IQ-Stations: Advances in State-of-the-Art Low Cost Immersive Displays for Research and Development

William R. Sherman
Indiana University
Bloomington, Indiana
shermanw@indiana.edu

James H. Money
Idaho National Laboratory
Idaho Falls, Idaho
james.money@inl.gov

Eric Whiting
Idaho National Laboratory
Idaho Falls, Idaho
eric.whiting@inl.gov

Shane Grover
Idaho National Laboratory
Idaho Falls, Idaho
shane.grover@inl.gov

Figure 1: Examples of IQ-Stations. The left system with the lower touch display is deployed at University of Indiana's Advanced Visualization Laboratory. The system on the right is deployed at Idaho National Laboratory's Applied Visualization Laboratory showing a Unity 3D based volume renderer.

ABSTRACT

This paper discusses recent advances in IQ-Stations, which are one wall inexpensive immersive displays. A number of these displays have been deployed in academia, industry, and national laboratories. This paper covers recent advances in technology, use cases, and new portable options. The use cases discussed cover various opportunities for IQ-Stations in STEM education outreach, development, and production use.

CCS CONCEPTS

• **Computing methodologies** → **Graphics systems and interfaces**; **Graphics input devices**; **Virtual reality**;

KEYWORDS

IQ-Station, virtual reality, tracking systems, consumer hardware

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1 INTRODUCTION

During 2010, Sherman, et. al, published a paper on a low cost fish-tank style virtual reality (VR) system called an Inexpensive Interactive Immersive Interface (I-quaded-, or IQ-) station [13]. Since that time, technology improvements have significantly improved the functionality of the IQ-Station, especially in the areas of display quality, tracking performance, and portability. These systems are now viewed in contrast with the current generation of head mounted displays (HMDs) such as the HTC Vive [1] and the Oculus Rift [6], which provide excellent single person VR experiences. Stationary-screen VR systems, such as the original CAVE and derivatives (including IQ-stations) have been a staple in the scientific and research communities for the past 25 years.

CAVEs and CAVE-like systems [2] have enjoyed many benefits over HMDs for much of this time. In particular, a significant benefit of stationary (or large-format fixed) screen systems comes from enabling groups of users to experience the same scene together in the same space. To be sure, except in the most advanced CAVEs only one user was provided the precise perspective, but collaborators could still share enough of the experience to make comments and ask the "driver" to move this way or that, or just swap control since this only required exchanging a pair of glasses. There are other benefits of CAVE-like systems over HMDs as well, such as the easy to don/doff glasses, plus the wider field of view, generally higher resolution, and less likely to induce nausea. The two biggest negative factors of CAVE-like systems has been the monitary cost and the large space required.

Over time, and in particular sparked by the successful Oculus Kickstarter campaign in 2012, HMDs have eroded many of the factors weighing in favor of CAVEs starting with the cost. In the decade prior to the modern consumer-market HMDs, a good head-mounted display would cost perhaps 15%-25% of a typical CAVE, which means 4-6 people could be immersed in HMDs at the same cost as up to perhaps 8-10 people at the same time in a CAVE. But those HMDs were heavy and full of wires, hard to don and doff and provided mid-quality resolution. By 2017, HMD prices had fallen such that $600 per person might now compare to $250,000 for a standard CAVE, and so the ratio tilted wildly in the favor of the HMD. Perhaps if you include the cost of the computer, the ratio is reduced, but still tilting significantly toward the HMD. (If we consider $3000 for a computer to drive a CAVE and $1500 to drive a consumer HMD —we now compare $253,000 vs. $2100 and get a comparison of 8-10 people in a CAVE vs. 120 people wearing HMDs.) Couple this new ratio with HMDs that are lighter and more easly worn, and the tables have been turned. (Not to mention advances that are just around the corner such as wireless and form-factors approaching large eye glasses.)

Even before the HMD reinvigoration, research facilities sought to lower the cost of entry for VR systems similar to a CAVE. The IQ-Station design is meant to provide a CAVE-like environment, at several orders of magnitude less in monitary costs, and perhaps less personnel effort as well.

In this paper, we review the catalysts for these types of displays, the technology migration of the display and graphical computing technology, and evolution of the design. We also discuss current supported software, state of the art designs, and future directions for the IQ-Station.

2 CATALYSTS FOR LOW-COST IMMERSIVE DISPLAYS

A number of groups have been involved in the development of the IQ-Station technology over the years. Initial research was completed at Desert Research Institute (DRI) in 2009 and later transitioned to Indiana University (IU). Concurrently, University of California - Davis campus completed similar research into this technology. Idaho National Laboratory (INL) worked closely with IU on the continued development of their instantiation of this technology. Other, more costly options, and sometimes not including tracking were also developed such as a system from the 2008-2009 era through a joint collaboration with Pennsylvania State University Advanced Research Laboratory's Synthetic Environment Applications Laboratory. Also Mechdyne developed a similar commercial system dubbed the "mini-CAVE".

Table 1: Various display technologies utilized in IQ-Stations

Year	Manufacturer	Display Technology	Projection Type
2006	Samsung	DLP	Rear-Active, Enclosed TV
2009	Samsung	Panel	Front-Passive TV
2010	Mitsubishi	DLP	Rear-Active, Enclosed TV
2012	LG	Panel	Front-Passive TV
2016	Panasonic	DLP	Rear-Active, Short-throw
2017	ViewSonic	DLP Laser	Rear-Active, Short-throw

2.1 Displays

The first iteration of this setup primarily relied on stereoscopic televisions utilizing checkerboard active stereo Digital Light Processing (DLP) projection technology from Texas Insruments and found in consumer-of-the-shelf (COTS) products from Samsung and Mitsubishi. The possibility of consumer-priced large stereoscopic screens was the first indicator that a consumer-based VR system could be feasible.

Over the course of a decade, stereoscopic TVs went from enclosed rear-screen projection, to flat panel active and passive screens, to eventually being phased out of the consumer market. Ultimately, a dearth of stereoscopic content drove manufacturers to end support. Since the reduced production of stereoscopic panel televisions, INL has moved it's technology stack to include low-cost phosphor-based stereo short-throw projectors and eventually, in 2017, laser based projectors. Table 1 shows the various iterations of the television/projector technology utilized and approximate years of adoption.

2.2 Tracking

An authentic VR system must also include a means of tracking the user's head such that the rendered perspective is continually adjusted for their point of view. The development of commercially available relatively low cost tracking was the next hurdle overcome that led to the proliferation of IQ-Station technology.

The ability to buy position tracking systems at costs under $10k USD permitted the wider deployment of IQ-stations into places where larger CAVE-style systems were cost prohibitive. Initial deployments of IQ-Stations utilized the NaturalPoint [8] multi-camera tracking system based on video processing. These systems initially provided a low cost entry approximately around $5K USD, but required software that only ran on an MS-Windows platform. Thus, as most of our immersive visualization tools ran under the Linux operating system, an additional PC to drive the processing of the video tracking was required. This roughly, depending on the desktop configuration, brought the cost close to $6K USD.

Some initial issues were discovered for utilizing this system for tracking since the infared (IR) from the video-based tracking

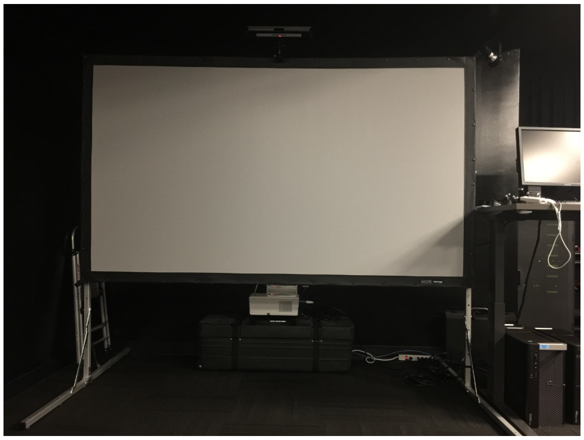

Figure 2: The short-throw rear projection IQ-Station utilizing the ART SMARTRACK at INL.

interfered with the active stereo impulse signals. Eventually NaturalPoint resolved this with a new hardware synchronization box, without which other solutions would have been immediately required. The problem of IR-conflict could later be avoidable through the advent of passive stereo screens, and active glasses making use of RF rather than IR for the stereo synchronization.

However, the NaturalPoint tracking system was still insufficiently robust for wider use. Tracking was often imprecise and error prone, and often required a cumbersome recalibration process. Mounting the cameras near the operating area, exacerbated the problem by making them susciptible to physical disturbances, where small dislocations of the camera would put the system out of calibration. This limited their use for deployed sites without the appropriate technical expertise to regularly perform the calibration.

Over time, the preferred solution became a mostly calibration-free system. This system, the Advanced Realtime Tracking (ART) SMARTTRACK [16], came at an increased cost, but not forbiddingly so. The SMARTTRACK is ART's low cost position tracking solution that uses a two camera IR-based method with an integrated controller. This solution currently costs $7.5K USD, which is sufficiently close to the price point of the NaturalPoint system when the cost of the tracking computer is included.

The advantage of the SMARTTRACK is its higher reliability as well as the avoidance of the challenging calibration process. Both advantages enable remote sites (without onsite technical expertise) to use IQ-Stations for months without a full recalibration. Also, INL has been able to rely on their robustness for conferences and travel-based STEM events in the local area and at remote conferences without any further calibration. A picture of the current setup is shown in Figure 2.

Future improvements in the tracking realm include utilization of even lower costs systems available with commodity VR headsets, such as the HTC Vive. In particular, the SteamVR/LightHouse tracking system [10] provides access to developments kits and components that enable tracking at costs below $1K USD. Additionally, the latest version of SteamVR Tracking can handle a room with dimension 33'x33'. Using this technology would enable final system costs to drop below $10K USD.

2.3 Input and Rendering

Historically, the gaming consumer market has provided the VR community with both low-cost graphical rendering and common hand controller devices. On the rendering side, the hardware continues to get faster, and usually without raising issues for VR developers, except when new drivers introduce bugs in areas important to VR users. For example, stereoscopy with active glasses is a common issue with drivers that is typically not apparent to gaming enthusiasts.

Regarding hand input devices, IQ-stations have relied both on low-cost game controllers such as the Nintendo Wii controller (aka "wiimote"), and occasionally controllers associated with the tracking system such as the ART Flystick-3. Augmenting commodity "game" controllers to work within the scheme of of many professional-grade position tracking systems is as simple as adding a constellation of reflective markers to the controller. Pairing the tracking of a system such as the ART SMARTTRACK position tracker, with the button controls on a Wiimote it is possible to have high quality tracking with a low cost controller.

Again, controllers come and go, sometimes changing between singled hand ergonomics (e.g. the wiimote) and double-handed such as with devices like the Logitech Rumblepad 2[7]. On the positive side however, most controller inputs connect to the computer via standard USB HID interfaces that can be read by most VR libraries.

2.4 Issues in Consumer-based Hardware Space

While the consumer-based hardware space provides low-cost solutions for display and controller technology, it comes with a big disadvantage of frequent turnover of the particular models and capabilities. In particular, the ebb and flow of stereoscopic televisions mentioned above saw great improvements for a few years but then were entirely discontinued within the last three years. And yes, there are commercial vendors manufacturing stereoscopic displays, but the price is much higher than the consumer-grade products that used to exist. We are fortunate in that moderately priced, stereoscopic-capable, short-throw projection systems remain on the market. Although the problem of model turnover from year to year continues to be an issue.

Presently, we are on the cusp of being able to make use of the new consumer-oriented position tracking systems. Again, gaining a great cost advantage by virtue of the game consumer market, perhaps enough to offset the cost of commercial stereoscopic flat panel displays. Yet model and corresponding protocol changes may happen on a yearly basis, perhaps requiring replacement trackers just as often. The *financial* versus *effort* tradeoff of the rapidly evolving consumer market is a consideration that must be evaluated when adopting low-cost consumer-oriented technology.

3 EVOLUTION OF DESIGN

We have discussed the many issues that result from working within the consumer product arena, both good and bad. These circumstances have often pushed the design of the IQ-Station in particular directions, thus the system design reflects the course of product availability.

The original systems were based on DLP projection televisions available from Samsung and Mitsubishi. These were the first stereo-ready consumer televisions. In both cases, the active stereo display provided by the Texas Instruments' DLP system used IR emitters to send the signal to active stereo glasses. Indeed, the same glasses that worked with existing CAVE-style VR displays could be used with these televisions.

Once stereo-capable flat panel screens became available, there was a bifurcation of the styles of IQ-stations. INL continued to use the DLP systems that provided a larger display surface and worked well for systems deployed off-site. Indiana University explored the use of dual-screen systems, using flat passive-stereo displays, including models with a touch input surface that can be used to enhance the user interface.

Prior to the ability to add touch overlays to existing screens, touch interfaces were only available on specific displays, none of which were stereo-capable. Thus to explore the use of the touch interface, one screen with touch, but without stereo was positioned within reach of the user, below another screen which was stereo-capable, and became the primary viewing surface. Interestingly, it was found (anecdotally) that with proper alignment between screens, the transition from monoscopic to stereoscopic viewing was not jarring, and in fact provided a usable view. Later, through the use of newly available touch-screen overlays, this discrepancy was avoided by abutting two identical screens, both stereo-capable, and installing the touch interface on the lower screen, within reach of the user. This design became the preferred format for the Indiana University systems.

As has already been alluded to, the tracking went through an evolution from a six-camera Natural Point solution to an ART SMARTTRACK integrated dual-camera in a rigid bar configuration. Although marginally more expensive ($6000 raised to $7500), the increased robustness of the SMARTTRACK paid great dividends in VR technology adoption.

4 SOFTWARE

In order to keep systems low cost, the initial software focus was on open source tools. In particular, the developers relied on systems already in use within the immersive visualization community —tools with which we were already familiar; namely the Virtual Reality User Interface [5] and FreeVR [12]. Given their open source disposition, both of these VR systems are primarily geared towards Linux. Using one or both of these tools, a user can, out of the box, quickly compile and install several visualization tools for volume visualization, LiDAR, mesh visualization, molecular/protein visualization, CAD models and more. (This same suite of software can also be deployed on full CAVE-style systems, HMDs, and in most cases work on standard desktop interfaces.) A summary of some of the software packages and libraries they utilize are shown in Table 2.

In more recent history, two game engines (Unreal Engine[3] and Unity 3D [18]) have been utilized to develop applications across a range of disciplines. Especially in the case of Unity 3D, developing new applications can be fairly straightforward as it has a friendly user interface, and allows for the quick creation of simple virtual worlds, making it popular with sites where new developers are encouraged to create their own projects. The use of game engine technology has permitted an economy of scale as any enhancements to the game engine come free to the end user of the engines.

Table 2: Various Software Systems Available

Software	Library Required	Version
Toirt Samhlaigh	VRUI	20131017
LiDAR Viewer	VRUI	2.12
3D Visualizer	VRUI	2.13
ProteinShop	VRUI	3.1.3
Tele-Collaboration	VRUI	2.8
VMD	FreeVR	1.9.3
ParaView	OpenVR	4.0

Recently, several locations have had success using Unity 3D as it now includes native stereographic support (via DirectX) on the Microsoft Windows platform. Along with position tracking inputs from utilities such as VRPN [15], the support for stereo display has led to the development of open source toolkits to bring Unity 3D into CAVE-style and dual-screen IQ-Station implementations. In particular, the UniCAVE project [17] provides an open source implementation suitable for IQ-Stations. Given the unique usage (immersive display and scientific content), there can be quirks in the way tools such as Unity 3D work. For example, for stereoscopic rendering to work properly, the current version of Unity (5.5 and later versions as of this writing), requires the stereographic projector (and not a secondary monitor) be set as the primary display.

Game engines such as Unity 3D are particularly good for creating educational experiences and those that require illustrative virtual worlds. However, through the use of GPU shader technology (compute, fragment and vertex), more sophisticated renderings can be created, including those desired for the purpose of scientific visualizations. Our work with Unity initially began as educational and explorative inquires at INL and IU, but now is used in production use, replacing some open source tools.

5 CURRENT STATE OF THE ART

Beginning with the Kickstarter campaign for the Oculus Rift in 2012, modern VR has evolved quite raplidly. Yet, some of the tried-and-true hardware and software are still viable. One big technological leap has been the promulgation of "VR-ready" computers, and even VR-ready laptops, the latter making portable IQ-Stations much more feasible. DLP projectors have become the primary method for stereoscopic display (since consumer flat panel TVs are essentially no longer available). Furthermore, DLP projectors can be found in portable models with short-throw lenses, which, coupled with collapsible screens, contribute to the portable nature of newer IQ-Stations.

With respect to input technologies, the ART SMARTTRACK remains the preferred solution for position tracking. For hand-based inputs, the Wiimote is no longer widely available, so the two primary options are 1) the Flystick-3, which is a companion product to the SMARTTRACK, but as a professional device is more costly;

Table 3: List of deployed IQ-Stations including location, display technology, tracking system, and year initial deployed.

Location	Display	Tracking	Year
INL Applied Visualization Laboratory	Projector	SMARTTRACK	2016
INL STEM Outreach	Projector	SMARTTRACK	2015
University of Wyoming	DLP TV	OptiTrack	2010
Indiana U. School of Med. Center for Neuroimaging	2-flat panels w/ touch	—	2014

and 2) a standard game controller with tracking constellations added on. (A snap-on constellation of reflective balls is available from ART for many consumer hand-controller models.)

Finally, the suite of software for immersive visualization is still a good option when Linux is an acceptable operating system for the user base. On Microsoft Windows platforms, more and more software options are available and continues to become available, especially for the Unity 3D software system.

6 DEPLOYMENTS

A number of deployment sites have adopted both prior and more recent iterations of this technology. INL has deployed over ten of these systems throughout the state of Idaho and Wyoming. Additionally, several companies and museums have adopted this technology for day-to-day use. There are been instantiations of these systems in labs such as the Indiana University School of Medicine's Center for Neuroimaging. There are several libraries that have also adopted the use of the technology including the University of Idaho Library. An example list of some of the deployed systems are provided in Table 3.

7 FUTURE

The most significant change in the future is that more software (especially for scientific analysis) will be at least more VR-friendly, if not fully VR-ready, in particular for the fishtank paradigm of VR of IQ-stations. We already see this in the ParaView software, which yes, we had a hand in moving in the VR-ready direction [14] [11], but it has also independently been enhanced with the OpenVR framework to work directly with consumer HMDs as well [9].

The other likely future enhancement is the consumer-based position tracking that has already been alluded to. Either or both the Valve Lighthouse system, or the Oculus camera system could be made to work with the stereo-glasses employed by IQ-stations and other fishtank-style VR displays (and CAVE-style). The difficulty for each of these is that both methods make use of electronics contained directly on the tracked object, and the generic Vive "puck" tracker is too unwieldy for use with glasses. However, at least in the case of the Lighthouse, a developer kit is available that can be used to add position tracking to any object [10]. Also, there have been do-it-yourself efforts to accomplish the same feat [4].

8 CONCLUSION

Through a decade of work prototyping, designing and deploying low-cost solutions for fishtank VR systems using commodity hardware, we have evolved an effective tool that has worked in a variety of venues with varying degrees of on-hand expertise. Deployments have been sufficiently robust as to work in computer labs, museum settings with docents, libraries, and visualization centers. In particular it works well in public venue environments where people can partially share in the experience by donning non-tracked glasses, and thus can provide suggestions to the user with the controls.

In the future, more technological advances will enable further price reductions similar to the current cycle of consumer-grade HMD improvements. This will enable mass adoption at facilities and other venues where it is not currently feasible to deploy systems.

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