. Crane operators may be required to operate when they do not have direct visibility of the load, which is referred to as a "blind lift". This type of lift has been recognized by the industry as one of the most hazardous activities, as it poses a significant threat to both personnel and nearby property. In general, reduced visibility in the working area can lead to lower operator efficiency and have an adverse impact on both the end product's quality and overall productivity (Price et al., 2021).

Diminished Reality (DR) has emerged as an effective solution for overcoming occlusions by recovering background scenes and giving an unobstructed view of the workspace. Meanwhile, Building Information Modeling (BIM), which is a digital representation of the building geometry and information (ISO, 2015), can be beneficial in the DR process. BIM can integrate data from various data-capture technologies, such as laser scanners, Global Positioning System (GPS), and imaging sensors, to provide complete data about a construction project (Alizadehsalehi & Yitmen, 2016). Considering these features, BIM data can be used to create a digital representation of the background scene that is required in the DR process.

In this study, we investigate the implementation of BIM-based DR to enhance crane operator visibility. Our proposed approach aims to facilitate a safer and more efficient construction environment by providing crane operators with a clear and unobstructed view of their work area. By utilizing BIM data and DR technology, we seek to improve awareness, empower operators to make informed decisions, and to elevate safety within the construction industry. The integration of BIM and DR holds the potential to significantly improve crane operations and enhance overall productivity and safety at construction sites.

2. RELATED WORKS

2.1 Occlusion handling in crane operations

Various technologies have been developed to handle occlusion and to enhance visibility for crane operators. The most widespread approach used by the industry is to ensure that the crane operator remains in constant radio communication with either a rigger or a signal person, who can provide guidance throughout the lift. However, these methods of communication can be unreliable and cause various accidents (Mansoor et al., 2023). Many solutions have been developed to overcome this limitation and improve safety and efficiency at construction sites. For example, a crane monitoring system is presented in (Price et al., 2021) that can provide the crane operator with real-time 3D visualization and the ability to give and receive feedback during blind lift tasks. In this study, the safety warning system is also created based on a 3D model of the crane environment. This 3D model is developed

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in real-time utilizing sensors, cameras, and laser scanners. An alternative approach involves the visualization of information using transparent displays (Sitompul et al., 2020). This information, which includes important details such as the height and weight of the lift, is displayed through head-down displays, which are installed near the operator's line of sight in the cabin. However, research has indicated that operators often pay minimal attention to the information presented on head-down displays (Wallmyr, 2017). This is primarily due to the placement of these displays far from the operator's line of sight, as they are positioned in a way that avoids hindering the operators' view. A major drawback of using these techniques is that a user is unable to view the information from their own point of view.

2.2 Augmented reality in crane operations

Augmented Reality (AR) can be used to combine computer-generated information with the user's view of the environment. AR systems may give the operator real-time feedback by superimposing valuable information such as the load weight, distance to the target, and other crucial data on their field of view, making AR a valuable tool for improving visibility for the crane operator, the surrounding area, and the operation to be carried out (Sitompul & Wallmyr, 2019). For example, (Yang et al., 2015) developed an AR system to assist operators by providing visual information, such as arrows. The findings indicated that the implementation of AR support led to a significant reduction in task completion time, as it allowed operators to perceive the environment more clearly and effectively. Moreover, it minimized collision frequency and enhanced the overall user experience, demonstrating the usefulness of AR in familiarizing operators with new environments (Yang et al., 2015).

Nonetheless, despite the numerous benefits of AR techniques in crane operations, there are certain limitations that can be overcome by Mixed Reality (MR) techniques. One of the disadvantages of AR is that it may suffer from limited depth perception and occlusion issues. In AR systems, virtual objects are superimposed onto the user's view of the real world, but they may not always appear in the correct position relative to real-world objects, leading to misinterpretations and potential hazards (X. Li et al., 2018).

(H. Li et al., 2022) presents a novel application of MR technology in the form of a night hoisting assistance system, highlighting the potential of MR for enhancing visibility and operational safety in crane operations. This system enables operators to perceive and interact with a virtual model of the hoisting process in real-time. The system offers variety of interaction modalities, including voice interaction, gesture recognition, and gaze tracking, allowing operators to intuitively manage and navigate the virtual environment.

2.3 Diminished Reality

Diminished Reality (DR), which is an advanced visualization technology for removing or reducing the visibility of objects in real-time, can go a step further by visually removing obstructive objects such as buildings, trees, or other equipment that may obstruct the operator's view of the workspace (Mori et al., 2017). Thus, DR can provide new opportunities for more accurate visualization for operators of heavy machinery such as cranes. (Aromaa et al., 2020) introduced the concept of DR for generating see-through visualization, allowing the operator to perceive the machine's physical structure as transparent from their viewpoint (see Fig. 1 (a)). Instead of making the machine's cabin transparent, (Palonen et al., 2017) developed an alternative method for visualizing the view in front of the machine using point clouds (see Fig. 1 (b)).

(a) (b)

Fig. 1. (a) See-through visualization of the boom presented in (Aromaa et al., 2020) , (b) Visualization of the environment using point cloud presented in (Palonen et al., 2017)

Implementing effective DR solutions for operator visibility enhancement comes with a set of challenges that researchers and developers need to address. The main challenge of DR is obtaining reliable and accurate information about the hidden background, especially in dynamic construction sites where the surroundings may change frequently. Since DR aims to remove or reduce the visibility of obstructive objects, it requires access to real-time observation data or an accurate representation of the background scene to create a seamless visualization. Another challenge is the precise alignment of the virtual model with the real-world environment. For effective DR visualization, the virtual model must be accurately registered with the physical scene to ensure a seamless blend between the two. Achieving precise alignment often requires robust marker-based registration methods or other sophisticated tracking techniques, which can be complex to implement and may require specialized hardware or software. Furthermore, in scenarios where the background scene is dynamic and constantly changing, maintaining real-time updates of the hidden background information becomes critical. The DR system must continuously receive and process the latest observation data to accurately reflect any changes in the environment. This real-time processing can place significant computational demands on the system, requiring efficient algorithms and powerful hardware to handle the data in a timely manner. Overcoming these challenges and creating a seamless DR experience for crane operators requires sophisticated data processing techniques and a good understanding of the specific requirements of the construction site environment.

3. PROPOSED DR SYSTEM

The proposed system for enhancing crane operator visibility using BIM-based diminished reality allows for the seamless alignment of physical and virtual scenes, enabling the visualization of occluding objects and their removal from the crane operator's view in an MR environment. This approach aims to enhance visibility, safety, and situational awareness for crane operators in real-life construction scenarios.

Using our proposed system, the crane operator, who controls the overhead crane from the shop floor and is equipped with a head-mounted display, interacts with the system using hand gestures to visually remove the sections where obstructive objects are present. The process begins with scanning the QR code markers, followed by alignment of the 3D virtual model onto the physical scene. Subsequently, specific objects within the virtual model can be selected. Afterward, the system seamlessly integrates the real-time video feed from CCTV cameras, showing the dynamic real-time background and further enhancing the operator's field of vision.

The system architecture consists of three main layers, as illustrated in Fig. 2. The first layer involves data collection. The BIM model provides additional contextual information, such as the physical layout of the construction site, the positions of obstructive objects, the dimensions, and characteristics of the crane. The laser scanning system in combination with the BIM model can create the initial static 3D environment map. Accurate placement of QR code markers in the model ensures precise registration and tracking. Subsequently, real-time data is collected from video streams captured by CCTV cameras placed strategically in the environment. A data integration and processing layer includes both the alignment and DR processing modules. In this layer, the aligned BIM model is integrated with the real-time observation data from the CCTV cameras. Through this integration, the dynamic updating of the DR visualization is achieved, ensuring a seamless and accurate representation of the background scene. The last layer involves the visualization of the enhanced scene in a MR environment. In our implementation, a Microsoft HoloLens 2 headset was utilized to present the MR visualization to the crane operators, allowing them to perceive the virtual and physical elements seamlessly. The visualization module provided the crane operator with an enhanced and contextually accurate representation of the construction site. The headset's advanced hand and gesture recognition capabilities enabled precise and responsive interaction with the MR environment. Crane operators could easily manipulate and navigate the virtual content using natural hand gestures, allowing for efficient and fluid control over the DR visualization.

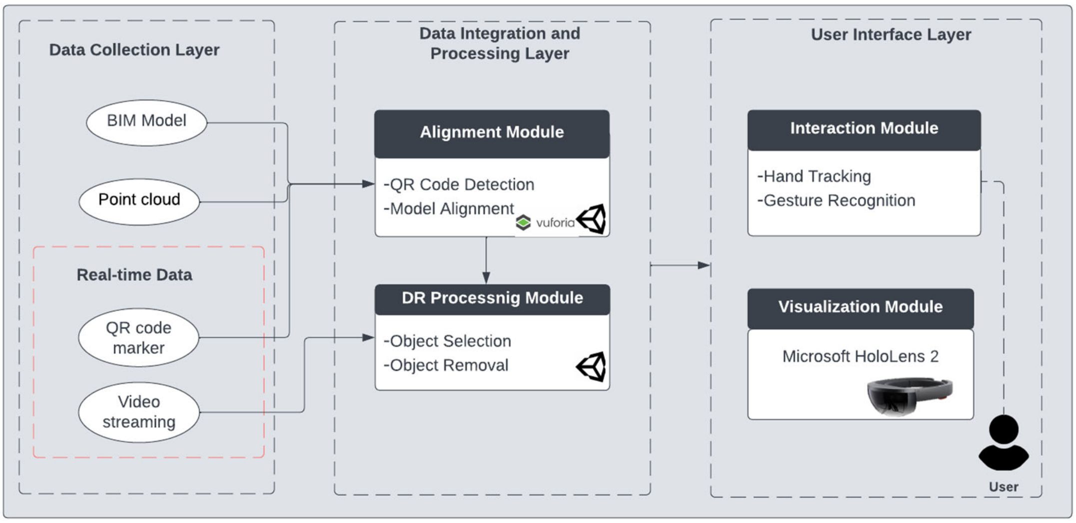


Fig. 2. System architecture for enhancing crane operator visibility

The system is implemented using C# programming in the Unity 3D environment. Unity 3D facilitates integration of video streams into a virtual environment. The OpenCV framework is employed to execute real-time image processing algorithms on the frames, enabling efficient and responsive operations. Additionally, a Wi-Fi connection is established between the HMD (Head Mounted Display) and the CCTV cameras. This wireless network connection allows seamless video streaming to the HMD, ensuring real-time visualization of the environment.

Fig. 3 shows the process flow of the generated prototype system, which will be elaborated in the following subsections.

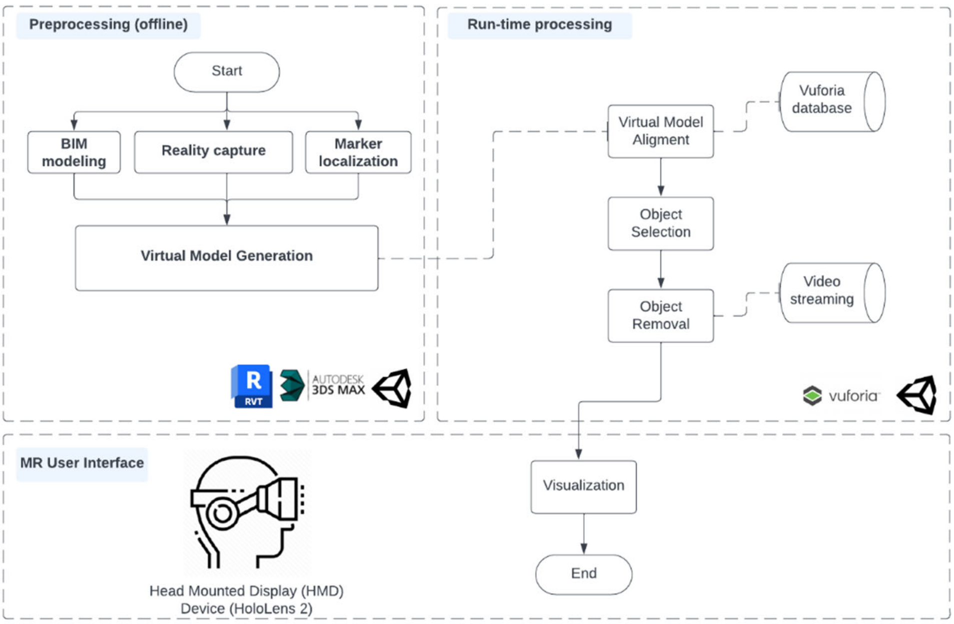


Fig. 3. DR process flow

3.1 Virtual Model Generation

First, the virtual model of the environment is generated using the BIM model in combination with reality capture techniques. The 3D scanner plays a vital role in reality capture by providing highly accurate and precise point clouds of the environment. It captures intricate details and geometries, ensuring that the virtual model is an accurate representation of the real-world site. Compared to the Structure from Motion (SfM) method (utilized in (Inoue et al., 2018)), which heavily relies on the quality and number of images taken to reconstruct the background, the 3D scanner captures data directly from the environment, minimizing the dependency on photo quality and providing a more robust solution. Furthermore, accurate scene reconstruction can be highly challenging when applying the SfM method to complex construction environments. The 3D scanner, with its high precision, can handle such complex environments more effectively, leading to a more reliable and detailed background generation. Then, Autodesk 3ds Max is used to create a high-quality 3D model of the scene using the BIM model and point cloud data. This 3D virtual model can then be optimized and converted into a low-polygon model suitable for real-time rendering in game engine environments. In addition, the location of the QR code is defined in the virtual model in this step for the marker-based registration. The physical QR code marker is subsequently placed in the correct location within the environment.

3.2 Virtual Model Alignment

As indicated in the previous subsection, to adequately align the virtual model in the physical world, QR code markers are used. A Microsoft HoloLens 2 headset tracks the camera's position, ensuring accurate alignment of the virtual and physical scenes. Vuforia image target technology (Vuforia Enterprise Augmented Reality (AR) Software | PTC) plays a crucial role in achieving precise alignment between the virtual and physical scenes in this study. As the user scans the QR code marker using a headset equipped with the Vuforia engine, the system identifies the unique image target and establishes a reference point. By recognizing the image target (the QR code marker stored in the Vuforia database), Microsoft HoloLens gains an understanding of its position and orientation in the real-world environment.

3.3 Object Selection

Users can interact with the virtual model by selecting objects they wish to remove from their view. Upon selection, information about the object, including its metadata transferred from the IFC model, is displayed in the user's view. This interactive process allows for a more user-friendly and intuitive experience.

3.4 Object Removal

The process of object removal involves several steps in an MR environment. First, the system captures real-time video streams from CCTV cameras, which provide a view of the target environment, including obstructive objects. Using the interactive HoloLens interface, the operator can select a region of interest, which includes obstructive objects like walls. The frames captured by the CCTV camera are transmitted in real-time, accompanied by annotation information, including the camera's pose at the time of each frame. After any distortions are repaired, these frames are decoded and uploaded as textures to the GPU (Graphics Processing Unit) of the headset device, enabling the generation of a DR view. The image warping process is then initiated, identifying corresponding points between the selected region in the operator's view and the frames coming from the real-time video stream. By calculating a transformation matrix based on these points, the system precisely aligns the background view with the real-world environment from the crane operator's perspective. As a result, the selected obstructive objects are visually replaced with the corresponding background from the virtual model. The HoloLens application renders this augmented view, providing the crane operator with an unobstructed and clear representation of the environment. The entire process happens in real time, updating when the crane operator moves or changes their perspective, resulting in better awareness of the situation and informed decision-making during complex lifting operations.

3.5 Visualization

The final MR visualization, presented through the headset, seamlessly combines real-world observation data from CCTV cameras with the DR-processed view. Obstructive objects, previously removed using image warping, are no longer present in the operator's field of view, ensuring an unobstructed and clear perspective. This MR visualization empowers the crane operator with real-time and accurate information.

4. CASE STUDY

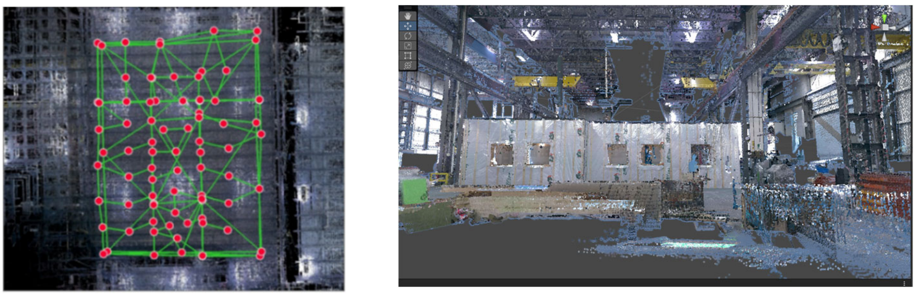
In this case study, we conducted initial steps for the validation of our developed system in a real-world setting at a prefabrication factory's shop floor located in Montreal, Canada. The manufacturing of prefabricated modules is done on the factory's production floor, with distinct zones and the presence of cranes for material handling (see

Fig. 4 (a)). The type of crane used in this study is an overhead crane, which is defined by its ability to move along rails that are located overhead, thereby offering flexibility in the lifting and handling of material. The system's capabilities in improving operator visibility and safety during crane operations are the focus of this case study. The crane operator is equipped with a remote controller to manipulate the crane's movements and operations. The modules are placed in close proximity on the shop floor due to a lack of space. The operator's viewpoint is obstructed by this setup, which reduces their ability to see crucial parts such as the hook of the crane. In these situations, the operator requires the presence of additional workers near the hook to help manage the entire operation. The integration of the overhead crane with the proposed BIM-based DR system provides a solution to overcome the challenges of limited visibility faced by crane operators. As shown in Fig. 4 (c), the CCTV cameras were strategically placed around the module. Fig. 4 (b) shows the 3D virtual model of the prefabricated module.

(a) (b) (c)

Fig. 4. Experimental area; (a) Physical factory environment, (b) Virtual model of one module, and (c) Factory and camera settings in Unity environment.

Point clouds of the environment are collected by Leica Cyclone REGISTER 360, as illustrated in Fig. 5 (a), (b). The point cloud in combination with BIM model helps us to generate a low-polygon virtual model of the scene (shown in Fig. 4 (b)). The process began by placing a QR code marker at the same location in the physical scene as in the virtual model. When the crane operator wore the HoloLens and scanned the QR code marker, the HoloLens accurately tracked the camera's position and orientation, ensuring precise alignment between the virtual and physical scenes.

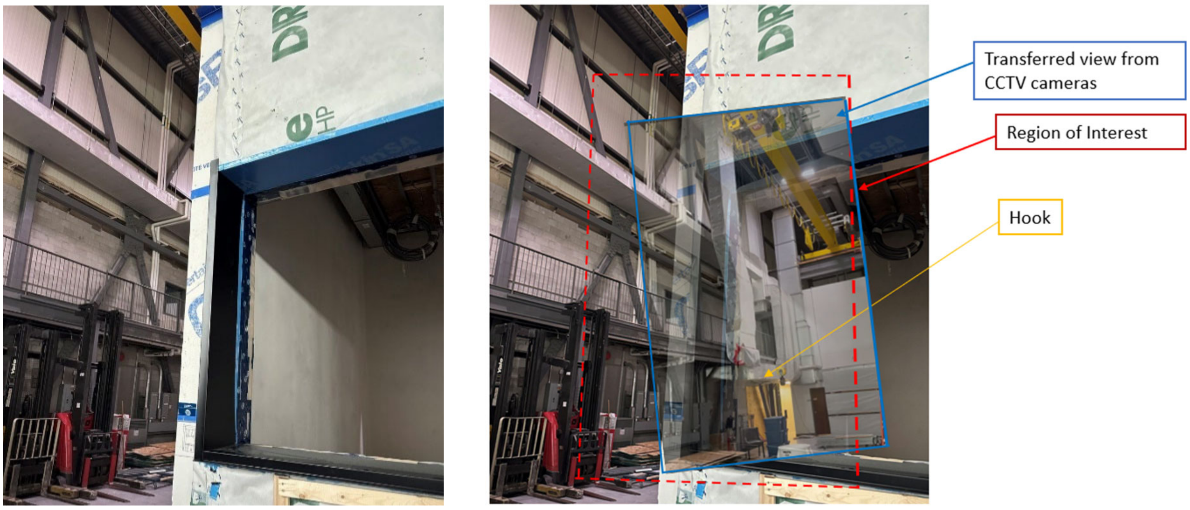


(a) (b)

Fig. 5. Point clouds of the environment collected by Leica Cyclone REGISTER 360; (a) Scanning stations; (b) Point cloud data of the target module.

Fig. 6 (b) illustrates the final result of the DR process within the HoloLens 2 environment through a screenshot of the user interface. In the screenshot, the actual prefabrication shop floor is displayed, and obstructive objects are highlighted as regions of interest. Crane operators can use the HoloLens 2's gesture recognition capabilities to select specific obstructive elements by drawing regions of interest around them using natural hand movements. Once the regions of interest are selected (red dash line in Fig. 6 (b)), the DR visualization algorithm processes the data in real-time to remove the obstructive objects from the operator's view.

Fig. 6 (a) shows the operator's view prior to the application of the DR process, providing as a reference point for the visual change affected by DR, as shown in Fig. 6 (b).



(a) (b)

Fig. 6. HoloLens view, :(a) before the DR process; (b) after the DR process.

5. DISCUSSION

The application of BIM-based DR for enhancing crane operator visibility presents a promising solution for addressing challenges related to obstructed views in construction sites. The proposed system effectively combines advanced visualization technologies and real-time data integration to provide crane operators with a clearer and unobstructed view of their operational scene.

The integration of BIM data and real-time observation from CCTV cameras improves the DR visualization's accuracy. This integration tackles the issue of reliable background information by providing a continually updated view of the surroundings via real-time video streams. This ensures that crane operators are provided with a realistic and up-to-date representation of the construction area.

Despite the demonstrated effectiveness of the developed system, some limitations and challenges have been identified. The accuracy and reliability of the DR visualization heavily rely on the quality and availability of real-time observation data. In addition, factors such as changing lighting conditions and dynamic physical environment can influence the accuracy of tracking and registration. Future research can explore potential solutions, such as leveraging advanced imaging technologies or integrating cutting-edge technologies, including sensors and cloud solutions. For example, sensors such as LiDAR (Light Detection and Ranging) can be used to create detailed 3D maps of the environment to help operators in navigating complex environments, detecting obstacles, and improving situational awareness. Position sensors, such as GPS (Global Positioning System), can precisely track the crane's location. Cloud solutions can also be used for data storage and accessibility, providing a centralised and secure repository for storing large amounts of sensor data such as photos, videos, and sensor readings. In addition, cloud-based analytics tools can process sensor data in real-time, providing valuable insights to crane operators. By overcoming these challenges, we can further enhance the precision and reliability of the system, opening up new possibilities for improved crane operator visibility and safety at construction sites.

6. CONCLUSION

This research investigated a BIM-based DR approach to enhance crane operator visibility and safety at construction sites. By dynamically removing obstructive objects in real-time, the proposed system offers crane operators an unobstructed view of the construction scene, significantly improving their visibility and decision-making. The seamless integration of BIM data and real-time observation data enables a realistic and accurate DR visualisation. While our developed system shows promising results, further investigation is needed to address limitations such as the quality of real-time observation data and challenges related to registration and tracking.

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