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A Hydraulic Excavator Augmented Reality Simulator for Operator Training

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Abstract

A significant evolution in the design of modern heavy mobile equipment like the hydraulic excavator due to advancements in component technologies has further entrenched the need for effective operator training in the heavy mobile equipment industry in order to ensure safe and efficient operation of equipment. Current methods for training hydraulic excavator operators have been based on on-site and offsite (classroom) training, which requires significant cost and time commitments, and virtual reality simulated training which is limited in its inability to provide a realistic real world training experience. A state of the art in training based on Augmented Reality (AR) is being explored by researchers as an effective alternative to provide training because of the technology's unique characteristics. This paper presents ongoing work on a prototype AR system for simulating hydraulic excavator operator training – the Hydraulic Excavator Augmented Reality Simulator (H.E.A.R.S). The system features the overlay of virtual objects that describe the working parts of the hydraulic excavator, inserted into the user's view of the workspace and a simulated work environment to provide firsthand information on how each working part functions. The paper also discusses a preliminary evaluation of the prototype system to assess its effectiveness.

Keywords
Hydraulic excavator, augmented reality, operator training, simulator

1. Introduction
Hydraulic excavators are a class of heavy mobile equipment that are familiar for performing digging and leveling operations, material handling, heavy lifting, and demolition work in industries ranging from construction and forestry to agriculture and mining (Haddock, 2007). While their basic function has not changed in decades, modern hydraulic excavators have evolved in terms of their technical design, incorporating new and improved technologies that seek to make their operation safe and efficient (Boyanovsky, 2005; Zubko, 2007; Roth, 2010). To make their operation more efficient, many of the significant changes in excavators have been in relation to the controls; old linkages have been eliminated in favor of features such as electronic controls and pilot-operated hydraulics, as well as joystick controls (Zubko, 2007). In order to take advantage of the capabilities provided by such new changes, hydraulic excavators operators must be adequately trained to develop the skills sets needed to ensure a safe, effective and efficient operation of the equipment.

Heavy equipment operator training programs have historically been based an on-site and offsite instruction, and often time consuming and costly. Recent advances in software and computer processing capabilities have fostered the development of virtual reality (VR) simulators as a low cost alternative to on-site operator training. The use of virtual reality simulators have been explored as a training vehicle in a variety of research and industrial applications (Wakefield, 1996; Bernold et al., 2002; Torres et al., 2004; Fisher, 2008; Engel et al., 2009; Ni et al,. 2009; Dopico and Luaces, 2010; Caterpillar, 2011; Simlog, 2011). Assessment of VR as a training tool has shown that, although VR generates a complete virtual environment, where unlimited training scenarios could be provided, it gives a novice no opportunity to experience the real working conditions. Consequently, VR is limited by the fact that it does not provide a high degree of realism; thus even with adequate training with a virtual simulator operators are still not expected to perform with the same proficiency as they would in real world situations. To this end, a number of researchers have begun exploring augmented reality (AR) as an extension of VR for providing a high fidelity

environment to effectively train novices. AR compromises between the real and virtual work environment and generates a composite view where virtual entities are inserted into the physical space where the work is being performed to provide a more realistic training experience. The fidelity of an AR simulator has the potential of assuring a positive transfer of training, that is, the potential of allowing operators to reach the same level performance in the real world. Based on this contention, we and other researchers like Wang and Dunston (2007) are of the view that AR will be particularly beneficial where training in real-world situations would be impractical due to high training expenses, logistical difficulties, risk of causing harm, or equipment control complexity.

AR has opened a tremendous scope of applications in domains such as architecture, manufacturing, medicine, military training, and consumer design (Azuma, 2001; Haller et al., 2007); yet very little AR strategies have been attempted for heavy mobile equipment, where its successful application has the potential to provide better realism of the actual work environment, leading to more effective operator training. It also promises to better support human-system design efforts aimed at identifying interaction modalities that can enhance both operator and system performance. The few research efforts that have attempted to use AR to develop effective operational strategies (training inclusive) for heavy mobile equipment can be accessed from (Segura et al., 2007; Wang and Dunston, 2007; Sanat et al., 2010)

Having clearly established the benefits that can be derived from AR, we propose a hydraulic excavator AR simulator (H.E.A.R.S) for operator training. This work draws from the work by Wang and Dunston (2007), which discusses the potential of using AR in the construction industry as well as present the conceptual design and development of mechanisms/strategies for an AR-based real world training system (ARTS) that trains the novice operators in a real worksite environment populated with virtual materials and instructions. While ARTS is only conceptual, H.E.A.R.S presents a prototype AR application for operator training.

The paper is sectioned as follows. A number of AR design strategies for simulating hydraulic excavator operator training are enumerated in Section 2 to guide the development of the simulator. Section 3 concentrates on the development of the simulator and highlights the architecture of the system and the details of its implementation. Section 4 presents a preliminary user study conducted to evaluate the effectiveness of the newly developed simulator. Section 5 concludes the paper and identifies potential areas of future work to extend the present work.

2. AR Design Strategies for Hydraulic Excavator Operator Training

Properly addressing the challenge of providing efficient and effective training of hydraulic excavator operators require proficiency in identifying the training method that provides the best training in the shortest time, at the least cost and results in the longest retention of knowledge and skill acquired through the simulator. AR has the potential to deliver these benefits of effectiveness and efficiency in operator training.

Before presenting the AR design strategies for operator training, we first seek to establish a philosophical basis for the role AR plays in operator training. The role of AR in operator training is to provide a *performance-support* system. The performance support approach is “a philosophy that assumes that information and training activities (such as practice) should be provided on an *as-needed* basis, shifting a “learn and apply cycle” to a “learn-while-applying” cycle. A performance support system, thus, provides a set of information and learning activities in a context-specific fashion during task performance. Seemingly, such an approach is more efficient in allowing people to access information (and learn) while they are performing their tasks in lieu of studying and committing to memory a large body of knowledge, which might be difficult to retrieve when needed (Wickens et al., 2004).

The following, therefore, are some design strategies/mechanisms, adapted and expanded from the work by Wang and Dunston (2007), that can be developed using AR and presented directly into the novice’s real view of training scenarios without reference to manuals or experts. These proposed strategies can be used to create the AR metaphors for developing a performance support system that has the potential to significantly accelerate the fundamental operator training process.

1. Virtual objects overlaid on controls to describe the working parts of the system, such as the bucket, stick, boom and swing, to show how work being accomplished with each move. This intuitively provides firsthand information to users about how each working part functions and accelerates control familiarization without the need for manuals.

2. Virtual objects describing operations such as conducting before-operation inspections, operating equipment safety procedures, use of safety equipment, and other similar functions.

3. Features and objects that do not have constant configuration can be modeled and displayed by an AR system. For example, a specific haul road route and major destinations (loading and dumping sites) can be highlighted with virtual indicators, which the operators can follow as they practice how to operate the equipment in a real environment. Also, virtual targets/stimuli such as stockpiles that move and react intelligently to the manipulations of an operator.

4. The use of an *intelligent virtual coach/ tutor*, inserted into the operator's view in real time to guide them in task performance. The intelligent virtual coach/ tutor can understand the user's goals and guide them in the accomplishment of those goals. The virtual coach/tutor can be in the form of virtual digitized verbal information, including instructions, commands and real-time advice.

In this work, a prototype of the first design strategy described above is developed. Virtual elements corresponding to control functions for operating the working parts of the hydraulic excavator, specifically the bucket, boom, stick and swing, are used to provide additional information to reinforce a novice operator's knowledge of system functions. The rationale behind this strategy is that, providing such information to the novice will make the human-machine interface intuitive and eliminate the need for manuals and training lessons aimed at helping them familiarize themselves with the controls.

3. Simulator Development

3.1 System Architecture

In general, a typical augmented reality system consists of a *graphics generation system* (e.g. a computer), a *video acquisition/display medium* (e.g. video see-through, optical see-through, projection or hand-held display), a *tracking system* (e.g. mechanical, ultrasonic, magnetic, optical, or hybrid), reference markers (fiducial or markereless), and *interaction devices* (e.g. mouse, joystick, haptic devices, tangible interfaces, etc). The architecture we developed for H.E.A.R.S (Figure 1) consists of the *Main PC*, an *AR system* which comprises of a video see-through head mounted display (HMD) with an embedded tracker and fiducial markers for registering virtual objects, and a pair of *joysticks* for interaction.

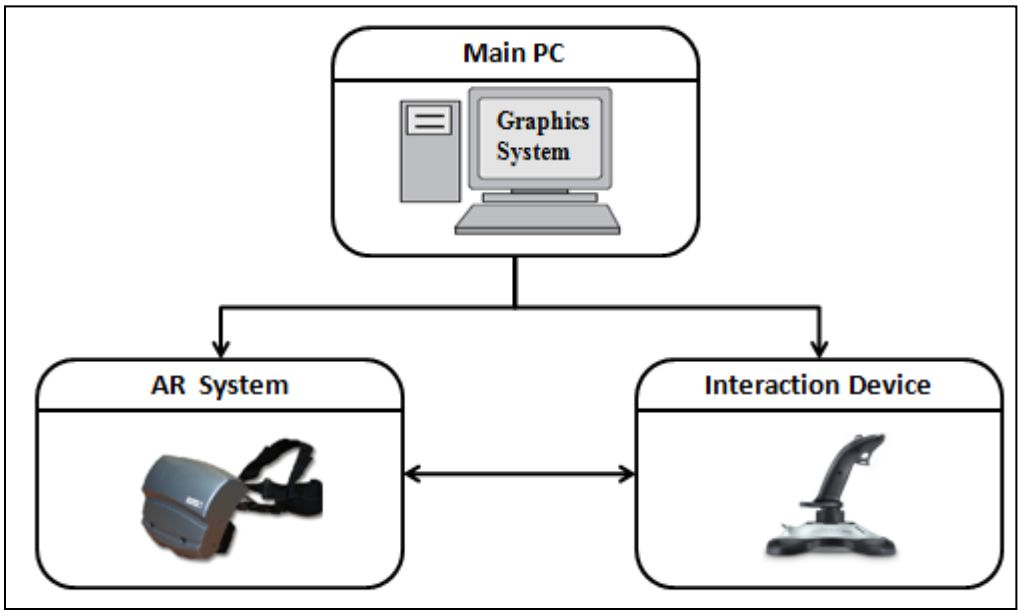

Figure 1: H.E.A.R.S system architecture

The Main PC is a custom desktop with a 2.4GHz Intel Core i7 processor and 8GB of RAM running Windows 7 operating system. The Main PC is used to run a virtual excavator simulator and generate virtual objects for use as AR metaphors. It also tracks the position of the user. The virtual excavator simulator is based on an off-the-shelf Simlog Personal Hydraulic Excavator Simulator from Simlog (2011), which comes with twelve simulation modules with scenarios to simulate different tasks. It has key performance indicators allowing us to measure how quickly and how carefully the simulated work is performed, including execution time, truck loading accuracy, the maximum tilt angle when the excavator climbs/descends benches, and the number of slams that sound when the bucket is over-extended either in the open or closed position.

The AR display, the Mirage AR system (Arcane Technologies, 2010), features a high performance vision-based positioning system that uses random fiducial markers on any real surface. The Mirage AR system (Figure 2) has four main functions for developing an AR application - *image acquisition*, *fiducial detection and pose estimation*, *3D overlay generation*, and *merging*. For *image acquisition*, the HMD includes two cameras that are placed in front of the OLED ocular displays. The cameras capture and send the images of the surroundings to the attached computer. For *fiducial detection and pose estimation*, the software uses image processing algorithms to detect marker patterns in the image. If one or more marker patterns are detected, those patterns are used to compute the 3D pose of the associated contents. The *3D overlay generation* module allows virtual objects associated with the detected markers to be drawn over the camera images for both eyes. The images are then sent back to the OLED ocular displays in front of both eyes for *merging*. The result is a highly realistic and accurate stereoscopic real-time AR experience.

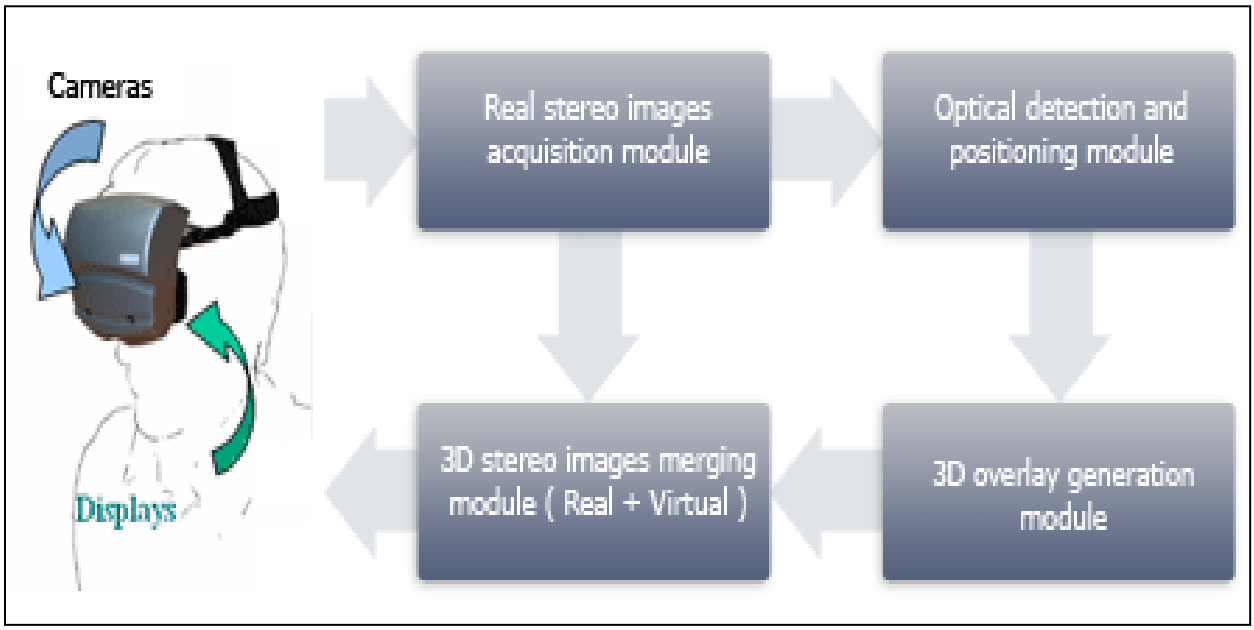

Figure 2: Functions of the Mirage AR system

A pair of Logitech Attack 3 programmable joysticks were interfaced with the excavator simulator and used to control the simulation. The joysticks were used to control the functions of the bucket, stick, boom and swing.

3.2 Implementation Details

Modeling of Virtual Objects

The first step in implementation of this concept was to model the virtual object or AR metaphors (Figure 3) using a 3D CAD software whose format is supported by the Mirage AR system. Figure 4 shows CAD models of the four system functions - the swing, the bucket, the arm and boom – that represent the AR metaphors.

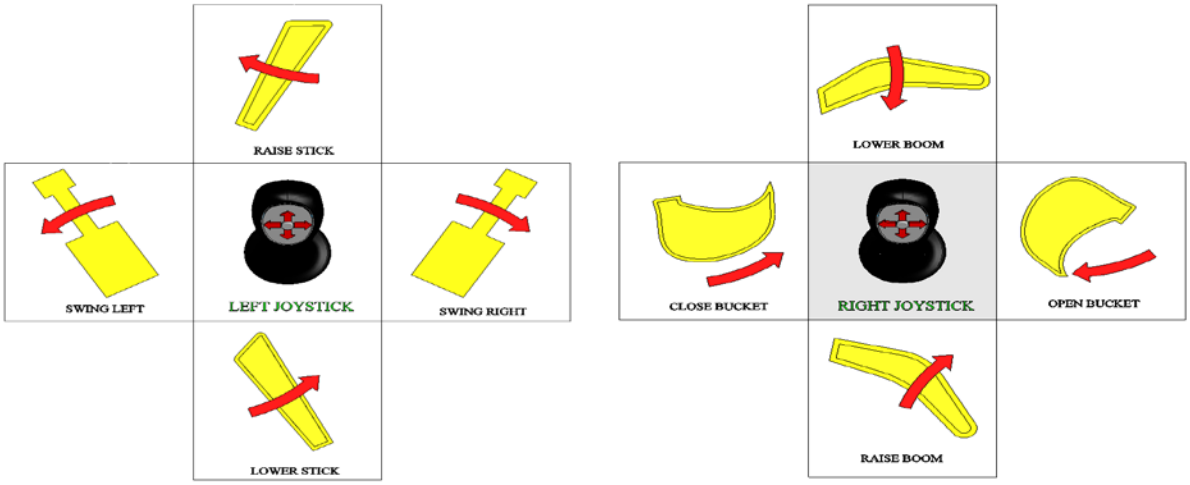

Figure 3: Virtual objects (AR metaphors)

Fiducial Preparation

The preparation of the fiducial markers involved affixing them in a random pattern on square-shaped plain white paper and placing them in the real world. Two markers were prepared for the left and right joysticks, each serving as a container to hold the virtual object or AR metaphor corresponding to each joystick. Figure 4 shows one of the two marker patterns that were used.

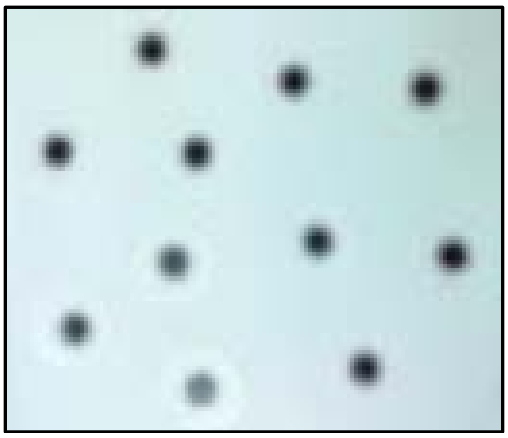

Figure 4: Fiducial marker

AR Simulation

The AR simulation was created in three simple steps using the MirageBuilder AR authoring interface. The first step involved placing the prepared patterns in the real world. In the second step, the HMD is worn and used to record the marker patterns. The MirageBuilder is set in Pattern Record mode and the AR engine of the Mirage AR system records each pattern by learning and storing each pattern in "memory". In the third and final step, the 3D models (AR metaphors) are imported and associated with their corresponding markers.

Once the AR application has been developed, the virtual excavator simulator is run and fed into the HMD to provide the user with a blended view (Figure 5) of the virtual environment and real world with the AR metaphors.

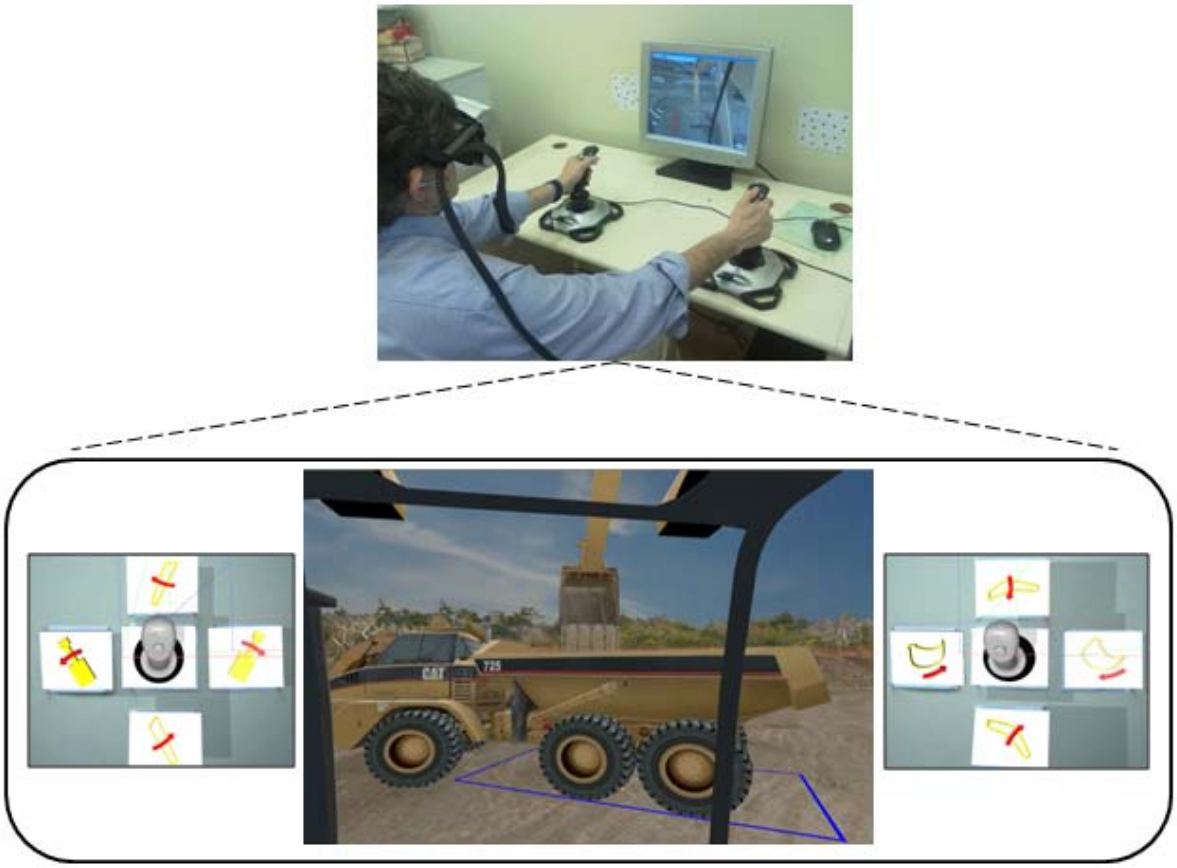

Figure 5: AR simulation

4. Evaluation

The main goal of H.E.A.R.S was to determine whether having an AR interface can provide effective operator training. Needless to say, an apposite evaluation of H.E.A.R.S will, therefore, require conducting user studies with operators, both novice and expert, of hydraulic excavators to assess its effectiveness. A preliminary user study was carried out with novice users (non-operators) in the lab for this study.

We sought to measure the effectiveness of H.E.A.R.S using the following metrics: degree of intuitiveness, learning rate, error rate, and task completion time. For our initial user evaluation of HEARS, we assessed the degree of intuitiveness of the simulator. The degree of intuitiveness is an important metric that gives a qualitative measure of the effectiveness of H.E.A.R.S. We found that the AR metaphors introduced in developing H.E.A.R.S provided an intuitive interface which allowed users to easily operate the equipment without the need for previously acquired declarative knowledge of how the controls worked; as the AR metaphors automatically provided the needed cues (or information) to support cognition. In addition, since the cues were provided in real-time, users could always go back to reinforce their knowledge of system functions in the event that there was loss of memory of how the working parts are operated. Compared to the traditional virtual simulator, H.E.A.R.S enriched the training experience and subjected users to very little cognitive workload. It can therefore be inferred that the degree of intuitiveness attainable with H.E.A.R.S can effectively enhance operator training.

The other measures of effectiveness – learning rate, error rate and task completion time – which are out of the scope of this paper, will be used to provide quantitative measures for assessing operator performance. These will be examined through detailed experimental designs, where their effects on operator performance will be determined. It is expected that low measures in error rate, learning rate and task completion time in training will be indicative of "good performance", hence establishing the effectiveness of H.E.A.R.S or vice versa.

5. Conclusion and Future Work

Finding effective methods for providing training to heavy mobile equipment operators, including hydraulic excavator operators, has become essential for ensuring safe and efficient operation of equipment and assuring gains in both operator and system performance. To this end, we designed and implemented an AR-based training simulator, H.E.A.R.S, to demonstrate the possibility of using AR to provide an effective training platform for hydraulic excavator operator training. The usefulness of AR in training is that, unlike on-site/off-site training programs and virtual simulators, AR combines both the real world and virtual training methods to offers a low cost, less time consuming and high fidelity simulation environment for effective operator training.

In our prototype system, H.E.A.R.S, the design strategy adopted sought to provide additional information about working parts of the machine, to provide first hand information to operators to familiarize themselves with control functions without the need for manuals or training lessons. The evaluation of H.E.A.R.S with novice non-operators under a research setting proved that it was an effective solution as it allowed users to easily understand how to operate the equipment with reasonable cognitive workloads.

Future work will concentrate on conducting detailed experimental designs to investigate the impact of operator training with H.E.A.R.S on operator performance, as well as developing the other design strategies discussed above to provide a highly enriched performance support system for operator training. Success with H.E.A.R.S will also open opportunities for developing similar applications for other heavy mobile equipment such as loaders, dump trucks and cranes.

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