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Ph.D. Thesis

DESIGN OF A SCENARIO-BASED IMMERSIVE EXPERIENCE ROOM

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Introduction

Thought is impossible without an image.

— *Aristotle, "On Memory and Recollection"*

Since the advent of computers and digital equipment, an evergrowing effort of research and engineering has been devoted to applying digital processing techniques to the management of multimedia data. The defining characteristics of digital multimedia is the incorporation of multiple, continuous kinds of information, such as voice, full-motion video, music, images, and the interweaving animation thereof, in a digital medium. In the last decades, advances in multimedia systems and applications have merged and pushed the interests, ambitions and innovations of three industries: computing, communication and broadcasting.

Research and development efforts in multimedia computing fall into two major groups.

On one hand there is continuous ongoing development focused on the aspects of content production and user-facing multimedia applications. That is, software systems and tools aiding music composition, video editing and playback, or computer-aided learning.

On the other hand, there is ongoing fundamental research in how multimedia content is encoded, delivered to users, stored, represented and is made to be easily available or—even—interactive to users. This aspect constitutes the basis of what makes multimedia possible in a digital world. Also, developments in this area have heavy ties to many other fields related to computer science and information theory, but also software engineering and distributed systems.

In fact, real-world multimedia systems are preeminently built as a form of distributed system, requiring notable engineering efforts in order to work reliably. This applies to multimedia information systems, content indexing and distribution systems, collaboration and conferencing technologies, on-demand delivery networks, and large-scale media databases. And more.

In particular, distributed multimedia systems require continuous media transfer over relatively long periods of time, may contain a huge amount of data, require equally large storage, synchronization, and special indexing or retrieval systems. As outlined in the overview by Fuhrt, the technical demands of multimedia systems largely depend on the specific application—for instance, large storage and high computational power is required for high-resolution video indexing, while interactive live conferencing has the entirely different requirement of low-jitter high-bandwidth data transmission [33].

For any of those specific requirements however, the complexity of multimedia applications stresses all components of a computer system: they require great processing power, fast and reliable encoding and decoding software, high data bandwidth, efficient I/O, high capacity and fast access times.

Satisfying these requirements has spawned many different research and development fields, that so often find their foundation in the more theoretical aspects of computer science, ranging from multimedia compression techniques, networking protocols, synchronization methods, and other algorithmic topics. And in physically bringing multimedia systems to reality, decades of engineering and development have been spent likewise.

It is in the convergence of those research efforts that today's world of rich multimedia applications is possible and, in some way, now taken for granted. Most real-world tech developments that touch us directly as users, from the pervasive availability of modern smartphones to our capability of getting pictures sent in from a rover on Mars, derive in large part from the growing stock of knowledge in this area.

Existing technologies have been transformed over the course of the last years to enable growing complexity and the skyrocketing demand for even better, more enticing multimedia systems.

This doesn't concern computer architecture and performance alone of course, but also—for instance—networking and storage solutions. It is both evident and impressing to ascertain the rapidity with which technologies have evolved over time, moving exponentially from the expensive memory cards of the '60s, with capabilities ranging up to a handful of bytes, to the huge storage capabilities which are available to us nowadays [20]. In fact, only in the last two decades, computing power, storage density, and network bandwidth have improved by more than three orders of magnitude.

This kind of impressive technological growth has been at the foundation of entire new industries, which—like the life-changing research developments cited before—have already deeply impacted our ability to experience, manipulate, create, and shape the world.

Not only that, the pace and scale of this technological acceleration also has profound sociological and economic consequences. Pervasive computing and its derivatives can clearly have a deep effect on society, especially a society that is increasingly dependent on the artifacts of said technology. As these artifacts further empower people—in almost all aspects of their lives—at the same time they encroach into the realm of human skills. And as digital systems are only going to become more powerful and capable in the future, they will indeed have an even bigger impact on human life.

Our technologies are racing forward, while many of our skills are lagging behind, in what—Brynjolfsson and McAfee argue—can be said to be a "Great Restructuration" of our relationship with technology and our respective roles [13]. As the following quote by David Leonhardt clearly substantiates, even groundbreaking change is difficult to predict and to notice except in hindsight.

> When Bill Clinton assembled the top minds of the nation to discuss the economy in 1992, no one mentioned the Internet.
>
> — *David Leonhardt*

And if the groundbreaking change is difficult to notice, it is safe to say that also the consequences of this technological acceleration are not easily predictable as well.

Ten years ago, not many people would have bet on the fact that in 2014, in some African regions, mobile Internet had a better reach than electrification and, in some ways, was exactly as important as improved water services [30].

Change can and will come in many unexpected forms, spawning new opportunities and radical rethinking that sound outlandish at a historical distance of only a couple of years. However, the increase in sophistication and the increase of the scale at which it operates, has given the multimedia realm and the tech industry an enormous leverage on how they affect our lives and how they dominate our attention [31].

But a strong impact can nonetheless be a positive impact. As Brynjolfsson and McAfee put it, when we have a look at the full effects of computers and networks, now and in the immediate future, there is reason to be very optimistic indeed. Technology at large, and these tools in particular, is improving our lives and will continue to do so. In fact, it can be argued that the only sensible stance to keep is to be "digital optimists" [13].

All the changing factors enumerated above have contributed to a world entangled by the massive availability of multimedia data of all forms, available at all times, matching an equally massive and growing demand. Multimedia data like pictures, audio, videos, text, graphics, animations, and other multi-modal sensory data have grown at a phenomenal rate and are now almost ubiquitous.

As a result, not only the methods and tools to organize, manage, and search such data have gained widespread attention, but the methods and tools to discover hidden knowledge from such data have become extremely valuable. The ability to extract meaningful information from a large collection of information is at the foundation of many aspects of our current world [8]. As Leigh et al. argue, whether sensor nets, supercomputers, or the *Cloud*, the changes to the global computing infrastructure are transforming the way that scientists and engineers study and understand complex systems. Whether physical, geological, biological, environmental, or atmospheric data is in play; whether at the micro or the macro scale; whether in time or in space—data is produced in higher volumes than ever and its interpretation is crucial to gain insight and knowledge [57].

The major challenge is in finding a way to effectively manage the increased scale and complexity of data, and thus be able to understand it without being overwhelmed by it.

Getting back to the opening quote: "*Thought is impossible without an image.*"

Today's computers have become a crucial tool for storing, transmitting and analysing information, giving us the opportunity to understand, manipulate, and grasp complex phenomena in novel ways. Many of these uses require some form of **visualization**. The same term that stands for the cognitive activity of forming mental images, also represents an important discipline of computer science related to multimedia.

The act of "visualizing" links the two most powerful information processing systems that we know today: the human mind and the modern computer [36]. It becomes more than a computing discipline—as Gershon and Eick put it, visualization is the process of transforming information and knowledge into a visual, understandable form, thus enabling users to observe the information, understand and elaborate on it, exploiting their natural strengths.

Effective visualization—Gershon and Page write—is far more than pretty pictures alone. The environment in which information visualization is best applied involves massive streams of information and data sources arriving in real time or from existing data sources. The users of the visualization need to integrate the information streams, thoroughly understand them, and make decisions based on their information in a timely fashion [37].

The impact of visualization in this scenario is formidable, in that is capable of leading to new insights, to more productive analysis, and to more efficient decision making. In fact Diehl too states that a good visualization often enables the user to perceive features that are hidden, but nevertheless are needed for a thorough analysis [27].

Much of the research in this field arose from the scientific community's need to cope with huge volumes of data collected by scientific instruments or generated by massive simulations. As an example thereof, it is easy to point to cases such as the *CERN Data Centre* surpassing a volume of over 100 petabytes of data over the last 20 years, and it is equally easy to see how these advances have and will further challenge the state of the art in computation, networking, and data storage [60].

Visualization can in fact serve three important roles: it can be used to verify the correctness of a model, as in a simulation; it can make results more readily available and suggest the presence of correlations or other unintuitive information; it can help in making results more easily understandable by the general public and lay audiences [57].

Visualization is in fact still the most effective mean to gain direct insight for researchers. It has been shown that nearly one-third of the human brain is dedicated to the endeavor of processing visual data, process in which 3D or stereoscopic cues have also been shown to be beneficial [105, 74].

A growing area of interest in this field is the visualization of big data sets on *very large displays*. The aforementioned process of analysis and perception of information through visualization is particularly suited to large-scale displays, given their capability to show *more* data, with higher bandwidth and higher resolution.

The trend of producing large-format displays for scientific visualization, such as video walls or immersive environments [48], is a natural approach that has started decades ago. In the last years, the introduction of more cost-effective solutions has driven this approach even to commodity PCs and consumer-level hardware [11]. Large-scale visualization provides several advantages over other forms of visualization, and of course it is not a complete novelty: large walls of standard TVs, that replicate or enlarge the image over an expanse of monitors, have long been a feature of museums, public fairs, trade exhibitions [25]—and science fiction movies, of course.

It is not by chance that in movies and other popular fiction, computing and visualization interfaces have long been evolving, fueling our imaginations. In the early '80s, while real computer interfaces were still revolving around the blinking cursors of a command line, the "Electric Dreams" movie predicted the fluid use of natural communication, giving an extremely personal look into our relationship with technology. Steven Spielberg's "Minority Report" gave us one of the most iconic futuristic user interfaces, in a scene that shows Tom Cruise's character shifting images and screens around on an enormous glass wall interface, using only his hands to "scrub" through huge amounts of video data, as shown in Figure 1.1. What in 2002 was seen as a very stimulating science fiction concept—perhaps the most memorable element of the movie in the minds of the general public—is now very much a reality. Same thing will be said, eventually, for the more recent "Avatar" by James Cameron, where futuristic visions of large touch screens and gesture technologies devolve into the ultimate *virtual reality* dream.

These futuristic visions of course serve a specific purpose: to immerse the audience—essentially a non-participating observer—to be actively engaged in the process of understanding the context and the meaning behind the character's actions. Physical interactions and larger wall-sized displays exploit an emerging idea in interface design, termed *external legibility*. External legibility is "*a property of user interfaces that affects the ability of non-participating observers to understand the context of a user's actions*", argues Zigelbaum [109]. This property does not need to be constrained to movie theaters alone, however. It is easy to conceive ways in which the immersive capabilities of these futuristic scenarios can bring better collaboration opportunities for single users and groups of people as well.

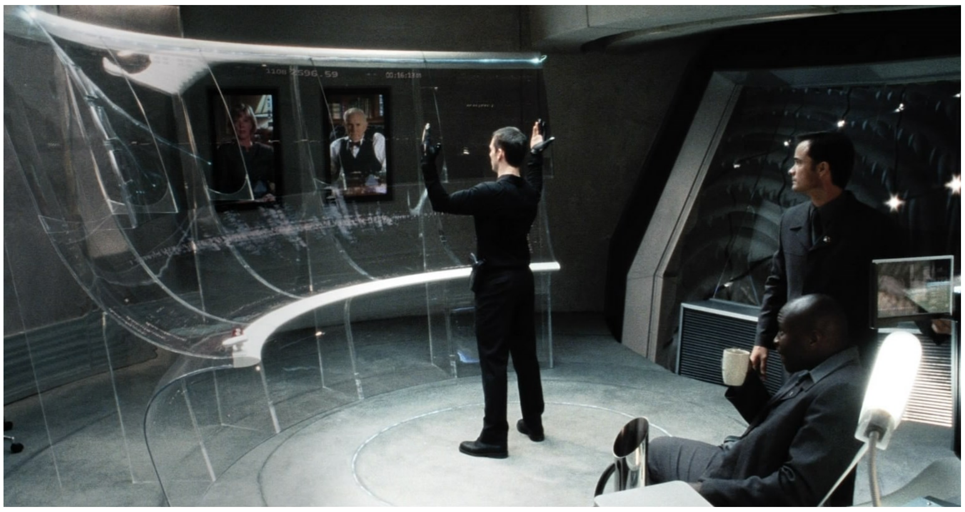


Figure 1.1: The iconic gestural interface as seen in “Minority Report”.

(© Twentieth Century Fox.)

As often is the case, emerging ideas make their way from fiction to the real world through a series of experimental setups, before becoming commonplace. Because of their immersive graphical nature, futuristic immersive interfaces have often found a rich playground in digital art, just like digital music was largely shaped by early musical experiments. These experiments pointed to the possibilities of the new medium, hinting at the new boundaries given by absolute freedom in copying, remixing, and generating music and sound. Paul and Werner in their “Digital Art” book [78] cite several examples, spanning from Brian Eno’s early soundscapes and recent audio-visual installations, like Golan Levin’s “Audiovisual Environment Suite” (AVES) software, which examined the possibilities of experimental interfaces in composition, allowing the performers to create abstract visual forms and sounds (see Figure 1.2).

Paul’s overview of digital art shows that this movement did not develop in an art-historical vacuum, but instead marks the natural progression of experiments with art and technology, also incorporating many influences from previous art movements [77]. In fact, the E.A.T. (*Experiments in Art and Technology*) project—as early as 1966—is cited as starting point into such explorations, without the preconception of either the engineer and artist. The ’70s marked the beginning of complex collaboration between artists, engineers, programmers, researchers, and scientists, that would become a characteristic of digital art.

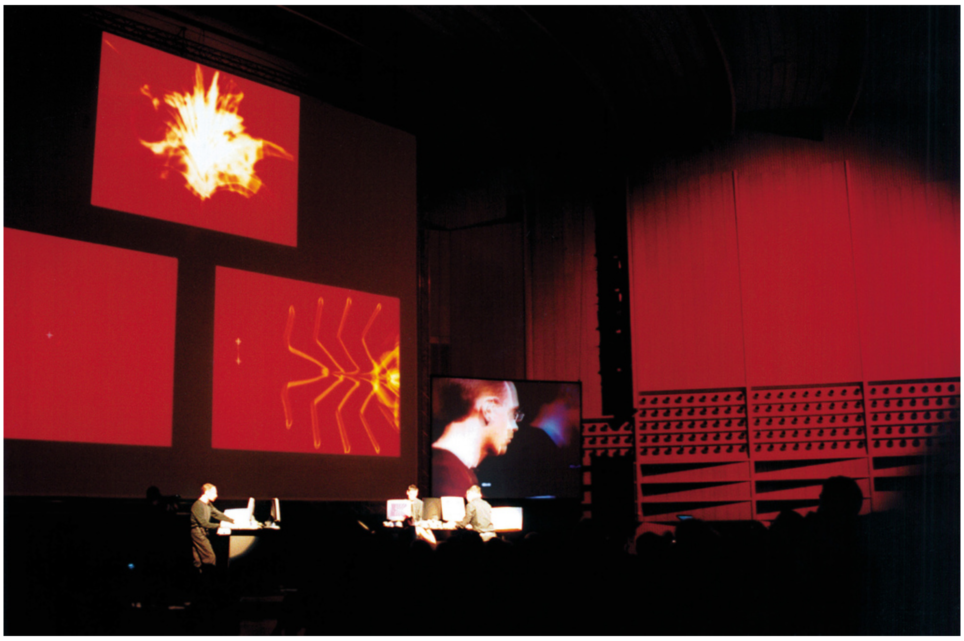


Figure 1.2: “Scribble” live performance by Golan Levin, Gregory Shakar and Scott Gibbons, live at the *Ars Electronica Festival 2000* using the “Audiovisual Environment Suite”.
Video: `https://youtu.be/ucVFa7re6xI`. (© Golan Levin, Flickr.)

Moreover, the digital medium displays other distinguishing characteristics as well. It is interactive, allowing various forms of navigation, assembly, and contribution to the artwork itself, which go beyond the traditional ways of experiencing art. It is often dynamic, in that it can respond to its audience. It can be participatory, relying on multi-user input. It can be customizable and adaptable to a single user's needs, to a scenario, or to the venue it is exposed in. These developments have challenged the traditional notions of artwork, audience, and artist, suggesting a paradigm shift in what constitutes an art object, as a fluid interaction between different manifestations of information [77].

These concepts of multi-user environments, interaction, sharing and dynamism, are central to John Klima's “Glasbead”. This experimental project, a musical instrument and toy at the same time, allows multiple players to manipulate and exchange sound samples, in order to create rhythmic musical sequences through a highly visual, aestheticized interface, rich in visual detail. Composition is done through the manipulation of a translucent blue orb, with musical stems and hammers that can be flung around. A cropped screenshot of a composition is seen in Figure 1.3. Not unlike the Herman Hesse novel "Das Glasperlenspiel" that inspired it, the project applies "*the geometries of absolute music to the construction of synesthetic microworlds*" [38].

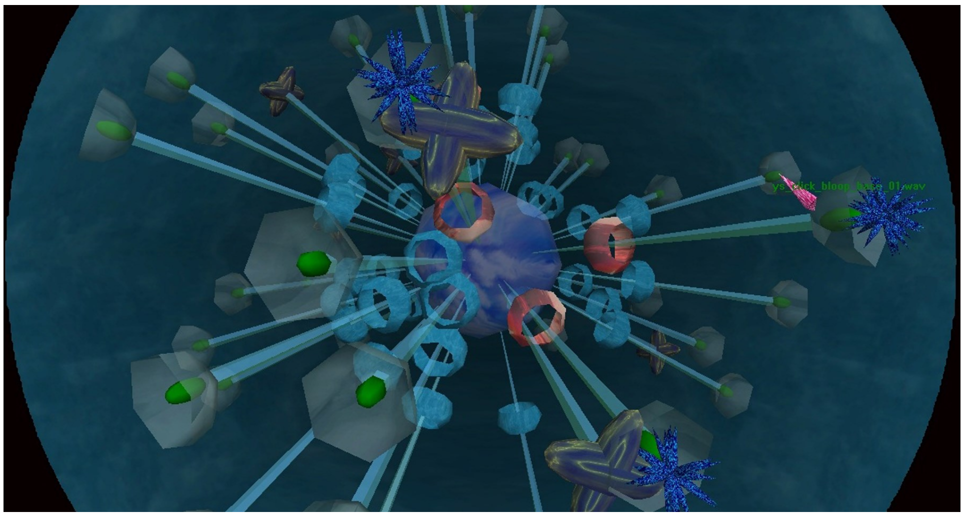


Figure 1.3: A screenshot of "Glasbead" by John Klima. (© John Klima, CityArts.com.)

As suggested by Bolter and Gromala in "Windows and Mirrors", digital art can indeed be considered the purest form of experimental design, as a medium that itself helps us understand our experience of it [12]. In John Lasseter's words, "*The art challenges the technology, and the technology inspires the art*".

Interaction, immersion, and physical presence are concepts that fit well with musical composition, as in "Glasbead", but the same principles can be applied to written text. Using a CAVE immersive virtual reality environment, Carroll et al. have developed "Screen", an interactive installation that allows users to bodily interact with text. Users entering the virtual reality chamber see text appearing on the walls surrounding them. One by one, words seem to peel off the screen and fly toward the reader, flocking around, while the reader can try to hit them with her hand (tracked using a wand or a glove), sending them back to the wall and thus creating a new text. Once the majority of words is lifted off the walls, the user will be overwhelmed by the words [16, 104].

The same concept has been explored further by Baker et al., developing a similar immersive VR system in which users could write and edit text, thus physically engaging with the hypertext inside the boundaries of a virtual environment [4].

"*The digital landscape is littered with failed virtual environments*", warns Guynup [41]. What is the real purpose of designing such interactive virtual environments, like those in the aforementioned projects?

In the abstract, a virtual environment can be interpreted as a pure information space. An environment can be organized, it divides information, categorizes it, places it within a narrative framework, in order to be presented and—by any chance—enjoyed by the user. This, in fact, mirrors real world galleries and museums.

This function of displaying objects and information is the underlying connection between modern virtual environments and the historical role of galleries. From the ancestral groupings of precious objects in ancient tombs, the small galleries of art hung in English country homes and French castles, to the Italian *studiolo*, the German *Kunstkammer*, there is a very specific purpose and a declaration of intent in the act of organizing, the act of imposing order on objects and space.

> Unlike other spaces like restaurants, bathrooms or garages, the purpose of a museum is not a physical one. It is an educational, often experiential, even spiritual one. With a degree of spatial freedom found nowhere else, museums structure space and house the widest possible array of objects and information. [...]
>
> Space itself facilitates the access of art. At their best, museums and galleries are flexible spaces that uplift, amuse, educate, classify and present information with a degree of spatial freedom found in no other structures. In this sense, the purpose of the gallery is the same as the [computer] *graphical user interface*.
>
> For the designer, art = information, in its widest array of configurations [41].
>
> — *Stephen Lawrence Guynup*

It can be said that the museum is the original virtual interface; the gallery is designed to support information, to allow users to visualize, access, and explore it. As Benedickt put it in his seminal cyberspace work, "*museums are ideal candidates for hybrid cyberspaces*" [6]. In the merging point between digital art, interactivity, dynamism, and the experiential role of the museum, lies the future of virtual environments.

Of course, one of the preeminent components of such virtual environments is *vision*, and—as far as this work is concerned—large-display systems.

As early as in 2000, Funkhouser and Li covered the incipient work in the space of building large-display systems using sets of screens, projectors, clusters of computers, and complex distributed multimedia systems [35].

Five years later, Fitzmaurice and Kurtenbach continued to collect the developments of the same topic. As they wrote: "*the emergence of large displays holds the promise of basking us in rich and dynamic visual landscapes of information, art, and entertainment*" [32].

1.1 Overview of this work

The scope of this thesis is to firstly present the state of the art in large-display technologies, focusing on their ability to provide an immersive experience to their users, giving an overview of existing techniques, systems, installations, and applications. In particular, one of the most widely used middlewares for managing such installations is presented in Chapter 3. In Chapter 4 an extension of this system is presented in depth, which allows the creation of interactive immersive scenarios and the management of a complex multi-room installation. Hardware acceleration of this system is discussed in Chapter 5. In closing, an overview of a real-world installation, that was designed and built during the course of the work on this thesis, is shown in Appendix A.

1.2 Contributions and acknowledgements

Work on this thesis was co-funded by *Università di Urbino*, *DSign Allestimenti*[1], and the "Eureka" scholarship offered by *Regione Marche*.

The experimental setup was designed and developed in collaboration with *DSign Allestimenti*, which culminated with the construction of an immersive experience room installation.

Significant parts of the IVE system, presented in Chapter 4, have been designed and implemented by Gioele Luchetti and Brendan D. Paolini.

[1]DSign di Cimadamore Anna Luisa & C. S.a.s., Monte Giberto (Fermo), Italy.
`http://www.dsignallestimenti.com`

Chapter 2

Large-scale visualization

2.1 Experience

As outlined in the previous section, multimedia systems are by definition capable of delivering various sensorial experiences, but the main and most common application involves **vision**, usually as the primary experience driver.

From the first consumer-grade color monitors in the late ’70s, the evolution of GUIs in application design, the continuous development of computer graphics hardware and software, to the wide adoption of touchscreens and *VR* (Virtual Reality) headsets, large part of the evolution of computing revolves around innovations in screen and display technology. Together with the continuous rapid improvements in performance, the progression of bandwidth and computational resources has made possible the support of high-resolution displays and more natural human-computer interactions. It could be argued, as in Funkhouser and Li’s essay, that nowadays the main bottleneck in an interactive computer system lies in the link between computer and human, instead between computer components within the system [35]. In fact, the developments in increasing computer performance and display technology are followed by research that addresses the user interface issues. More capable display technologies have changed and will continue to change how users relate to and interact with information.

Viewing experience can be divided into four main categories, according to a study by Mayer [65].

The “**postage stamp experience**”, where the field of view is very constrained by the display, bandwidth, or scarcity of other resources. This experience can be linked to the recent development of smart watches, but also heads-up displays, or LED displays in public places or transportation, where display size or resolution are necessarily constrained by space or cost requirements. The even more recent prototypes of "rollable" paper-like displays show promise in making this kind of display experience truly pervasive [55].

The second is the "**television experience**": this kind of experience is ubiquitous nowadays and can be likened to the general experience of using a modern computer system using a traditional interface. It is, usually, also the more comfortable for interacting with the device in most common home or office scenarios, like sitting at a desk or on a couch, close to the display.

The "**theatrical experience**" offers a large field of view, which expects the viewers to use eye scan motion in order to appreciate the entire image. This kind of experience ranges from home large-screen TVs to de facto theaters or cinemas, and thus usually evokes a more emotional experience. Viewing is however still constrained by the frame size, i.e. it doesn't grow across the display or projectable surface.

At last, the "**immersive experience**" is obtained when the scope and resolution of the imagery allows the viewers to leave the center of their focus, discovering and examining details of the scene and its context, in an entirely captivating environment. This experience can be, for example, found in an *IMAX* movie theater and will be further discussed in Section 2.4.

As described, the most common display surface used in computing and in multimedia systems lacks the field of view to provide anything more than a "television experience". Based on data provided by Czerwinski et al., despite large displays getting increasingly affordable and available to consumers, commonly the display space available by users (i.e. the effective pixels composing the screen area they can use) covers less than 10% of their physical workspace area [24].

Trying to browse through the growing amount of useful information in our storage devices or on the Internet using the limited viewport of a standard monitor con be as frustrating as attempting to navigate and understand our physical surroundings based on a view restricted to 10% of its normal range [40]. It can be assumed that a conspicuous share of an user's working time is wasted in arranging her workspace, in order to fit it inside an undersized display. In contrast, large-scale displays are able to almost fully immerse their users in their workspace as if it were a computer-generated scenery, thus transforming the space in front of them into an interactive and, potentially, collaborative canvas.

Such large-format displays have traditionally been used for very specialized high-end applications. For instance intensive scientific visualizations, *Computer-Aided Design* (CAD) applications, professional flight simulators, or immersive gaming setups.

Recently the software and hardware required to build and drive large displays have seen a dramatic lowering of price, with a parallel rise in performance. As lower cost technologies are developed, both by research and commercial institutions, the usage of such large visualization systems will spread to become commonplace. Potentially, any surface will be able to transform into a display site with interactive capabilities.

In the previously cited work by Funkhouser and Li, the following prescient but realistic scenario is described:

> *I'm walking down the hall toward my office when I'm reminded that I'm late for a meeting with Mary to discuss the design of the students' center being built on campus. Unsure of the location of her office, I tap on the wall next to me and a large floorplan appears. After following a path displayed on the floor to guide me, I arrive at her office, and we begin to work. Mary and I view an immersive walkthrough of the design on her "smart wall", and I draw modifications with a virtual marker, whose strokes are recognized and used to manipulate the computer model...* [35]

A future like the one envisioned above no longer pertains only to science fiction tales, but is quickly becoming our forthcoming reality, where the promise of rich, dynamic, and interactive visual landscapes of information, entertainment, and art will be at hand.

The introduction of large displays in our workplace and home also draws attention to another, orthogonal issue: as very large-scale displays radically change how users relate to the space around them and how they can interact with digital information, new *User Experience* (UX) paradigms must be developed.

Input technology lags behind display output technology, and many traditional desktop user interfaces and interaction techniques (e.g. the established mouse-and-keyboard model, but also the modern touchscreen interfaces that still are subject to change and rethinking) become awkward or next to useless on very large surfaces.

The implications are twofold.

On one hand, traditional UI metaphors and operations cannot be directly mapped to larger displays: pulling down menus from a side of the screen makes no sense in a context where the screen sides are too far apart and clicking on icons equally may be impossible with any input method less precise than a mouse [32]. Moreover, many of our current interfaces and usage paradigms revolve around the assumption of a virtual workspace much larger than the small display that is showing information to the user, thus forcing her to devolve large part of her time to the management of the viewport. For instance, scrolling, panning, and multitouch pinch-to-zoom are UI gestures that have grown to be commonly used and accepted, but their presence is justified primarily by the need of adapting a small display to a larger workspace.

Secondarily, while large-scale interface facilitate collaboration among several users and natural interactivity, many input technologies—including touch—are only feasible (or economically sustainable for consumer-grade hardware) on small displays. On large displays, different technologies are required. For instance, machine vision can scale up to wall-sized display formats where other technologies cannot [73].

This kind of user interface evolution is the focus of ongoing development, with new interface paradigms that are being explored, taking the UX into radically new territories. How do users benefit from displays that provide space for 25% or more of their workspace? How do they cope with displays that cover entire room walls?

A field where large-scale visualization, both physical and digital, finds application is in the field of industrial design. An important factor in design is the collaborative nature of the design process, which—by its nature alone—requires the ability to work on designs interactively, to represent them faithfully at large scale, and to show them to others in order to receive feedback or approval.

As can be said for large displays in the automotive industry [15], most design work revolves around the need to sketch models or blueprints at a significant scale, which then become a powerful artifact that not only facilitates the creation process itself, but also enables informal discussion around a table, interactive modification, review, feedback, and ultimately business decision-taking.

Models at large scale are traditionally drawn on large sheets of paper in order to address the scale issue. But large-scale displays can fill the gap between size requirements and the demand for interactivity, while closing the distance between physical and digital tools.

Especially in this case, affordability issues meet the technological and interfacing issues mentioned above. As large-scale displays become more common, new ways to bridge the gap between computer and human must be explored.

2.2 Technological overview

Large high-resolution display technology is gaining increasing popularity, both in terms of consumers and in terms of new research efforts—also pushed partially by industry interests. These efforts are firmly invested in addressing the fundamental issues that affect and limit the adoption of large displays: making large-display setups technically possible, commercially viable and approachable for the mass market, functional, and enticing for end-users [35].

As shown before, there are as many benefits in using large displays than there are issues. Research in this area is very active and is progressing rapidly, both on the software and the hardware side. The first is bringing to the table novel UX paradigms, GUI toolkits and ways to make the usage of these tools advantageous to users. The latter is exploring ways to cope with the extraordinary requirements of a large display, which push the boundaries of what is possible or economically feasible.

Building large display surfaces can rely on a wide variety of hardware technologies with very different characteristics, advantages and drawbacks.

This section will give a brief overview of state of the art technologies.

2.2.1 Single large displays

Even less than a decade ago, a single display surface achieving 4K resolutions would have seemed impossible (albeit certainly foreseeable in retrospect). This is corroborated by Grudin, who gives evidence that the size of the standard monitor has increased slowly throughout the years, not-quite keeping pace with Moore's famed law and its expectations [40]. Already in 2005 Fitzmaurice and Kurtenbach also claimed that there were different affordable solutions in creating a large, high-resolution display—but using a single ultra-HD screen certainly wasn't one of them [32].

However, current consumer grade monitors are rapidly reaching such definition levels and will quickly outgrow them. Screens sold in common electronic shops not only reach very high pixel density, they also have become quite big in terms of size in the last years. It is not rare to see television sets spanning more than 60 inches, and prices of such screens are rapidly becoming more affordable.

Even if other technologies, like tiled displays or projector arrays, provide more affordable, more capable or even the only *feasible* solutions in some cases, the possibility of using a single large display cannot be ignored nowadays.

Dedicated monitors reaching 80 or even 100 inches in diagonal exist and, even if not cheaply, are available to consumers. Single screen large displays avoid the need for complex software and configurations, since they work exactly like any other monitor. Not only that: dedicated solutions like the Surface Hub (see Figure 2.1) exist, which provide a tailored user experience with special input methods and dedicated applications, running on an 84' screen [69].

Custom hardware can also be used for large-scale ad-hoc installations, which can address very particular needs. For instance, in Las Vegas (USA), Beijing (CN), and Suzhou (CN), three Sky Screen installations have been specifically created to provide a huge display surface hovering above streets in large shopping malls. These screens are custom built using LED strips, chained together in order to form a screen of over 350 meters in length and 16 meters in width, as shown in Figure 2.2 [29]. In this case however,

Figure 2.1: Promotional image showing a Microsoft Surface Hub. (© Microsoft.)

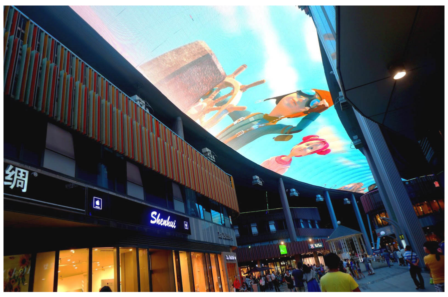


Figure 2.2: Picture of the Sky Screen, located in Suzhou, China. (© Electrosonic.)

both hardware and software will be heavily tailored to the target scenario and all advantages listed above are not applicable.

2.2.2 Multi-monitor desktops

For over a quarter of a century it has been possible to take advantage of multiple monitors on a consumer-grade personal computer. One of the first machines supporting dual monitors was the Classic Macintosh released in 1989. Thanks to the presence of a single expansion slot, the Macintosh could host an additional display adapter (which supported color output, in contrast to the built-in monochrome monitor). Later Microsoft Windows 98 also added software support for multiple monitors [40]. Technology continues to reduce challenges to setting up multiple monitors: high-resolution multiheaded graphics cards have become affordable for the mass market and are a viable alternative to mid-sized display walls for some scenarios [32].

Specialized application environments, such as *Computer-Aided Design* (CAD), day trading at stock markets, software development, accounting or multimedia editing, are increasingly using multiple monitor workstations. Especially in investment banking or similar work environments, where large amounts of data must be kept under control and the worker must be able to quickly cross-reference certain entries, it is not uncommon to see six or more monitors used at the same desk. Also, digital video or audio editing workstations often rely on multi-monitor configurations to increase the available area for the user interface [7, 84].

Multi-monitor use has several noteworthy advantages against other technologies presented here: it easily provides for more screen real estate, it is relatively inexpensive—two standard monitors usually cost less than one very large monitor—, and configuration has become easier thanks to better software support.

There are drawbacks as well. Multiple monitors take up more desk space of course, and can be unwieldy to configure in constrained rooms. The total screen space can be split between many, heterogeneous displays, which can make for an inconsistent work area. Better software support notwithstanding, managing a multiple monitor configuration can be troublesome for users, especially when using multimedia applications that were not designed with multi-monitor setups in mind.

As argued by Leigh et al., there mainly are two trends that have made multiple monitors approachable for general consumers [57].

Firstly, the introduction of flat panels, *Liquid-Crystal Displays* (LCDs) or based on *Organic Light-Emitting Diodes* (OLED). Though early LCD models had large screen borders, the vast difference in volume and weight with traditional *Cathode Ray Tube* (CRT) monitors makes the usage of many monitors much more practicable.

Secondarily, component parallelization in mainstream computers: while the race to higher frequencies has in a way stopped in today's computer industry, processing units have instead become increasingly parallel. A common laptop available in 2015 has as many as 4 cores (with 8 hardware threads), while workstations can sport even even better multi-core technology. Graphical processing units in particular employ a massively parallel computing architecture. The role of yesterday's cluster is being taken over by today's workstation, with large amounts of memory, processing power and the capability of driving a large number of displays.

Several hardware solutions are already available in the mass market. Most current graphical adapters support at least 2 displays, while many *pro-sumer* or professional-grade adapters may support even more[1]. Latest Intel Skylake processors feature GPUs capable of driving up to 5 displays over HDMI. Even adapters *not* supporting more than one output display, can be used in multi-monitor setups using hardware modules that disguise two or more monitors as a single larger display[2].

2.2.3 Tiled displays

In some way an evolution of multi-monitor configurations seen before, "tiled displays" are large displays built by joining many flat screen panels into a single wall-like surface. By keeping the panels as close as possible, and by using special panels with very small borders, the impression for users is that of one homogeneous screen. An example is shown in Figure 2.3. Displays built in this fashion are also known as *Single Large Surface* displays (SLS).

The innovation in flat panel technology has expanded the design space, having taken over both as desktop monitors and consumer high-definition TV sets. Current LCD panels work reliably for tens of thousands of hours, are easy to calibrate and present a homogeneous picture to the viewer.

[1]AMD adapters supporting *AMD Eyefinity* can theoretically support up to 6 displays. NVIDIA Quadro adapters supporting *NVIDIA Mosaic* can run up to 4 displays.

[2]Matrox DualHead2Go and TripleHead2Go: `http://www.matrox.com/graphics/en/products/gxm/dh2go/digital_se/`

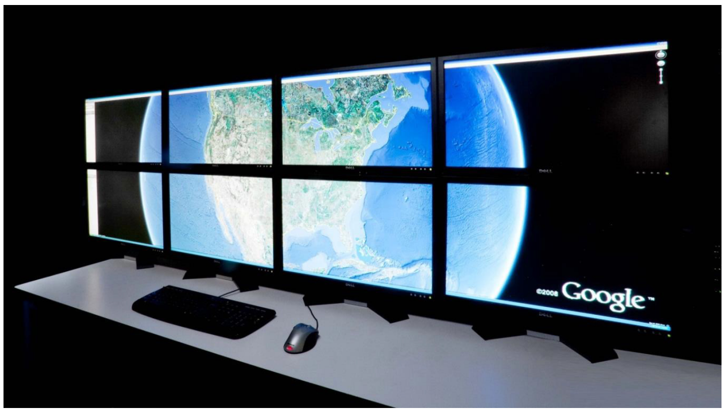


Figure 2.3: Sample NVIDIA Mosaic setup with 8 monitors and one single unified desktop, showing an almost seamless image. (© NVIDIA Corporation.)

They are also easily aligned in terms of color and geometry, and require little space, thus being very easy to mount into tiles arrays.

The most notable disadvantage of flat panels is given by their borders. So-called "bezel issues" are deemed to be quite problematic for end-users, particularly when displaying textual information which, when occluded by a bezel, tends to be very difficult to read. Effects of bezels breaking up the continuity of the large display has been examined in depth by several studies [61, 98], along with other usability issues [23, 5, 46].

The analysis by Ball and North underlines that—while some users are able to use bezels very efficiently to their advantage to align, segregate and differentiate applications—they are more often a distraction. The bezels around tiled monitors are in fact usually one of the first things that people notice. Interviews with users indicate that bezels are a source of inconvenience, irritation and frustration. They can distort documents or produce artificial image lengthening, resulting in confusion [5].

While the effects of bezels can be somewhat mitigated by software (for instance with UI techniques for creating *seam-aware* applications as seen in the work of Mackinlay and Heer [61]), the issue can only be avoided by using flat panels with no visible borders.

Starting around 2010, several LCD display manufacturers (e.g. NEC and Samsung) have introduced monitors with very small borders (as low as 2.5 mm from one display to the next). These panels, often referred to commercially as "seamless" or "near-seamless" displays, while still very expensive, provided the first opportunity to build a nearly bezel-less SLS. Some manufacturers have also introduced technologies improving their monitors for display wall installations, for instance *Frame Comp* by NEC synchronizes video output across monitors composing a wall, thus reducing tearing of animated images and further enhancing the illusion of one single video wall.

Other manufacturers specialized in video wall equipment have resort to slightly distorting lenses wedged between monitors, that optically extend the image surface above the bezel and thus creating a fully covered SLS with minimal distortion[3]. Projection-based displays (also known as retro-projected monitors) also come very close to seamless tiling. However, this technology presents other issues: for instance, higher maintenance cost, reduced clarity and brightness of the projected picture, larger space requirements, and higher price relative to flat panels. [57].

The combined pixel count of a tiled display video wall can reach up into the 100 million pixel range. Several live installations of high resolution walls have been created in the last decade, some of which are listed in the survey by Ni et al. [75]. For example, the *LambdaVision* display, developed at the *Electronic Visualization Laboratory* at the University of Illinois (EVL-UIC), uses 55 LCD with 1600 $\times$ 1200 pixels each, for a total of 17600 pixels by 6000—i.e., a resolution of 100 megapixels [80]. NASA has developed a wall, known as the *Hyperwall*, built using 49 LCD panels tiled in a7 $\times$ 7 array for specialized visualizations and interactive exploration of multidimensional data [87].

However, also creating more modest tiled displays is now both technically approachable and relatively affordable: a display wall composed of one PC with two graphic adapters and four tiles monitors is a viable and robust approach for many smaller scale scenarios [32]. Because of the growing component parallelization in mainstream computers, it can be practical to build even large high-resolution walls driven by a single computer, as seen in the overview by Leigh et al..

One such example is the *Cyber Commons* wall at EVL, an 18 megapixel display designed for science and education built around 18 near-seamless LCD panels and driven by one single PC with three graphical adapters [57].

2.2.4 Multi-projector arrays

A large array of tiled LCD screens has the potential to create a very large high resolution video wall, and also has an advantage of configuration and

[3]For instance, *Pallas LCD* proposes commercial solutions for very large seamless video walls: `http://www.pallaslcd.com`.

alignment simplicity. However, in terms of constructing displays on very wide surfaces, they are not very cost-effective: the most affordable solution still remains an array of front projectors, configured in order to simulate one uniform display space.

While not exactly inexpensive—projectors are still expensive and have a very high maintenance cost, with high-performance lamps that have lifespans counted in mere thousands of hours—the ratio of price against covered surface is strongly tilted in favor of projectors. They offer what flat panels cannot: a separation between the size of the device and the size of the projected image, i.e. a small projector can indeed be used to create a very large—or a very small—image. The possible range of image size is limited only by the lumen output of the projector, its resolution, and the optical capabilities of its lens. Also, multi-projector arrays are quite more versatile than their flat panel counterparts: they are easier to move, to reconfigure, to adapt to existing structures and require less hardware for the same area of covered wall. They also lack of bezels, making it possible to create a really seamless image when tiled together.

On the other hand, projectors require very dark rooms in order to appear at sufficient brightness, and thus need to be used in controlled scenarios. Also, while relatively easy to setup singularly, projectors require painstakingly precise alignment in order to simulate one contiguous display space. This process requires specialized software and, in some cases, equipment to be done even for small setups. Projectors can also be quite noisy, almost always requiring fans for active cooling. This can, to an extent, disrupt the large-display experience.

Research has been aimed at gradually perfecting projector technology and techniques in setting up tiled display walls, improving color gamut matching of the projected images [102], seams [96], misalignment between projectors [45, 18], luminance matching [62], and image blending [44].

Video walls based on projector arrays have been used proficiently for very large surfaces. For instance, as described by Wallace et al., the "Princeton scalable display wall project" scaled up its original setup to 24 *Digital Light Processing* (DLP) projectors, running on a custom built cluster of computers and distributed components. In order to configure, align and manage such a system, custom-built software was used—including a custom-built video decoder capable of handling the high bandwidth data presented on the screen [103]. In another research project conducted by Starkweather, the projection system *DSHARP* was built, using 3 low-distortion projectors on a surface curved at 90° and with an aspect ratio of 4 to 1, in order to achieve a truly immersive experience centered around the viewer [94]. Bishop and Welch instead created a simple desktop environment using projectors on the wall, in order to alleviate bezel and ergonomic issues, attempting to get the feel of the "office of real soon" [10].

Moreover, several kinds of commercial high-resolution tiled projector walls exist and are used in production. For instance the scalable *VisWall* solution by VisBox[4].

2.2.5 Stereoscopic displays

Stereoscopic displays show two sets of pixels for an image, making one set visible to the user's left eye and the other to the right eye. Typically the user is required to wear special glasses or viewing aids to notice the 3D effects. This kind of technology is risen to vast diffusion thanks to 3D cinemas, where stereoscopic movies are projected usually with the aid of polarized viewing glasses. Recent developments introduced *autostereoscopic* displays, which eliminate the need for special glasses or other aids.

When applied to large-scale displays, these technologies have been successfully applied to high-resolution stereoscopic video walls, like the autostereoscopic display *Varrier*, which involves a curved LCD tiled display with a parallax barrier affixed in front [86]. Liao et al. also have developed a high-resolution display using 33 projectors, capable of generating geometrically accurate autostereoscopic images, and reproducing motion parallax in 3D space [58].

2.3 Usability

Effects on productivity and usability issues of larger display surfaces are hard to gauge, but can be likened to the ones given by multiple monitor workstations. According to a survey (dated 2005) mentioned by Robertson et al. [82], as many as 20% of "information workers" using Microsoft Windows operating systems routinely run multiple monitors on a workstation or on a laptop. Most users, while possibly not using such a setup because of space issues or pricing, are at least aware of the possibility to do so.

[4]`http://www.visbox.com/products/tiled/viswall/`

2.3.1 Benefits

Grudin gave an overview of the usage patterns of multiple monitor users, such as CAD/CAM designers and programmers, air traffic controllers, and factory production managers. Despite the limitations of large-scale displays on the workplace, chiefly due to the presence of bezels between single monitors and scarce support from the operating systems used, multi-monitor setups are clearly loved by their users. In fact, most users claim "*they would never go back to a single monitor*" [40]. These findings are supported by other studies [82, 23, 5] that show significant performance benefits and satisfaction preference for large displays on the workplace.

It is also interesting to note that traditional multi monitor setups require the users to adapt their workflow and their application layouts to the number, size and orientation of their displays. In particular, additional monitors are not considered "additional space" by default: application activities, including ones that deal with large complex graphical objects, are rarely extended on multiple screens. Instead, monitors are used as a "space partitioning" method, consciously dividing primary task from secondary ones [40]. Secondary tasks may include communication channels and "live" information channels that are less disruptive when confined to the user's peripheral awareness. In the study of Ball and North it was shown that users tend to develop a certain preference in positioning applications, relying on their spatial memory abilities in order to dedicate regions of the screens to specific activities. In particular it was observed that the application with the user's main focus was usually positioned in front, while supporting tasks (like email clients, calendars or instant messaging applications) tended to be moved toward the periphery. Users are shown to naturally categorize applications when they have more available screen estate [5].

Notwithstanding the preference that users show for the partitioning of tasks, usually a multiple-monitor setup is considered to be inferior to a single-display setup with a comparable increase in total screen size. In Grudin's work the metaphor of a multi-room house is used to explain how people generally value *large* rooms and *more* rooms in different ways [40]. In a house, multiple rooms can facilitate logical separation and usage diversity. Similarly, tasks of different type can be logically subdivided onto multiple screens according to their priority or requirements. Tasks of lesser importance can be "parked" out to secondary surfaces. Using the same house analogy, as larger rooms are more likely to be used as a shared physical space, large-scale displays also are more suited as shared work surfaces or interactive multi-user environments.

In both cases, the increase in display surface allows the user to take advantage of peripheral awareness. As large displays become more common, it is getting easier to arrange the workspace in order to have instant access to a given resource knowing its location based only on peripheral vision. Recent monitors, as the one seen in Figure 2.4, are designed with a curved surface that supports this particular use-case. However, software has difficulty sensing where the user's attention is focus, therefore manual interaction is needed in order to successfully partition space. Like a one-room house, single monitors usually do not provide structural support that help the user in arranging tasks and windows. Instead, multiple-monitor setups intrinsically simplify space partitioning for their users.

Studies have demonstrated that there is a significant performance benefit to be found in using very large display surfaces, be it with multiple monitors or one large display. This advantage is particularly evident while carrying out complex and cognitively loaded productivity tasks or when navigating 3D virtual worlds, where users rely on optical flow cues that are easier to gather and process given a wider field of view. As Tan et al. demonstrated, while large displays increase performance for all users on

Figure 2.4: Large curved monitors, like the Samsung UN65H8000, are meant to exploit peripheral vision and enable a more immersive experience for the viewer. (© Samsung.)

average, female users improve so much that the disadvantage they usually have in virtual 3D navigation disappears completely [99].

Although these benefits may sound self-evident, it can be argued they are less obvious in light of the fact that current graphical interfaces are not optimally designed for very large surfaces [23]. Therefore, an even larger performance advantage could be expected by a tailored experience, specifically designed to exploit the capabilities of large-scale displays.

2.3.2 Issues

While the aforementioned studies demonstrate the benefits of using large displays, there are several serious usability issues that impact the user's experience, especially due to how current software behaves on very large surfaces and—as mentioned previously—because of unrefined UI paradigms still bound to small screen surfaces.

Desktop workstations are often used with multiple monitor configurations with visible seams between screens, because of the bezels found around consumer-grade monitors. Wall-sized displays instead offer seamless display surfaces using large or multiple projectors. However, most of the following usability issues are relevant for both approaches, while additional challenges can be given by the seams in multiple monitor configurations.

Formal laboratory studies [82, 47, 5] have been performed by observing real multi-monitor users in the field and gathering data from in-depth logging tools. Window management activities (like the number of opened windows and the frequency of window activations or movements) were logged in order to detect patterns for different sized displays. The analysis of real-world data discloses the following main friction points for large-scale display users:

Input method friction As mentioned before, traditional input methods are not very well suited for large displays and thus can rapidly become unwieldy to use. For instance, using a standard mouse and keyboard interface, it is easy to lose track of the pointer's position or the window which has keyboard focus.

Distal access to information Distance between users and the screen negatively influences the amount of time required to access information and UI elements needed for interaction. Also, if information is represented more sparsely on a large screen, acquiring the same amount of information may require more time and more cognitive effort.

Window management Standard UI widgets like windows of a standard operating system GUI are not designed to work well on very large surfaces. Windows, dialogs, pop-ups, and notifications are created with the constraints of a standard display in mind and may pop up in unexpected places, which makes them more prone to go unnoticed or harder to reach. Also, window management is made more complex on a multi-monitor setup, since users will try to move windows in order to avoid monitor bezels and distortions.

Task management As screen size increases, the number of windows and active tasks also may increase. This may especially be the case in a multi-user collaboration scenario. Better task management and multi-tasking support is required to handle this workload and, eventually, multiple concurrent input devices on different areas of the display. An approach to supporting multi-user input on large tiled displays has been proposed by Lou et al., for instance [59].

Configuration issues Multiple monitor or large scale setups entail a higher complexity in terms of configuration and maintenance. Setting up a system based on multiple projectors requires very precise alignment, color correction and hardware that may be difficult to configure. Also multi-monitor systems, while easier to align, are often configured through interfaces which are overly complex and hard to use. Operating system support for multiple output surfaces is rather poor as well, which is reflected in difficult use of applications, unreliable configuration and poor support for heterogeneous setups (like monitors with different pixel densities).

Insufficient software support The move from small scale to large scale displays exposes the lack of support by software applications. Programs written for small scale user experiences have a hard time adapting to the larger displays and sport interaction paradigms that often actively hinder the user in completing her task. For instance, simply maximizing browsing or text editing applications on very large surfaces make the information harder to find (even if it is visible) and move interactive UI controls such as buttons to the edges of the visible surface. Games or multimedia playback software may also work in ways that are difficult to predict. Even if users are initially excited by the prospect of playing games or watching movies on large surfaces, the experience can easily become disappointing [5].

Failure to leverage periphery Large displays sport a true "visual periphery", inasmuch that parts of the output are located far from the center focus of the user. This feature should be leveraged for better peripheral awareness in support of the user's primary task, for instance providing accessory information, context or notifications in a manner that is both supportive and non-invasive. (Benefits of peripheral awareness are mentioned before at page 34.) Failure to do so may provide for an underwhelming user experience.

Wasted space As shown in the analysis by Ball and North, as there is more space, more of it is wasted. Users are rarely able to use all the space available, because some parts of the image are out of the view field or uncomfortable to view. In comparison to workflows with one monitor, while the work process may be more efficient, the usage of display space is actually *less* efficient due to them being used only to a lesser degree most of the time (typically only about 50-60% at a time) [5].

Physical size An obvious, but unavoidable, issue of large-scale displays is their cumbersome physical size. In fact, most very-large-display setups would not fit in any standard office, thus requiring special provisioning and complicated installations. There is also potential for additional physical stress: if using a traditional keyboard and mouse input system for extended period of time can cause problems [14, 3], it can be assumed that their use with a large display may also cause discomfort or pain to the neck or the back. More research in large display ergonomics is needed in order to asses how their usage impacts user comfort.

Privacy issues When your computer screen takes up most part of the wall there isn't much privacy to be had. As reported in some office experiments with large screens, this usually is not a fundamental issue, but has to be taken in account when working with sensitive information [10].

2.4 Immersive visualization

So far, advantages and applications of large-scale visualizations have been presented, in terms that are close to the traditional computing model we are used to. However, a true computing model paradigm shift is required when discussing *Virtual Reality* (VR).

In a nutshell, VR replicates an environment that simulates the physical presence of the user, allowing her to interact with said world. The perception of this virtual world is created by surrounding the user in artificial sensorial experiences, including sight, hearing, touch, and smell.

In this context, *immersion* stands for the metaphoric submersion of the user into the virtual experience. The concept appears somewhat opaque and vague, but it can be summed up as the process "*characterized by diminishing critical distance to what is shown and increasing emotional involvement in what is happening*" [39].

While, as stated by Schuemie et al., a thorough understanding of the reason why VR is effective and what effect it has on the human psyche is still missing, most research on the psychological aspects of VR is also related to the concepts and the definition of *presence* and *immersion* [88].

Several definitions of *presence* have been proposed in literature. Even if none has really stuck, most often the concept can be intuitively described as such: people are considered to be "present" in an immersive VR when they subjectively report the sensation of being in the virtual world. An important distinction on this point is proposed by Slater and Wilbur: in this case *immersion* is an objective description of technical aspects of the VR (such as field of view or display resolution), while *presence* is a subjective phenomenon such as the sensation of being in a virtual environment [91].

Theories on *presence* are also debated and far from conclusive as well. Slater et al., for instance, stress that an user's sense of "being there" is somehow exclusive, and thus that a high sense of presence in a virtual environment implies a simultaneous low level of presence in the real world [92]. Biocca also states that users of VR constantly oscillate between feeling physically present in one of three places: the physical environment, the virtual environment, or the imaginal environment [9].

As mentioned before, there is no conclusive research on the relationship between *presence* and emotional responses caused by VR, as there is no unitary and clear definition of the concept in itself. However, it can be argued that the point of any virtual environment is to ensure that the user's awareness of her physical self is transformed or influenced by the artificial environment. An immersed user reaches partial or complete suspension of disbelief, and feels part of another world at least in a fraction of her consciousness.

It is interesting to note, as Grau brings to our attention in “Virtual Art: from illusion to immersion”, that the idea of installing an observer into a closed-off space of illusion—like in modern VR systems—is not an invention bound to computer-aided visualization. The idea seems to go back to the classical world, throughout art history, starting from the cult frescoes of the *Villa dei Misteri* in Pompeii, to the many illusion spaces of the Renaissance, such as the *Sala delle Prospettive* in Rome. Before the electronic virtual environment, there were successful attempts to create illusionist image spaces using traditional images and *trompe-l'œil* [39].

In his survey on immersive displays, Lantz states that immersive reality systems generally fall within three categories: *small-scale* displays for single users, *medium-scale* displays designed for a small amount of collaborative users, and *large-scale* displays intended for group immersion experiences [54].

These three categories will be taken under exam in the next sections.

2.4.1 Small-scale displays

The small-scale virtual reality display category is mainly divided into head-mounted displays and stereoscopic displays for desktop monitors. While stereoscopic displays have found good application in consumer grade electronics, latest research and industry developments are focused in bringing virtual reality headsets to consumers.

The Oculus Rift virtual reality head-mounted display has been in development since at least 2011. After a series of prototypes, the first Rift development kits were produced thanks to a very successful crowdfunding campaign on Kickstarter by Oculus VR. In 2014 the second development kit version started shipping, while the consumer version was announced to be released in the first quarter of 2016.

The headset, shown in Figure 2.5, will feature two OLED panels for each eye, with a resolution of 1080×1200 pixels each and a refreshing rate of 90 Hz. The system sports a sophisticated head-tracking system, called *Constellation*, which tracks the position of the user's head with millimetric precision.

Technically, the Rift works just like an old-fashioned optical stereoscope,

Figure 2.5: Promotional image of the Rift virtual reality headset by Oculus VR.
(© Oculus VR.)

presenting two different stereoscopic images to each eye. The Oculus SDK allows developers to write applications for the headset or to adapt existing applications, like 3D games.

Some technical issues, especially in terms of performance, are given by the need of rendering the whole 3D scene twice (once for the left eye, once for the right eye) for each frame, at a very high frame rate and a relatively dense resolution. Other issues are related to having to present the image tear-free and with very low delay against user input, to reduce motion sickness and create immersion.

A similar, but simpler, solution is represented by the Google Cardboard project[5]. The same VR of Oculus Rift is used, but instead of custom and expensive hardware, a simple Android-based smartphone is used as display.

The smartphone is set into a cardboard box provided with two openings and two lenses. The vision of the user is projected onto the smartphone's screen, which will present two stereoscopic images just like the Rift.

The solution by Google promises very low cost and very easy setup for a basic VR experience, trading it off against a generally lower video quality, far less immersion and no head-tracking system.

HoloLens, another similar device is planned for release by Microsoft in the next period. The device, which is shown in Figure 2.6, directly includes the computing hardware and a set of dedicated components that are able to detect the user's view and to superimpose 3D imagery on top of the

[5]`https://www.google.com/get/cardboard/`

user's real vision.

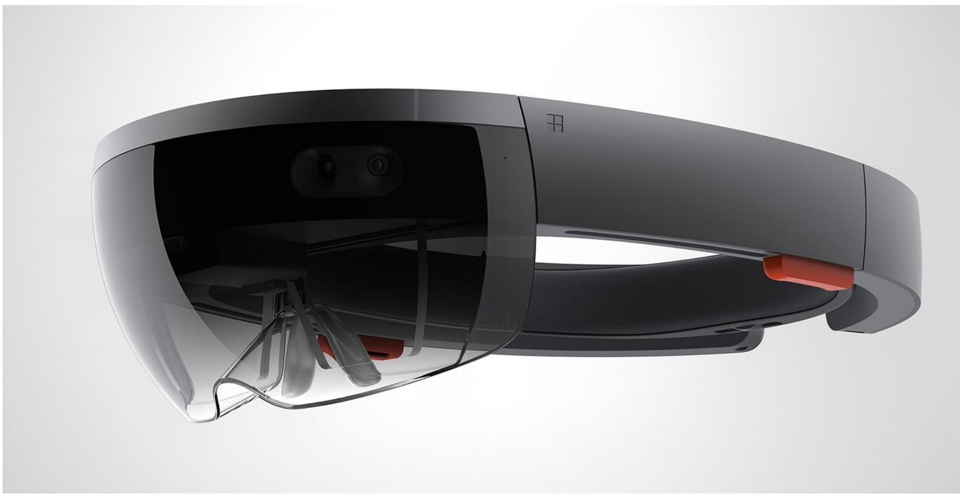


Figure 2.6: Promotional image of the Microsoft HoloLens headset.

(© Microsoft.)

2.4.2 Medium-scale displays

This category of immersive displays presents itself as room-sized VR systems, allowing single users or groups of users to collaboratively share the space and immerse themselves into the virtual environment [101].

A *Cave Automatic Virtual Environment* (CAVE) is one among the best known room-sized virtual reality systems to gain widespread adoption. It was proposed first in 1992 by Cruz-Neira et al. as a new virtual interface, consisting of a single room whose walls, ceiling and floor surround a single viewer with projected images of a virtual reality scenario [21]. A schematic view of the proposed system is shown in Figure 2.7. Suspension of disbelief and viewer-centric perspective (i.e., the capability of tracking the viewer and adapting the visualization to their position), other than the possibility of building the CAVE using only currently available technology, were the main selling points of the system.

A typical CAVE system arranges four 3 $\times$3 m screens in a cube, whose walls and ceiling are made up of rear-projection screens or flat panel displays, while the floor can be handled by a front-projector installed on the ceiling and pointing down [22]. Five-wall [108] and six-wall configurations [83] exist as well, but they require special screens that can support the weight of users and/or movable screens to enable entry into the facility. Collectively, all screens display a single image, representing the virtual environment.

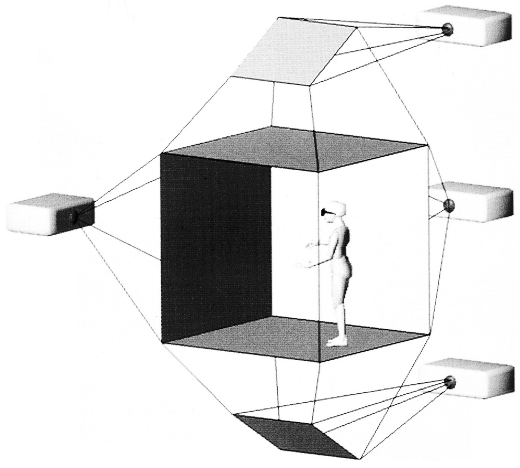


Figure 2.7: Schematic projection view of a CAVE installation.
Reprinted from "The CAVE: audio visual experience automatic virtual environment", by C. Cruz-Neira, D. J. Sandin, T. A. DeFanti, R. V. Kenyon and J. C. Hart, 1992, in *Communications of the ACM, Vol. 35*. Copyright 1992 by ACM.

In order to simulate viewer-centered perspective, the CAVE also has the capability of tracking the user's position inside the room and their viewing orientation. This is usually done using a dedicated 3D tracking sensor that is worn by the user during operation. The visualization is adapted in real-time by using a perspective projections on the rendered images.

Although multiple people can be in a CAVE at a time, the system only tracks the viewpoint of one viewer and the displayed image is truly correct only from that viewer's point of view. Since the viewer is effectively *inside* the scene being displayed, and the scene reacts to her movements, she experiences a greater sense of presence and immersion [15].

Changes, additions and a future roadmap for the original CAVE have been proposed by DeFanti et al., also documenting the improvements that have been already implemented over the course of two decades, mainly because commercialization and the availability of better hardware and software [26].

Several evolutions of the CAVE have also been presented in the same work, like the NexCAVE installation hosted by the *King Abdullah University of Science and Technology* (KAUST) at its *Visualization Core Lab* in Thuwal, Saudi Arabia[6]. The NexCAVE consists of 21-tiled displays (arranged in a

[6]`https://kvl.kaust.edu.sa/Pages/Showcase.aspx`

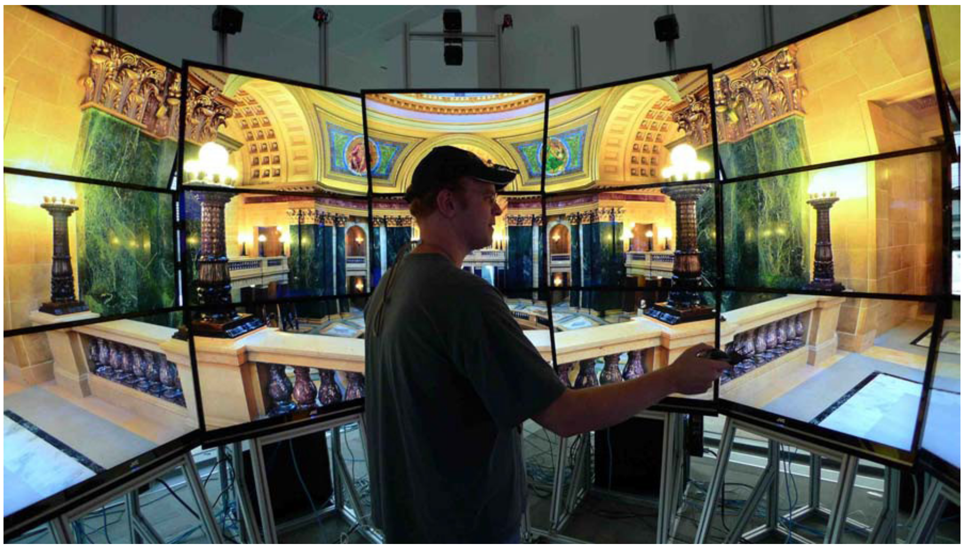


Figure 2.8: A *CAVE* installation using LCD screens in a curved configuration.

(© AESOP Laboratories.)

3 × 7 configuration), where the top and bottom rows are slightly tilted inward, toward the viewer, as shown in Figure 2.8.

2.4.3 Large-scale displays

Large-scale displays employ wide field of view screens, such as wrap-around cylindrical or dome screens, to provide a high sense of immersion for a substantial number of viewers. Such displays, other than a large surface, also provide a seamless appearance from almost all viewing angles.

The development of large-scale displays has been driven largely by innovations in digital projection techniques and commercial interest invested in proprietary technologies, states Lantz in his survey [54]. While there exist a wide range of large-scale displays, used for planetariums, science centers and universities, this kind of displays is usually the domain of *Cinerama* or *IMAX* large-format film cinemas.

Typically, dome display sizes range from small diameters (3 m) to the largest (27 m). On a standard dome, a 100 million pixel projected image would be necessary to display at eye-limited resolutions. In practice, projections with less than one million pixels can be used, while cinematic quality projections require at least a resolution of 6-8 million pixels. Most projection systems rely on one or two projectors, using a fisheye lens.

Chapter 3

Scalable Adaptive Graphics Environment

The *Scalable Adaptive Graphics Environment* (SAGE) is a cross-platform, community-driven, open-source middleware for flexible graphics streaming systems. It was originally conceived in 2004, at the *Electronic Visualization Laboratory* (EVL) of the University of Illinois at Chicago (UIC).

As the official project description states:

> SAGE provides a common environment, or *framework*, enabling its users to access, display and share a variety of data-intensive information, in a variety of resolutions and formats, from multiple sources, on tiled display walls of arbitrary size.[1]

SAGE is meant to enable teams of users, not only local but also distributed and dislocated, to share and inspect data on an interactive large-display visualization. In fact, it allows its users to make use of an entire room as if it were one seamless canvas. Information, visualizations and animations can be displayed through SAGE and manipulated directly by any participating user. As described by Renambot et al., the primary aim of the software is to aid scientific research and education, by enabling easy group collaboration on large datasets, which benefit from big-scale visualizations [79]. Users are thus aided to come to conclusions with greater speed, accuracy, comprehensiveness and confidence.

At its basis, the framework provides the means to compose multiple heterogeneous visualization applications, seamlessly and in real-time, on a

[1]Official web-site: `http://sage.sagecommons.org/`.

very large display. SAGE handles both the system's graphical output and the input provided by users. Its decoupled architecture, which is explored in more detail in the next section, allows rendering applications to take full advantage of the processing power of the platform they were developed for, without forcing them to be constrained or redesigned for a specific graphic environment. At the same time, this feature ensures compatibility with a large number of data sources in a variety of resolutions and formats.

Supported applications range from digital animations and video, high resolution images, high definition teleconferences with video streaming, presentations, document viewing and editing, spreadsheets, or live screencasts from common operating systems.

These applications may be running on any hardware system, for instance consumer-grade laptops, workstations, or high-performance rendering clusters. Potentially, applications can also run on remote rendering systems connected to SAGE through any *Wide Area Network* (WAN), including the Internet.

Data generated by these applications is streamed over a high-bandwidth network and displayed on collaborative graphical end-points. These graphical surfaces may also range widely in type, surface area, and resolution. In fact, practically every display technology presented in Section 2.2 is supported and can be used proficiently with SAGE. Each graphical end-point can thus efficiently visualize data from multiple sources and provide the means to interact with it.

The opportunity to develop visualization middleware based on massive data streaming, was made possible by the initial developments of the *OptIPuter*, as described by Smarr et al., and the exponential improvement in network bandwidth [93]. Over the past decade, in fact, network capacity grew from hundreds of megabits per second to over 10 gigabits per second, with a growth rate outpacing that of storage capacity and computing power. It is outlined by Leigh et al. that the capability of bridging high-performance systems with ultra-high-capacity networks (which in some cases approach the capacity of computer system buses), is the fundamental premise behind the concept of this and many similar infrastructure technologies [56].

After the initial work on SAGE in 2004, the project was continued with support from the US *National Science Foundation* (NSF) in 2009 and has been further developed until in 2014. The original SAGE project was then superseded by a ground-up rewrite of the entire software stack, now based on new and emerging technologies, in what would become SAGE2. This evo-

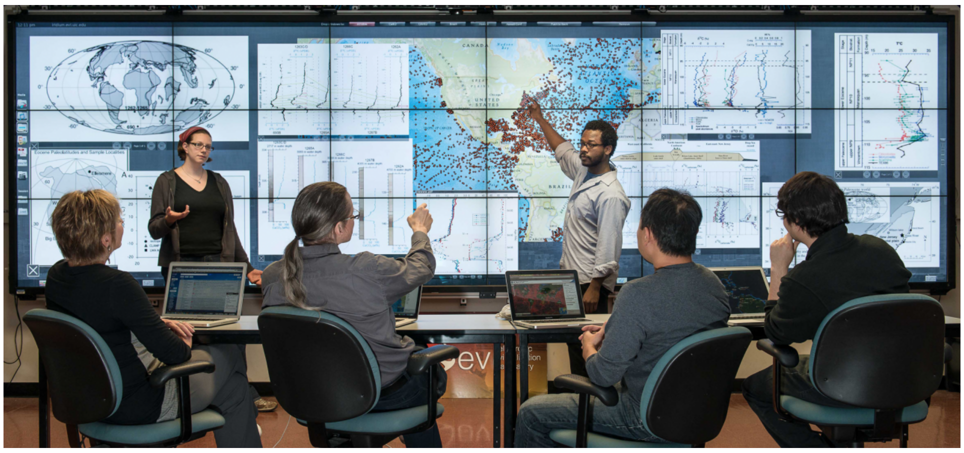


Figure 3.1: Sample SAGE use-case as a collaboration screen with local and remote screen-sharing. (© EVL-UIC.)

lution of the project is discussed in further detail in Section 5.1 at page 112.

SAGE has been successfully put to use in several real-world installations, including the *CAVE* [26], the *OptIPuter* [93] and the *LambdaVision* at the *Electronic Visualization Laboratory*, University of Illinois at Chicago (EVL-UCI) [80]. The software has been helping over 100 major industry and research institutions in the world to visualize a large variety of data on their display walls. Multi-user interactions and collaborative scenarios using SAGE have been described and evaluated in detail in the work by Jagodic et al. [49].

3.1 Architecture

SAGE is designed following a flexible and scalable architecture, allowing multiple applications and video sources to be streamed to a variety of displays, without requiring any special hardware.

All components (seen in detail in Section 3.1.2) are written using the C++ language and have dependencies on several commonly used software libraries—primarily *Simple DirectMedia Layer* (SDL), *X Server*, the Qt application framework, OpenGL and the *OpenGL Utility Toolkit* (GLUT), among others. The whole software stack is portable and can run on most GNU/Linux distributions, Apple Mac OS X and Microsoft Windows. However, SAGE is most easily installed and used on most recent GNU/Linux distributions.

SAGE has been designed based on a very decoupled architecture. A running SAGE installation is in fact composed of several independent processes running on, possibly, several different workstations.

This architecture makes SAGE quite modular and resilient, in the sense that parts can be added and can fail without having great impact on the rest of the system. This also allows a SAGE installation to be quite extensible, since more modules can be added almost linearly. There are however non negligible performance implications, which are taken into exam in Section 3.5.

While extensible in principle, installing and managing a SAGE configuration can be quite cumbersome when spanning multiple workstations—which is almost unavoidable with larger display surfaces or complex topologies. The system is based on multiple processes distributed on multiple machines, which are prone to be configured in different ways or to fail to synchronize their state.

The overall architecture of SAGE is depicted in Figure 3.2. Front and center the *Free Space Manager* (FSM) can be seen, controlling the other components through SAGE messages and, at the same time, controlled by an UI client. Applications generate pixel streams that pass through SAIL, a software layer, then through the receivers and finally reach the tiled display. All components are interconnected through a high-speed network. The following sections will give an in-depth overview of the structure and composition of a SAGE-based system.

3.1.1 Frame buffer and tiling

The SAGE system is built around the concept of a single "**scalable virtual frame buffer**". A frame buffer is rectangular in shape, and has a virtual screen size measured in physical pixels. There are no set constraints on its effective size.

The surface is further split up into multiple "logical tiles", that is, rectangular regions that take up non-overlapping parts of the frame buffer. Its total area must also be fully covered by the tiles—that is, the tiles must be a partition of the whole frame buffer.

Usually the frame buffer is tiled logically according to the system's configuration, i.e., in order to match the actual hardware topology. Each tile corresponds to a component of the SAGE installation, for instance an independent computer or an independent process running on a shared workstation, able to graphically manage that particular frame buffer region and to draw on it.

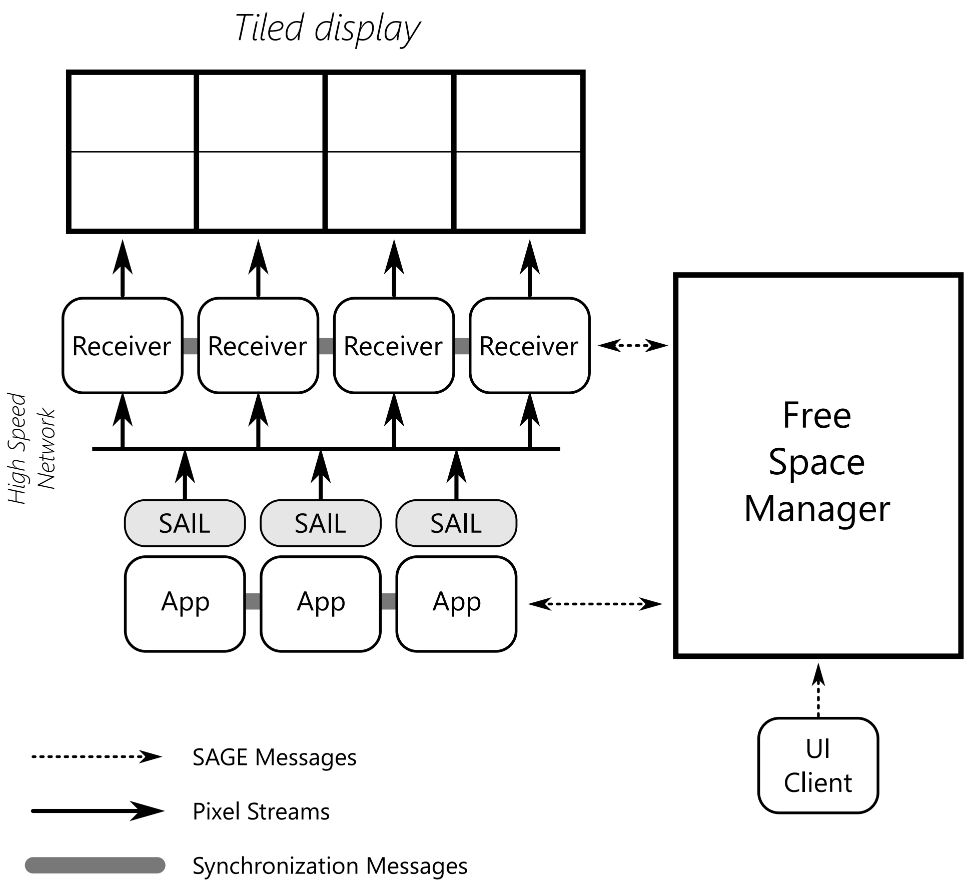


Figure 3.2: SAGE architecture overview.

In addition to the tiling done by SAGE, operating systems with multiple output devices already split up their graphical output on their own. This mechanism varies by operating system and configuration. How the graphical output is split up has an impact on how screen coordinates are interpreted by the operating system, and thus also on how SAGE operates.

Systems based on Microsoft Windows have one single *Desktop* spanning all output screens, i.e. windows and graphical objects exist in one connected rectangular region. GNU/Linux systems using the *X Window System* may instead create an independent *Screen* for each output device, or even multiple *X Server* instances. In these cases, graphical objects exist on multiple disconnected regions, each with its own coordinate system.

In the easiest case, all SAGE tiles live inside the same graphical region (for instance a single *Desktop* on Windows or a single *X Server Screen*) and thus the operating system's coordinate management has no impact on SAGE. In fact, in this case SAGE can act likewise any other graphical application on top of the operating system's desktop manager.

When multiple *X Server* instances are used instead, on one or more physical machines, they can still be merged into one SAGE screen. In this case SAGE will consider each server as an independent output component. *X Server* instances run independently and are identified by a unique IP and TCP Port combination. Instances running on the same physical server will share its IP address.

On some hardware, a special *X Server* mode can be used that merges multiple output devices—which would require multiple server instances—into one single logical screen at the operating system level. For instance, NVIDIA hardware can use the so-called "Xinerama" mode in order to unite multiple output screens into one single *X Server Screen*, with a single coordinate system.

Another way of creating a single screen at the operating system's level, is to use additional hardware devices. For instance, Matrox's *DualHead2Go* and *TripleHead2Go* can join the inputs of two or three screens respectively and can then be connected to a single adapter output. Multiple screens connected through these devices appear as a single screen to both the graphical adapter and the operating system, and thus can be managed by only one *X Server*. This solution is also useful in order to expand a system's capability of driving multiple displays: a single graphical adapter can be connected to more displays than the ones supported by default.

With any of those solutions, SAGE can be effectively configured in order to merge multiple screens together. SAGE thus offers a single unified frame buffer on top of the existing screen system exposed by the operating system.

An example of how the frame buffer can be tiled up—for instance on a GNU/Linux system using *X Server*—is given in Figure 3.3: square thick borders show the margins of the graphical limits of one computer (e.g., the maximum projectable region by an array of projectors or the limits of a tiled LCD panel wall). Square thin borders reflect the margins of one single component of the graphical output (e.g., one single screen or projector). Rounded borders with gray shading show the region occupied by an *X server* instance.

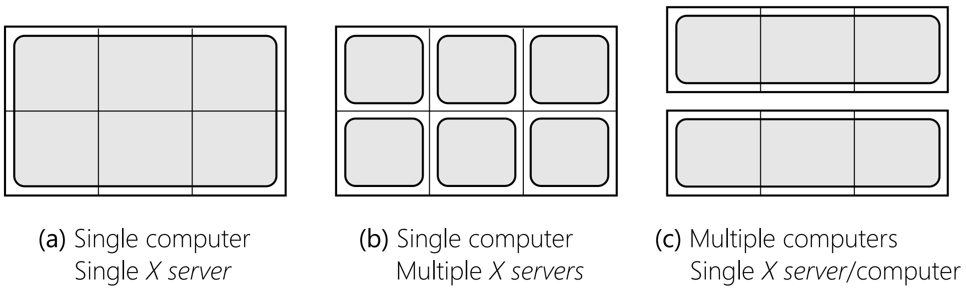


Figure 3.3: Examples of frame buffer tiling.

Example **(a)** can represent a tiled LCD panel wall, with a configuration of 3 × 2 monitors. The system in this case is configured in order to be managed by one single *X server* that controls all graphical output of the computer. Example **(b)** represents a similar system, where each logical tile (each monitor attached to the system) is managed by an individual *X server* running on the same host. Finally, example **(c)** shows a cluster composed of two computers, each running a configuration of three screens, managed by a single *X server*.

3.1.2 Components

SAGE is essentially composed by three high-level components, a window manager, one or more receivers, and any number of applications, connected through a high-speed network and managed by any number of UI controllers, as shown in Figure 3.2.

3.1.2.A Free Space Manager

Each SAGE instance is controlled by a single window manager, called the "Free Space Manager" (FSM), acting as a master controller for the system.

The window manager, like its homonymous counterpart in most operating system UI shells, manages the whole drawing surface (i.e., the "virtual frame buffer") and controls how and where applications are drawn on the screen.

The FSM also exposes a developer-facing layer, called the "Event Communication Layer" (FSM ECL), that allows SAGE's controllers and third-party UI controllers to interact with the system. The adopted message exchange protocol is seen in more detail in Section 3.6.2.

3.1.2.B Receivers

A SAGE instance is composed by one or more SAGE receivers. Each single receiver manages one of the independent "logical tiles" of the screen, as described before in Section 3.1.1, representing a contiguous screen area on the video wall.

Depending on the configuration, a single receiver may also drive multiple tiles. If the receiver runs on hardware capable of running multiple screens, configured as separated tiles, a single receiver instance can actually span more than one tile. Since tiling—on a single hardware system—is mostly just an issue of assigning screen space and handling coordinates, this has no real impact on the receiver. For the rest of this book, if not specified otherwise, it is assumed that a single receiver manages a single tile.

The layout of the screens is specified through configuration to both the FSM and each single receiver.

Receivers are managed by the FSM ECL and accept incoming pixel data transmissions from any number of SAGE applications. Receivers handle the pixel data, managing all operations needed to making sure they are drawn on the output surface at the correct position.

Internally receivers use a single accelerated *OpenGL* output surface to draw the data on screen with as little overhead as possible. In most cases a direct copy from the network stream to the output surface can be performed.

If needed, the pixel data can be transformed and converted as required to be displayed. For instance, when the incoming pixel stream is encoded in a different format than the one used by the *OpenGL* surface, a data conversion is unavoidable.

Receivers are also able to ensure that data display is kept in sync between components, using a simple synchronization mechanism between receivers (see Section 3.4).

3.1.2.C Applications

SAGE is capable of running any number of different application instances. Applications can be very heterogeneous, but share one common feature: they render the pixels that need to be drawn on the SAGE screen.

Each application runs in the context of the two-dimensional "virtual frame buffer", on which it is assigned a region where it is drawn onto. The region is strictly rectangular and can be sized and moved freely inside the frame buffer. A *z-index*[2] is also assigned to the region, indicating its depth ordering in relation to other application regions, and how it is drawn on screen (i.e., under or above other applications). During the course of operation, the FSM can alter the application's region (e.g., moving, resizing, or altering its z-ordering).

In fact, like windows of an operating system, applications live inside a rectangular region and are characterized by the pixel data that is drawn on screen. In a similar fashion, these rectangular regions can be manipulated and moved, both by the system and by the users. As this exemplifies, SAGE in large part behaves like any compositing window management system of a modern operating system.

Applications contributing to a SAGE setup may run on any workstation connected to the system, even remote computing systems—for instance an external rendering cluster—which are connected through a wide-area network.

Lifecycle All running applications inside a SAGE system are registered by the FSM. Acting as a window manager, the FSM configures receivers and applications, making sure that pixel data is generated and sent to the correct target receivers.

[2]The *z-order* is a property of overlapping two-dimensional objects, such as windows or other GUI elements. When the covered areas of two objects have an intersection, how they are represented on screen depends on their relative z-ordering, i.e., their ordering along the viewer's looking axis. When the order is determined by an integer value expressing the object's depth (along the so-called Z-axis), this value is usually known as *z-index*.

When an application has to be started, the FSM creates a channel to the target workstation through a *Secure Shell* connection (SSH) and executes the application as a remote process. Parameters and other configuration options are passed through command-line parameters or preconfigured setting files.

Once an application is running, the SAGE *Free Space Manager* practically has no control over its execution and has no further understanding of its lifecycle. In a nutshell, an application in SAGE is considered to be "running" as soon as its process is spawned and as long as its termination is not signaled. In most cases, it is up to the application to notify the FSM of its own termination. If this is not the case, the application is considered to be alive even if the process has been terminated and no graphical data is generated anymore.

As long as the application is considered to be running, the FSM makes sure that it streams pixel data to the correct receivers of the system. When needed, the FSM sends reconfiguration messages to all involved applications to update their streaming targets.

Interface library As mentioned before, applications do not need to be redesigned or rearchitected for a particular system in order to contribute to a SAGE system. There is no strict dependency on any runtime or graphical environment, nor is there any effective technological requirement. In fact, applications on SAGE can be of very heterogeneous nature: they can run on a simple workstation or run as a distributed system on a full-fledged cluster, they can have a graphical user interface or run "headless", as a command-line executable.

All applications must, however, make use of the *SAGE Application Interface Library* (SAIL). This library includes the simple primitives needed to interact with SAGE and exposes a limited set of APIs to application programmers. These interfaces can be accessed either by using the low-level C++ code in which SAIL itself is written, or a higher level interface written in C. Both these interfaces provided by the library allow the programmer to initialize the application's cooperation context with the SAGE system and then to provide pixel data to receivers at runtime.

Most communication tasks, like sending and receiving messages, managing the streaming configuration provided by SAGE's FSM, and actually performing the transmission of the graphical data, are handled internally by SAIL itself.

Additionally, SAIL also takes care of splitting up the generated pixel data and streaming it to multiple receivers if needed, based on the directions from the *Free Space Manager*. For instance, when the application's draw region spans across two separate tiles, its output is split and sent to two independent receivers.

Messages sent by external components are received by SAIL and can be processed by the application using a standard *message pump* pattern[3] (see Section 3.6.2 for details). Even though SAGE provides standard message types for events and UI interactions by the user, SAIL does not provide a coherent standard way to manage the application's behavior and lifecycle. Also, there is no facility to provide feedback back to the UI component (except through graphical updates visible to the user). In fact, extensions to SAGE have been proposed in order to overcome this limitation of the messaging protocol, and to enhance the interactivity of applications [34].

SAIL exposes a very simple programming model: application programmers render directly to raw data buffers, that are transmitted using a double-buffering swapping technique. This simple architecture, while making the developer relinquish some control over transmission and buffer management, makes porting existing rendering applications to SAGE very easy.

In fact, the software package in which SAGE is distributed by default provides a version of the widespread *MPlayer* multimedia player, modified in order to make it work with SAIL's buffer swapping mechanism.

The full C API and the messaging aspects of SAIL are discussed further in Section 3.6.1.

Other than *MPlayer*, the SAGE distribution includes several other sample applications that make use of SAIL and can be used out of the box. Most commonly used applications include:

- **Checker**: sample benchmark application to test streaming performance.

  On start-up a simple checker pattern is generated procedurally in an in-memory buffer and is the continuously streamed to output at the maximum frame rate.

- **ImageViewer**: basic image viewing application.

[3]The *message pump* pattern, also known as *event loop* or *message dispatcher*, is a common programming construct that waits for and dispatches events or messages. It is a central pattern for UI programming, where messages from the UI toolkit must be processed in order to interact with the user.

The application uses the *ImageMagick* library to convert the input image (any common format is supported, including JPEG) to an in-memory buffer using the compressed DXT format. The converted image is then streamed as a single frame to the tiled display.

- **MPlayer**: a modified version of the very popular open-source media player, based on the *FFMpeg* libraries.

  The version distributed with SAGE includes a custom video output module which streams individual decoded video frames to the SAGE video wall. Thanks to the underlying decoders, a large variety of formats are supported.

- **VNCViewer**: simple desktop sharing application.

  For each shared desktop session (usually launched through SAGE pointer), an instance of the application is spawned. A VNC client is started on the host running the application, that will attempt to connect to the VNC server on the desktop through SSH. Once a connection is established, the desktop stream is forwarded to SAGE as a continuous sequence of images.

  Because of the nature of the connection, VNC is capable of bridging wide-area networks, thus enabling remote collaboration through the Internet.

- **qShare**: advanced desktop sharing application.

  This custom program, capable of running on Windows of Mac OS X desktops, written to be a SAGE application itself. That is, no client-server bridge is needed like with VNC, but a direct connection between the shared desktop and the SAGE system can be established.

  While the desktop can thus be streamed in high quality and at a very high frame rate, a direct LAN connection is required and bandwidth consumption can be quite high (the minimum of a 1 Gbps link is specified by the documentation, while 10 Gbps are suggested for 4K screens).

- **DeckLinkCapture**: video application that connects with a *DeckLink* HD high-performance video capture card by Blackmagic design.

  Blackmagic hardware is capable of real-time capture of a HD, 2K or even 4K video source (over dual-link SDI, HDMI, S-Video, analog component or analog composite video connectors). The captured stream can be sent to SAGE receivers to be presented on the tiled display.

- **OfficeViewer**: viewer for common Microsoft Office file formats or Adobe PDF files.

  Office files are passed through an on-the-fly converter using the *LibreOffice* environment (if available on the system) and stored as PDF files. Original or converted PDFs are rendered as bitmap images and streamed.

- **Webcam**: sample webcam capture application.

  The application uses the *Video for Linux* (V4L) interfaces in order to capture video data from a specified hardware device, representing the input webcam. Captured images are streamed to the video wall.

Some other, more specific, applications are also included in the SAGE distribution, like the *UltraGrid* video transmission streamer[4].

Generally, existing streaming applications—like movie players—, and applications making use of an interoperation API that works using a frame-swapping mechanism can be easily adapted to make use of SAIL.

3.1.2.D Controllers

The SAGE components examined this far do not concern themselves with user-facing features, such as UI features for manipulating the frame buffer and its applications. The *Free Space Manager*, receivers and applications are managed by a message passing protocol that provides the primitives for additional applications to provide support for users.

These applications are known as "SAGE controllers" (or simply "SAGE clients", as they act as clients of SAGE applications and the FSM) and can be quite heterogeneous in terms of interface and usage experience.

The SAGE distribution includes a basic controller module, known as "**SAGE pointer**". The pointer application runs on a standard desktop computer and extends the user's desktop interaction space to cover the whole tiled display managed by SAGE. That is, the user's mouse pointer can be *transferred* over to the tiled display—as if it where an extension of the computer's

[4]`http://www.ultragrid.cz`

desktop—and can be used there to move, scale, and interact with application windows.

When running, SAGE pointer displays a little text window and starts monitoring the edges of the user's desktop. As soon as the user's pointer hits the monitored edge, the pointer is hidden from the desktop and a pointer is shown on SAGE's tiled display. This gives the illusion of transferring the pointer from one desktop to the other[5]. Pointers on the tiled display are displayed using the same techniques used in displaying applications on receivers.

The pointer on the tiled display can be shown in various colors, as defined by the user inside SAGE pointer's configuration files. This allows multiple users to control SAGE concurrently with different pointers, each with its own color and an additional text label identifying the user. A SAGE pointer running on a Mac OS X workstation and displayed on the tiled display is shown in Figure 3.4.

A pointer on the tiled display can also access additional SAGE features through the SAGE pointer interface. For instance, new applications can be started directly through an easy UI menu. Also, the SAGE media store (hosted on FSM's machine) can be explored and used as source for image viewer or movie player applications.

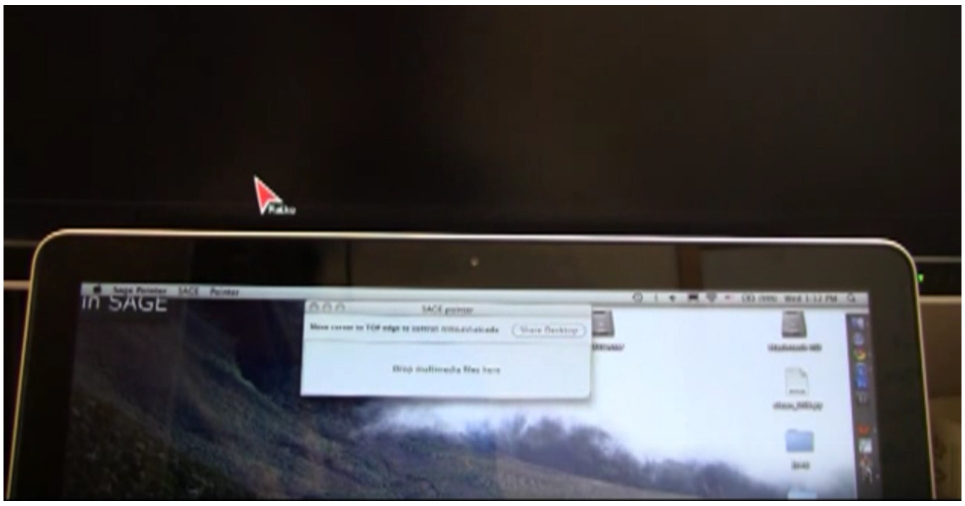


Figure 3.4: SAGE pointer running on a computer desktop, being shown on a tiled display. (© EVL UIC.)

[5]SAGE pointer's usage and its transfer to the tiled display are demonstrated on this video: `https://youtu.be/610YyUfyf_w`.

User interactions through SAGE pointers allow users to move applications (by clicking and dragging), scale applications (by scrolling the mouse wheel), and interact with the applications themselves (by entering the so-called “deep interaction” mode). Click and drags are sent from the SAGE pointer to the FSM, which updates the state of the tiled display by moving or resizing the application on screen. Any clicks performed in “deep interaction” mode are sent directly to the application as a SAGE event and can be handled by them directly. For instance, the default *MPlayer* application can play or pause its playback when clicked by any user.

Additionally, SAGE pointer also allows users to upload files to the SAGE system: by dragging and dropping media files on the SAGE pointer window, they are uploaded to the SAGE media store (that by default resides on the same workstation hosting the FSM process). Files on the SAGE media store can be then picked as sources when launching image or movie player applications.

Screen sharing applications (VNC specifically) can be started directly from SAGE pointer, instead of launching the applications on separate workstations through SSH. When this option is selected, a VNC receiver application (i.e., *VNCViewer*) is started on a SAGE workstation and a connection with the desktop computer hosting SAGE pointer is established. The VNC client shares the screen to the VNC receivers, which will then stream the video feed to the tiled display wall. It is also possible to share portions or only certain windows on the computer’s desktop. In many common use-case scenarios a Skype video-conference call is shared onto the video wall to enable remote collaboration. Note that screen-sharing through *qShare*—which usually features a higher frame-rate and better quality—cannot at this point be directly launched through SAGE pointer, but requires a dedicated setup process.

Albeit being the most common, SAGE pointer is not the only controller available to users. In fact, advanced SAGE configurations may incorporate a variety of user interaction alternatives, such as multi-touch surfaces, head tracking for CAVE-like setups (see Section 2.4), game controllers and motion sensing input devices for 3D hand/body tracking (e.g., Leap Motion, Nintendo Wii Mote, Microsoft Xbox 360 controllers, Microsoft Kinect, or Thinkgear’s experimental brainwave interfaces).

Such controllers can interact as clients for a SAGE installation through the *Omicron SDK*[6], also developed at EVL UIC likewise SAGE. Omicron SDK provides a server that connects to the aforementioned devices and abstracts user input using modular event services. User input events can easily be streamed over the network using an Omicron connector API. Input is then evaluated by the SAGE system and processed like the input coming from SAGE pointer.

Most devices enumerated before represent their input, as unconventional as it may be, as a traditional pointer on a 2D surface. For instance, the Nintendo Wii Mote is able to track the direction it is pointing to and its rotation, but its usage is comparable to that of a traditional mouse. Likewise, as shown in Figure 3.5, also the Microsoft Kinect can be used as a novel way of interacting with the SAGE desktop manager using a conventional click and drag interface[7].

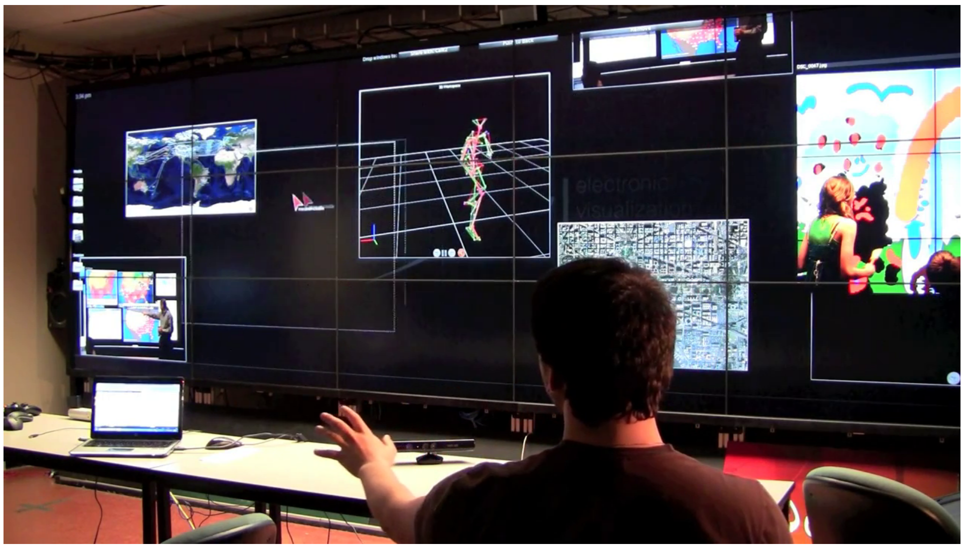


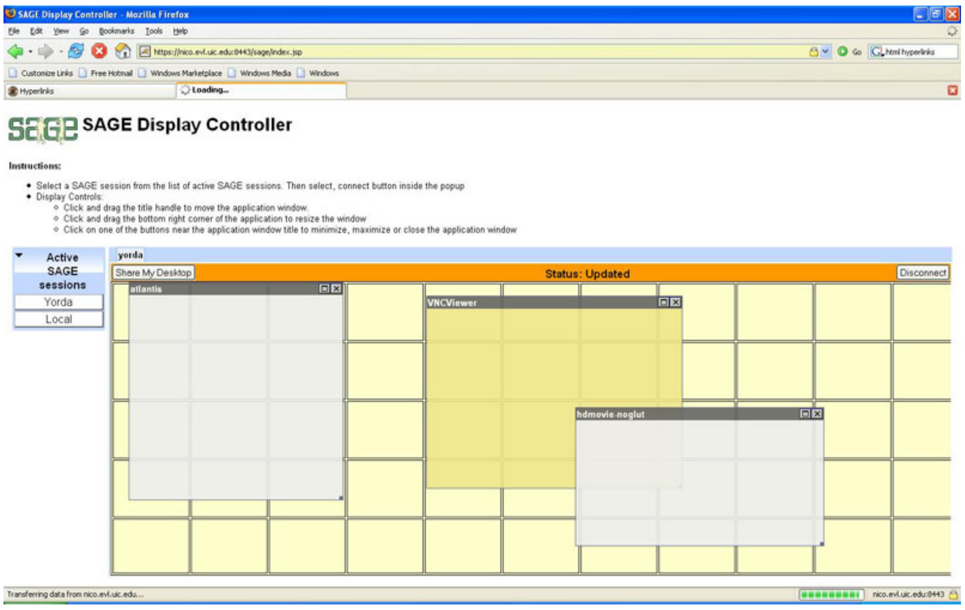
Figure 3.5: A SAGE users manipulates the SAGE setup—in this case moving an application from one side to another—using only his hand through Microsoft Kinect. (© EVL UIC.)

In a similar fashion to the *Omicron SDK*, a SAGE tiled display can be configured to support multi-participant touch interactions. In this case, a custom *PQ Labs* multi-touch solution is adopted: a small server connects to the *PQ Labs* touch server—a dedicated Windows machine running the proprietary multi-touch software and managing the touch overlay hardware

[6]Official repository: `https://github.com/uic-evl/omicron`.

[7]A sample demo of SAGE controlled through Microsoft Kinect (moving and resizing applications) is shown here: `https://youtu.be/oFQeszkCaPU`.

through USB—analyzes the touch information and the gestures performed by its users, thus translating them into the SAGE pointer protocol to behave just like a standard pointer. This allows users to perform the usual SAGE interaction commands (opening applications, moving and resizing them, etc.) in addition to some custom multi-touch commands (such as "clear the wall" or "close application", that can be performed with a simple touch gesture).



SAGE Display Controller

Instructions:

- Select a SAGE session from the list of active SAGE sessions. Then select, connect button inside the popup
- Display Controls:
  - Click and drag the title handle to move the application window.
  - Click and drag the bottom right corner of the application to resize the window
  - Click on one of the buttons near the application window title to minimize, maximize or close the application window

Figure 3.6: A screenshot of the SAGE Web Control interface, running inside Mozilla Firefox.
(© EVL UIC.)

Moreover, the SAGE distribution also includes a **Web Control interface** that allows remote users as well to interact with the system. This component provides a customizable web-based portal, built on HTML 5, Node.js and client-side Javascript (using the *jQuery* library), in order to present a cross-platform browser-based interface, that works on any device connected to the Internet (e.g., tablets, mobile phone, laptops). The portal shows an overview of the tiled display and its running applications. Just like the SAGE pointer, it allows user to start applications, navigate the media file store and interact with running applications.

The controller is itself built with a server and a client component. On start-up, the Web Control server connects to the FSM and exploits the same SAGE message passing protocol to detect and to manage the system's state.

The Web Control client interface can be loaded by any modern browser by connecting to the controller server, thus presenting the system state to the end-user. Details about the design, the implementation and the inner workings of the SAGE Web Controller are given in the thesis byMeerasa [66].

The primary UI is mainly composed of a schematic overview of the tiled display managed by SAGE: boxes with yellow background indicate single tiles of the setup, while applications running inside the environment are shown as gray overlaid rectangles, as shown in Figure 3.6. By dragging and dropping the application rectangles, the user can move and resize them interactively on the tiled display. Applications can also be started from scratch or terminated by clicking the “X” symbol on their placeholder rectangles.

3.2 Communication and streaming

The overall architecture of the entire SAGE system is shown in Figure 3.2, at page 49. The figure shows how the components of SAGE interact with each other, and how the tiled display managed by SAGE is split up into independent tiles, each one of which gets pixel data from a SAGE receiver. Receivers are connected to a given number of applications, which stream data through the SAIL software layer and a high-speed network. All components are managed by the *Free Space Manager*, which on its turn can be managed by an UI client.

Communication between components can be distinguished by their line stroke. Streams marked in the aforementioned figure include *pixel streams* (high-bandwidth connections between applications and receivers, transferring pixel data to the tiled display), *SAGE messages* (that use the custom message exchange protocol in order to sent commands and events to the FSM), and *synchronization messages* (used to keep application rendering and receivers in sync).

As mentioned before, SAGE can be seen as a distributed windowing manager, matching all components above to the corresponding elements of a windowing system analogy.

According to SAGE’s decoupled architecture, all components are interconnected very loosely, with only the FSM having an overview of the system at a time. In fact, since even the FSM does not actively manage the lifecycle of its applications—as mentioned at page 53—the overview it has over the whole system can be out of sync or partial.

3.2.1 Interconnection

The interconnection between SAGE components is achieved using standard *Transmission Control Protocol* (TCP) and *User Datagram Protocol* (UDP) network sockets. Using this low-level type of connection primitives entails several advantages and some disadvantages for SAGE's use-case.

On one hand, this choice allows to use the same communication mechanisms both between remote and local processes. Processes local to the same machine can communicate efficiently through the loopback interface[8], without effectively hitting the network, using the same primitives also used to communicate with remote processes. This is particularly effective when applications and receivers run on the same hardware device, where a very expensive network data transfer of video data is avoided in favor of an in-memory copy.

A benefit of this solution is also that a highly distributed system requires almost the same configuration steps of a localized simple system, running on a single machine. The type of SAGE processes and components interacting stays the same, and they use the same mechanisms and configuration files. Once a SAGE setup is running on a local machine, provided that the network works correctly, the setup can be replicated on multiple machines just by setting the respective IP addresses. Also, this extends to remote machines connected through a wide area network: both when data is streamed through a local high-performance network or through a slower WAN, like the Internet, as long as the two hardware devices can communicate through IP routing, they can participate in a SAGE setup.

On the other hand, raw sockets are a low-level network interface which is hard to use for reliable, rich communication. Messages between SAGE components must be formatted and encoded according to a custom protocol, in order to fit the required information into single packets, with correct client-server synchronization. For several SAGE use-cases, foremost the message passing protocol seen in the next sections, a higher level network protocol would be perhaps more useful and easier to use, like for instance the *HyperText Transfer Protocol* (HTTP).

However, using sockets instead of a higher level protocol layer, allows SAGE to make use of some IP-level routing features that make better use

[8]In signal routing, a *loopback* refers to a flow of items back to their original source, without modification. In terms of IP routing used by sockets, using the "loopback interface" is intended as opening a socket on one machine and connecting it to a second socket on the same network adapter.

of the network's bandwidth on LAN. For instance, it is possible to send some commands using *broadcast* IP addresses, thus flooding the message to all components on the local network. Likewise, it would be possible to use *multicast* addressing to send certain multimedia streams to multiple receivers. The advantages in using multicast addressing for video delivery has been examined in a real-case scenario by Seraghiti et al. [89]. This feature is not used by SAGE, and not useful by default for video streaming, since normally there is no overlap on the tiled display. However, multicasting could well be used for audio streaming or for some other specific use-cases, in order to reduce SAGE's bandwidth requirement.

In practice, SAGE uses the reliable TCP for most messaging-related communications and *Reliable Blast UDP* (RBUDP) for bulk data transfer, as in video streaming. The latter is seen in detail in the next section.

3.2.2 Reliable Blast UDP

As made evident by the presence of a "high-speed network" in Figure 3.2, when not operating through loopback on a single machine setup, SAGE's data transmission from applications to receivers may reach very high data rates. This is especially true given the way pixel data is encoded, as described at page 69.

The standard and widely used *User Datagram Protocol* (UDP), with no handshaking, no guarantee of delivery or ordering, and no duplicate protection, is usually described as being a very good fit for video streaming [107]. In fact, since the network bandwidth can be one of the main bottlenecks for its performance, SAGE makes use of *Reliable Blast UDP* (RBUDP).

Essentially, RBUDP is an aggressive bulk data transfer scheme, intended for extremely high-bandwidth on *Quality of Service* (QoS) enabled networks. The protocol was developed for QUANTA, a cross-platform adaptive networking toolkit for data delivery in interactive bandwidth-intensive applications, especially on optical networks. As described by He et al. [43], the paradigm taken in exam by QUANTA is a distributed computing system, where optical networks serve as the system's bus and computing clusters, taken as a whole, serve as peripherals in a—potentially—planetary-scale computer. This same paradigm, on a smaller scale, is similar to the aims of SAGE, where workstations serve as parts of a heterogeneous system that streams video onto a large tiled wall.

The protocol is described in detail by He et al.: its main goals are to keep the network pipe as full as technically possible during data transfer,

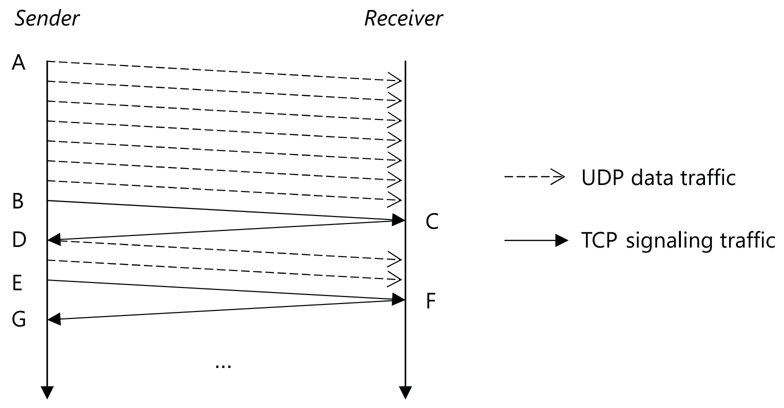


Figure 3.7: The communication scheme adopted by RBUDP, for bulk data transfer between sender and receiver.

Reprinted from "Reliable blast UDP: Predictable high performance bulk data transfer", by E. He, J.Leigh, O. Yu, T. DeFanti et al., 2002, in *Proceedings of the 2002 IEEE International Conference on Cluster Computing*. Copyright 2002 by IEEE.

and to avoid the overhead of per-packet acknowledgments as used by TCP [42]. RBUDP's target application scenario is based on long distance, high-speed networks, colloquially referred to as "long fat networks" (LFN). These networks present unavoidable latencies due to distance, leading to gross under-utilization of the available capacity when using TCP for data delivery. This is due to TCP's windowing mechanism and its "slow start" strategy[9]. This behavior often attributes packet loss to congestion when it is instead due to poor data-link transmission (as in wireless networks) or computational delays on the path between sender and receiver. Moreover, since TCP waits for acknowledgments before growing its transmission window and thus reaching higher transmission speed, in several situations the protocol will wait for an inordinate amount of time, which in turn means that the transmission speed will never reach the network's peak available capacity.

Alternative solutions—using TCP—are possible: for instance providing better "congestion window" estimates for the network it is being used on, in order to more readily exploit the available capacity. Also, using striped (or parallel) TCP connections, the payload is divided up into N partitions,

[9]*Slow start* is one of the congestion control algorithms used by TCP, also known as *exponential growth phase*: it initially requires an acknowledgment almost for each packet, slowly increasing the "congestion window" over a growing number of packets. This usually enables TCP to slowly measure the maximum rate achievable by either the network or the routing elements on the path between sender and receiver. If at any time a packet loss is detected, the "congestion window" is reduced again to reduce load on the network.

which are delivered over N parallel TCP streams. This technique is shown by Allcock et al. in *GridFTP* to achieve a throughput as high as 80% of the network's available bandwidth. However, it is difficult to correctly estimate the number of connections to use [1].

The *Reliable Blast UDP* scheme takes a more aggressive approach, by sending the entirety of the payload at an user-specified sending rate using simple UDP packets (i.e., "blasting" the payload through the network). Since UDP is unreliable, a number of packets may be lost—especially if the transmission rate is too high for the network or the receiving host. The receiver will keep a tally of the packets received, in order to signal the need for retransmission. Missing packet notifications or the completion signal (i.e., the "DONE" signal) are sent via TCP, back from receiver to sender. The sender will respond resending the missing packets, as requested. A sample interaction of this scheme is seen in Figure 3.7.

To minimize packet loss and retransmission needs, the sending rate should not be greater than the capacity of the bottleneck link. It has been shown experimentally that RBUDP eliminates TCP's *slow start* issues, and is capable of fully exploiting the available bandwidth, given that the target sending rate is estimated correctly. In controlled scenarios, it is possible to further optimize transmission by assuming that the capacity of the network will not be exceeded and that UDP packets—albeit not guaranteed to be ordered on arrival—will in practice arrive in order [42].

Even if designed for use across high-bandwidth, high-latency networks, RBUDP can provide efficient delivery at user-specified sending rates, especially with large payloads (with smaller payloads, the time needed to complete the delivery approaches the time needed to acknowledge the payload). This protocol can in fact be easily extended for use in streaming applications [43].

In practice the SAGE system makes use of the protocol for video streaming between applications and receivers, even if SAGE setups are usually not centered around a "long fat network"—quite the contrary, high-speed local networks are frequently used as the system's backbone. However, RBUDP makes sure that data transmission is as fast as possible, reliable and does not require TCP's long exponential growth time.

3.2.3 Message passing protocol

The *Free Space Manager* orchestrates the system's configuration through a message passing protocol. It allows direct communication with both applications and receivers, in order to get updates about other components and send commands to them if needed.

Messages are very varied and serve various components through their lifecycle. Not only does the FSM signal events about the whole system's status (start-up, shutdown, pausing and resuming of streaming), receivers can give indications about sync and performance, UI client applications (like SAGE pointer) can query the FSM, which will return status updates and information about running applications as messages. Likewise, message exchanges can also be generated by the action of UI clients as SAGE pointer. User commands are sent to the FSM and can entail an exchange of messages between it and its receivers. Also, UI clicks and interactions by the user can originate a sequence of commands to applications, which will be able to react accordingly.

Most important commands concern application execution, for instance application start-up, window movement, resizing and reordering. Additionally, the FSM also collects and maintains the information needed to setup the dynamic pixel streaming from applications to receivers. One of its paramount roles is in fact to issue a streaming reconfiguration when needed. Whenever applications change in state or are moved across the frame buffer, the FSM sends out messages reconfiguring the applications and ensuring that they send the appropriate data to the correct receivers [51].

To deliver these control messages among SAGE components, data is sent through reliable TCP sockets and encoded using a very simple data format, with a fixed structure.

As described before, some UDP features (like *broadcast* and *multicast* routing) could be used to enhance network utilization in some circumstances. However SAGE always uses direct TCP connection to each of its components, even when distributing events.

More details about SAGE's control messaging system, its protocol and its message encoding, are given in Section 3.6.2.

3.3 Drawing and composition

A running SAGE system is composed of one *Free Space Manager*, one or more receivers and any number of applications, which produce graphical data and can in fact run on any hardware component of the system.

Once one or more applications are running on a SAGE system and have been configured by the FSM, through a sequence of configuration messages, their main mode of operation is exclusively the generation of graphical data streams. These streams of graphical data need to be visualized on the "virtual frame buffer", and thus displayed on the physical output devices of the system.

3.3.1 Pixel-streaming protocol

The SAGE system is architected as a "pixel-streaming system". That is, it is a system where actual pixel data is streamed and directly drawn onto the screen. Raw encoded bitmap data is transferred through the network, directly to the display, without further processing or decoding on the receiver's end. This is in contrast with other system, where instead geometrical primitives are encoded and sent through the network to the display.

For instance, the Microsoft *Remote Desktop Protocol* (RDP) also provides remote display capabilities over network connections. On the server, RDP uses a custom video driver to render display output and sending it through RDP to the client. The latter receives this rendering data and interprets the packets into corresponding *graphics device interface* (GDI) primitives [68]. *X Server* also makes use of a protocol in which the client application sends drawing operations to the server in terms of drawing primitives, expressed using the *Xlib* library. The actual drawing is then efficiently executed on the server, with very low bandwidth consumption, except for the transmission of bitmap data (which cannot be expressed as a vectorial primitive).

The advantage of pixel-streaming is that the generated output is fully platform-independent, requires almost no transformation in most cases and is very easy for receiving systems. In practice, the server part of a pixel-streaming client-server system has only to perform the actual memory copy from network to display driver.

On the other hand, primitive drawing commands are much more efficient in terms of bandwidth occupation: raw rendered pixels, especially when paired with high resolutions or lack of good compression (often required for real-time streaming), have an extremely high bit-rate. Pixel encoding and bandwidth requirements in SAGE are further discussed in the next section.

In some cases, SAGE's pixel streaming protocol is not only about sending a constant stream of pixel data to a single receiver, but must be also concerned about some corner-cases. For instance, when an application is resized or moved in a way to span multiple output tiles—that is, the appli-

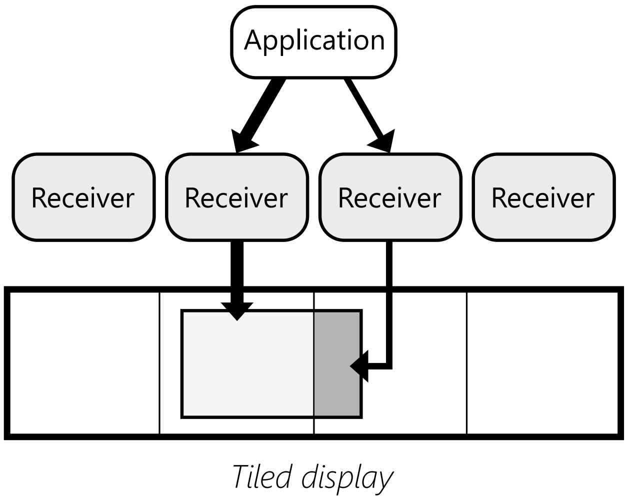


Figure 3.8: Pixel streaming from one application to multiple receivers on overlapping tiled display regions.

cation covers a region that is part of the tiled display managed by multiple receivers—its output data must be sent to all involved receivers in order to be shown correctly. As shown in Figure 3.8, an application may generate two (or more) output streams to receivers even if owning only one output surface.

In this case, the library support provided by SAIL will automatically take care of splitting the generated pixel data buffer up into separate regions. This is particularly easy because of the pixel encoding used internally by SAIL buffers, as discussed in the next section. Since pixels are stored as raw color data, the split operation can be completed by simply taking care when indexing into the application's output buffer. No additional transformation operation is needed, nor the additional computational cost of memory copies or encoding.

3.3.2 Pixel encoding

Applications running on SAGE and using SAIL for inter-communication (see Section 3.1.2.C) create and manage their output surface through SAIL's C API. All functions of SAGE require the application to first initialize the library by creating a special object, which also represents the drawing surface used by the application (see page 80 for an overview of the actual C API).

This drawing surface is mainly characterized by its size and the pixel encoding format used internally to store graphical data. Size and format also impact the size and type of the data buffers used by the application when generating and transmitting rendered frames to be displayed on screen.

The library supports a variety of pixel formats which are common for graphical applications and largely overlap with pixel formats defined by the *OpenGL* standard. Most 16, 24 and 32-bit formats are supported, including some formats with an alpha channel (4 8-bit channels following the RGBA layout). Raw YUV pixel data is also supported (a format mostly used as raw source data for video encoders and decoders), in addition to the *DXT* compressed pixel formats [10].

Due to the match between SAIL formats and *OpenGL* formats, incoming pixel streams can directly be forwarded by SAGE receivers to their *OpenGL* rendering pipeline, without further transcoding. Eventually, transcoding can be performed by fast *fragment shaders* running directly on the graphics hardware.

3.3.3 Composition pipeline

A standard, “feed-forward” rendering pipeline—like most pipelines used in real-time graphics production, including 3D renderers adapted for parallel rendering—consists of two main parts: *geometry processing* and *rasterization*. Both this parts can be parallelized: geometry processing is parallelized by assigning each processor a subset of objects or primitives to render. The second part is parallelized by assigning each processor a portion of pixel calculations. When both parts are done in parallel, the pipeline is *fully parallel* [71].

In essence, each rendering task is concerned in computing *what* effect on *which* final pixel is applied by each primitive (be it geometry or actual color pixels). Due to the arbitrary nature of input data and viewing transformations, one of the main operations is to detect *where* on screen a particular input structure will be located. As noted by Sutherland et al., rendering can be seen as a problem of sorting primitives in relation to the screen. The nature and location of this sorting step largely depends on the rendering system [97].

[10] SAGE makes use of the *S3 Texture Compression* compression formats, which are a group of commonly used compression algorithms. They provide very quick lossy compression and are well suited for real-time graphics, as they are currently supported both by the *OpenGL* standard and the Microsoft DirectX platform.

In general, the sorting step can take place anywhere on the rendering pipeline, as described in the classification by Molnar et al. [71]:

- **Sort-first**: primitives are sorted early in the rendering pipeline. This is generally done by dividing the screen into disjoint regions and making processors entirely responsible for the whole rendering process of each single screen region.

  When rendering begins, enough transformation must be done in order to determine which primitives fall into which screen region. This *pre-transformation* step, and the following redistribution of the workload, clearly involves some overhead.

- **Sort-middle**: primitives are redistributed in the middle of the rendering pipeline, between processing and rasterization. At this point primitives have been transformed into screen-ready primitives. Since geometry processing and rasterization are performed on separate processors or on separate tasks in most system, this is a very natural place to break the pipeline.

  This approach is general and straightforward, since primitives need only to be sorted and redistributed to the appropriate rasterizers, keeping the rest of the pipeline intact.

- **Sort-last**: this approach defers sorting until the end of the rendering pipeline—i.e., after primitives have been rasterized to pixels. Renderers can process primitives to pixels no matter where they ultimately fall onto the final screen (including off-screen regions).

  This greatly simplifies the renderers, at the cost of having to transmit the pixel data over an interconnect network to a *compositor*, that will resolve the visibility of each pixel. Renderers operate independently, up to the composition stage.

A SAGE system can be interpreted just as a rendering pipeline. In SAGE's case however, the *geometry processing* phase is represented by the work done by applications: they could be effectively rendering 3D geometry, or simply decoding a video file. The *rasterization* step is done by receivers actually presenting the data to screen.

Notice however that the result of the first phase is *not* represented in terms of primitive geometric data (3D vertices or such), but instead is composed of rendered video streams, i.e. pixels.

Among the previously described sorting schemes, SAGE adopts the *sort-last* approach in its rendering pipeline. The *sort-first* strategy clearly appears as not feasible: albeit sorting before rendering could be done (the FSM has information about where applications are rendered on the tiled display), applications cannot easily be moved from one machine to another, in an attempt to move them close to the receiver. Also, the *sort-middle* approach has no useful applicability, since the final primitives generated by applications are given as raw pixel buffers. Since SAGE—and its auxiliary streaming library SAIL—have no higher level representation of the data shown on the video wall, *sort-last* appears as the only feasible strategy.

As a reference, *PixelFlow* is presented by Molnar et al. as an architecture for high-speed image generation using composition—that is *sort-last* ordering—which works using a method similar to the one adopted by SAGE. *PixelFlow* is presented as having several advantages: it is linearly scalable and offers a very simple programming model. The bandwidth required to compute the composition is determined only by screen size, frame rate and the number of sources generating pixel data. Very little synchronization is required, renderers can operate in a perfectly independent fashion (like applications on SAGE), and the parallel nature of the rendering process is fully transparent to the programmer [70].

Also, in the work presented by Cavin et al., a *sort-last* pipelined rendering approach using non-dedicated hardware with several similarities to SAGE is presented. As noted by the authors, many optimizations could take advantage of any sparsity in the input data to the rasterization phase, in order to save bandwidth and speed up rendering [17]. Tay gives an in-depth overview of techniques and optimizations that can be used in rendering pipelines adopting the *sort-last* strategy, such as tree composition, binary-swap, direct pixel forwarding and snooping [100].

However, since SAGE applications send full bitmaps for each generated frame, none of these optimizations can lead to real performance improvements. Nonetheless, SAGE retains all advantages already mentioned for *PixelFlow*, associated to the *last-sort* approach, including decoupling of applications and receivers (applications have a very simple programming model that does require very few modifications to existing code), little synchronization between components, and no additional rendering phases.

Image composition architectures entail several disadvantages, however. Even though the bandwidth required by the system is fixed, the network must transfer every pixel for every frame. As noted by Molnar et al., this can result in very high data rates for interactive applications [71]. Secondly, pixels must be reduced to a common format for compositing, reducing the amount of compatible data formats the system can accept (this can be mitigated by transforming pixel data on the fly, as mentioned previously, however this entails a computational cost). Finally, up to an entire frame of pixel storage is required for each renderer, since frames must be buffered before being sent and being composited [70].

During composition of the final image, receivers must pay particular attention to the way SAGE applications are ordered spatially. Each SAGE application is ordered using a *z-index*, which expresses its depth position in relation to the other applications, on the *Z* axis (i.e., the axis along the viewer's sight). Applications with a lower *z-index* are rendered first, applications with higher indexes are rendered later, covering up existing pixels of other applications if there is an overlap.

This depth-ordering process lays bare another inefficiency of SAGE's rendering pipeline: *all* pixel data is always transferred, independently of how those pixels are then composited on the final output image. Since visibility testing and compositing is entirely done on the receivers' end, applications that are fully covered up exercise the same pressure on the network as if they were fully visible.

On the up side, this approach allows applications and receivers to be fully decoupled from each other. Applications do not need to be updated about their status, nor about their position on the screen, while receivers don't need to care about applications *per se*, but only about incoming pixel streams to layout on screen.

3.4 Synchronization

Most part of SAGE's video streaming architecture derives from the *Tera-Vision* system, also developed at the *Electronic Visualization Laboratory* (EVL) of the University of Illinois at Chicago (UIC). The need for synchronization, in delivering a coherent, high quality video experience on a large scale display, emerged largely from this preliminary work.

When multiple video streams need to be transmitted and presented in the context of a complex display system, such as stereoscopic displays but also tiled-display clusters, there is a stringent requirement to synchronize both the video rendering aspect and the video display aspect at the viewing end. Synchronization must be kept for each frame, for the video to be displayed effectively to the end-user [19].

This principle is also confirmed in the work by Singh et al.: in *TeraVision*, and thus SAGE as well, not only display nodes but also rendering nodes need to be synchronized to yield better results. Failure to do so would produce de-alignment between videos from different rendering nodes or de-alignment during the composition and display phase. While the first issue only causes visible problems in case of applications that require synchronized rendering, the latter produces tearing, misaligned pictures, and distortions between tile boundaries [90].

3.4.1 Synchronization channels

The SAGE software stack makes use of two synchronization channels: the display synchronization channel among SAGE receivers, and the rendering synchronization channel among applications using SAIL. These two channels are visible in the architecture overview in Figure 3.2 at page 49.

Both synchronization channels can optionally be turned off, when not needed. For instance, if a parallel application naturally synchronizes its output, the additional rendering synchronization is unnecessary. Moreover, users may also want to turn off synchronization on the receiver end, in order to remove its overhead in case synchronization is deemed to be non critical for the use-case scenario.

In practice, both synchronization channels are implemented as high-priority, low-latency channels used by multiple peer processes in order to closely synchronize the video streams across processes potentially running on different machines. Sync channels are implemented as a two-way handshake over TCP, among a group of processes which elect a "master" node, signaling sync steps to all other slave nodes. To get the best results possible, this TCP channel should provide very little latency. In order to ensure this, Nagle's packet buffering algorithm used by TCP is disabled by settings the `TCP_NO_DELAY` option at the socket level.

Details about the synchronization mechanisms, as described in the work by Jeong et al., are explained in the next two sections [51].

3.4.2 Rendering synchronization

All SAIL applications with enabled rendering synchronization participate in the rendering synchronization process. A master synchronization thread is elected on one of the SAIL nodes, while the other applications act as slaves.

During the normal buffer-swapping operation of an application, each SAIL node will send an "update" signal to the master as soon as it finishes transferring an image frame to its receivers. This means that the application has correctly sent a full frame and is ready to send the next.

When the synchronization master has collected signals from all slaves, it sends a synchronization signal back to all SAIL nodes. After receiving the signal, SAIL nodes may start to transfer a new frame as soon as it is rendered by the application via a buffer-swap.

This simple process keeps all applications in step in their rendering process, throttling fast applications to render at the pace of the slowest application in the SAGE setup.

3.4.3 Display synchronization

Synchronization of screen rendering is done in a similar fashion to the application synchronization mechanism seen before. For each running application, SAGE creates a *network worker* thread on every receiver. The worker creates a circular buffer that will collect frame data coming from that particular application, and will setup the synchronization infrastructure. One of the receivers is elected to be the "master", while the other receivers act as synchronization slaves in reference to that same application.

As shown in Figure 3.9, describing the internal synchronization architecture of a SAGE receiver, a single receiver can act as a master for one application (application *B* in the example), while also acting as slave for another application (applications *A* and *C*).

Synchronization occurs on a per-application, per-receiver basis. That is, each SAGE application is effectively lock-stepped at a receiver level (frames do not advance until all receivers have obtained the next frame from that application), but applications can advance independently one from each other. A stalled application does not block rendering, nor does it prevent other applications from sending new frames.

For each application displaying data on a receiver, the following mechanism is applied:

1. The network worker waits until all the data of frame N has been transferred into the circular buffer.

2. Once the image data is stored, it is transferred to the graphical memory of the display adapter. This will update the internal *OpenGL* data buffers used to render the application on screen.

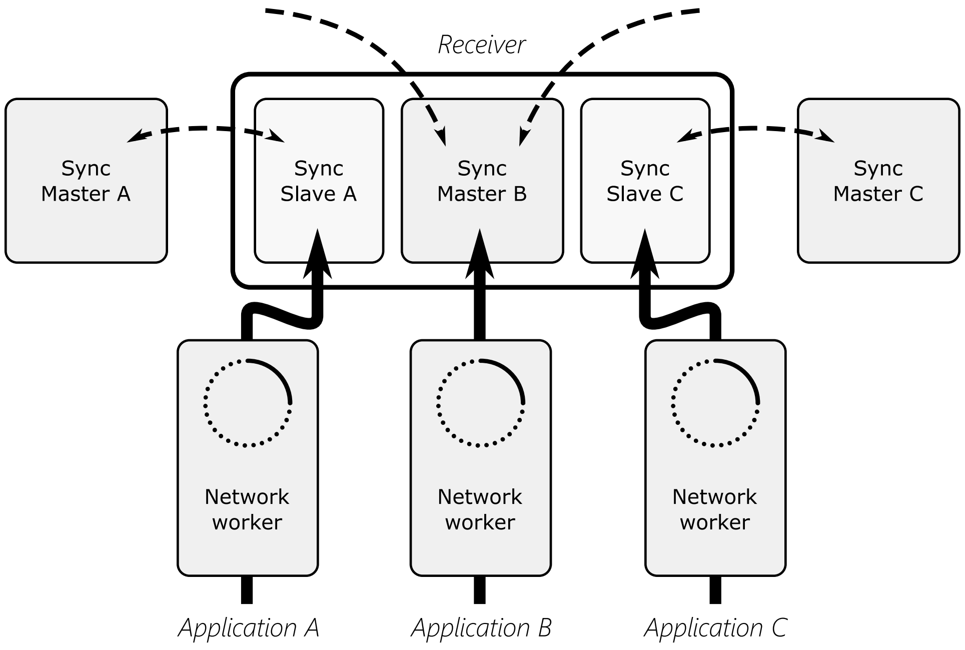


Figure 3.9: Architecture of a SAGE receiver and components of the display synchronization mechanism.

3. The synchronization slave sends an “update” signal to its master (the synchronization master of the same application, potentially running on another receiver).

4. The synchronization master receives the update signals. As soon as all signals are received, it sends a signal back to all its slaves.

5. When the “clearance” signal is received by the slave, the receiver clears the screen and makes a complete composition pass.

   Current frames of all applications streaming to the receiver are rendered to screen, including frame *N* which was just received, completing a full display refresh.

6. Steps are repeated for frame $N + 1$ and onward.

The same steps are repeated for each frame and for each application, refreshing the screen when a new frame is available to be presented.

In the worst case, all frames of every application are sent one by one, without temporal overlap. Assuming that there are $|A|$ applications running concurrently at a frame rate of f_r, a total number of $N \times f_r \times |A|$ screen refreshes are needed to get all applications up to frame number N. However, once a frame has been transferred to graphical memory, a screen repainting is a very simple operation that can be done quickly even by very slow hardware [51]. Repainting inefficiency never represents a bottleneck, except with extremely high frame-rates (which however will max out the network before hitting the maximum graphical fill-rate of a receiver).

3.4.4 Effects on performance and scalability

Synchronization implicates a non-negligible impact on system throughput. Not only does the total available sending bandwidth from applications to receivers decrease, but the mean CPU utilization increases as well.

In particular, it has been shown that increasing the number of receivers an application is connected to, the amount of video data received by the receivers decreases, and this also lowers their CPU utilization [90].

On the contrary, when increasing the number of applications on the system, the amount of data received by receivers increases, and their CPU utilization goes up. This may create a communication bottleneck in synchronization, causing TCP's congestion mechanism to reduce the sending rate. This pushes the frame rate down, also reducing the CPU utilization of applications.

3.5 Performance

Large-scale collaborative visualization environments intrinsically have very high requirements, both on the software and the hardware side, to achieve a satisfactory performance.

At the time when SAGE was being designed, the ability of visualization software to scale—in terms of amount of data they can visualize and in terms of visualization resolution—was still an area of intensive graphics research. And it still is, based on the work by Stoll et al. on *Lightning-2* [95], the work by Blanke et al. on the *Metabuffer* [11], *Equalizer* by Eilemann et al. [28], and the more recent *Piko* by Patney et al. [76]. Most of SAGE's video streaming architecture derives from the work on *TeraVision*. As described by Singh et al., this particular architecture provides support only for pixels being routed to the actual display machines [90]. In the original plans, SAGE would then allow to route also geometry and custom graphics format, drastically reducing the amount of data required for presentation and shifting the computational requirement from the network to the renderers. However, this has not been implemented so far.

As mentioned in Section 3.3.3, since SAGE adopts a *sort-last* composition engine based on pixel-streaming, its requirements in terms of network bandwidth are intrinsically very high. When a receiver and an application are not located on the same machine, the amount of video data that must be streamed through the network can be very substantial, growing with video resolution and frame rate.

Performances of pixel compositing systems based on a *sort-last* approach have been widely taken under exam in literature [85, 72, 17]. Unlike *sort-first* and *sort-middle* strategies, the performance of *sort-last* parallel rendering drops sharply as the resolution of the display increases. As specified before, this is not due to fill rate or graphical throughput, but mostly to the cost of distributing the rendered pixels to the receivers for display.

Video streams that traverse the network on which SAGE runs may be of the order of multiple gigabits per second, since the streams need to be transmitted without compression, or with a very inefficient compression encoding. Even if SAGE, theoretically, could accommodate on-the-fly compression and decompression, inexpensive dedicated network connections of multiple gigabits per second are far easier to envision than performing real-time high quality compression without comparably expensive dedicated hardware, as argued by Singh et al. [90].

For example, a single desktop screen, with a resolution of 1280×1024 pixels, at 24 bits per pixel and at a frame rate of 30 frames per second, translates to a raw network stream of approximately 943 Mbps. This video stream is thus enough to saturate a 1 Gb network.

Interesting performance metrics about a SAGE testing environment have been compiled by Jeong et al. [51]. Since the output rate of an application, once the rendering resolution, frame rate and pixel format are known, is easy to estimate, the network requirements of the full system is easy to estimate. As seen in the work referenced, given a number of applications with a perfectly foreseeable output rate (nearly 1 Gbps in the example), the throughput of the system scales linearly when adding more applications, until the network is saturated. The results point to very good network utilization, reaching up to 93.5% using RBUDP and 90.3% when streaming through TCP.

In the same work, different tests using applications streaming through a wide area network and using heterogeneous streaming sources have been taken in exam. It was also shown that performance can be improved linearly by adding more rendering nodes (that is, more receivers handling the input streams and pushing the pixels to the screen). Given the nature of the pixel streaming, there is a hard bound on the system's capability of handling very large video sources. Increasing video resolution leads to higher latency and lower frame rate, with a higher packet loss rate.

These inherent limits to the system call for high-grade multiple gigabit network equipment, in order to accommodate video streams at sufficient resolutions. Particularly when reaching 4K resolutions, or higher, handling video in real-time puts a very high strain on the network, more than on the processing components. Large resolutions can however be taxing computationally if videos need to be scaled or their pixel format needs transcoding before presentation. These operations need to be executed either on CPU or through a GPU-based transformation.

3.6 Interoperation

The SAGE system is built up on a group of independent processes, the *Free Space Manager*, applications, receivers and controllers, that cooperate in order to present multiple video streams onto a common tiled display. The quality of the visualization depends entirely on the interoperation of these components, thus an efficient communication and interfacing layer is required.

Applications contributing to the tiled frame buffer make use of the *SAGE Application Interface Library* (SAIL). Each application pushes its data through the high-bandwidth network that bridges the SAGE system using the same protocol provided by the library. The protocol represents a thin layer between application and network, that allows application developers to easily transmit output pixels and stream them to the correct display as uncompressed pixel data. This library and its interface will be discussed in the next section.

All SAGE components also communicate with each other using a message exchange protocol. Messages sent and received range from informative events about the system, to important commands and reconfiguration instructions. An overview of the control message exchange is given in Section 3.6.2.

3.6.1 SAIL interface

As described in the SAGE Documentation [50], two compatible software levels can be used to program SAGE applications: a low-level API provided in C++, and a simplified higher-level API in plain C. Both APIs are exposed by SAIL, the library that provides access to all SAGE features for application developers.

The first API is built upon the programming constructs of the library itself, thus providing insight into the primitives on which SAGE and SAIL are built.

The latter API instead provides a simple wrapper around these components, which make the task of writing a SAGE application more approachable. Being exposed as a plain C interface, this API can be used easily both from C and C++ code, and almost any other programming language and environment—for instance using the *Java Native Interface* (JNI) on Java or *Platform Invoke* (PInvoke) on .NET.

In the following overview, only the high-level C API will be taken under exam.

The exposed surface of this simplified API reduces the interoperation with SAGE to a couple of simple method calls which entirely wrap setting up the context and the streaming configuration with other SAGE components. More advanced features, like messaging, can be used only if needed by the application developer.

The following are the primary C API functions used by applications:

- `createSAIL()` is the main starting point for SAGE applications. This synchronous function takes the *application name* and the *FSM's IP address* as parameters, in addition to other parameters defining the graphical properties of the application (*width*, *height*, *desired frame-rate* and *pixel format*).

  When the function returns, a *SAIL object* is returned: this opaque structure is used as a handle to the SAGE context and is required as a parameter for almost all other functions.

  The SAGE handle can be destroyed using `deleteSAIL()`, the specular function which will disconnect all existing connections to the FSM, stop streaming and correctly dispose of the SAIL object.

- `getWallSize()` allows an application to query the full size of the FSM's wall (i.e., the "virtual frame buffer" size). This can be used to scale the output region's size according to the scale of the wall.

- While the application runs, it will be concerned almost exclusively with functions that handle output data generation and streaming. SAIL offers four different functions that perform these operations with different semantics.

  All functions work on data "frames", i.e. a simple data buffer that represents a single full frame of the application to be shown on the display. A SAIL frame is always as large as the application's whole output region.

  The data buffer is seen as a raw array of bytes (that is, expressed in standard C's type system, an array of `unsigned char` values) and its size is expressed as

  $$width \times height \times pixel\ depth$$

  where *pixel depth* is the size in bytes of a single pixel (usually 16, 24, or 32 bits).

  Internally, SAIL adopts a *double-buffering* technique in handling outbound data frames. This technique is based on a *producer–consumer* pattern, that allows the application to create a new data frame while SAIL transmits the previous data frame to the receiver in order for it to be displayed. Data production and transmission can thus occur in parallel.

  At any time, there is a *current* frame that is available to the developer (that needs to be filled in), and a *previous* frame that is held by SAIL and is transmitted to one or more SAGE receivers. Frames can be "swapped" by the developer: in this case SAIL ensures that the previous frame has completed transmission and swaps pointers to the frame buffers. The previous frame becomes the current one, and vice-versa.

  Calling the `nextBuffer()` function will, at any time, return a pointer to the current frame's data buffer. The developer can freely access data inside the buffer and alter it as needed by the application.

  When the buffer is ready to be transmitted, calling `swapBuffer()` will block until the previous frame is transmitted and then will swap buffers. Transmission of the current buffer (that now becomes the *previous* buffer) begins at once.

SAIL also exposes two additional convenience functions: swapping buffers and getting the new current buffer can be done with a single call to the `swapAndNextBuffer()` function. Conversely, the function `swapWithBuffer()` allows the developer to pass in an external data buffer, to be used as the source of data. (Notice that SAIL does not take ownership over the data pointer given as argument and keeps operating on its internal buffers.)

- As mentioned before, some applications may need to process incoming SAGE messages in order to react to particular events of the system.

  In this case SAIL works by adopting a blocking "message pump" pattern: the running thread calls into the `processMessages()` function, which will process any pending message if available. When message processing is completed, execution is returned back to the application.

  SAGE messages are parsed and passed to a callback function specified by the developer for further processing. Applications can distinguish between different kinds of messages based on their code and their payload data.

  For instance, applications may receive a `APP_QUIT` message when they are terminated by the FSM and need to exit the process. An `EVT_KEY` message is received when the user generates a key press on a UI controller, and so on.

  More details about SAGE's message exchange protocol and mechanisms can be found at page 80.

As seen, an application basically needs only two function calls in order to start working inside SAGE: one function to initialize SAIL and to configure its output surface, one function to get access to the output data buffer and to swap it out for transmission.

Thanks to this simple application and streaming model, existing programs, for most platforms and written in most programming languages, can easily be adapted to take advantage of the large visualization capabilities of SAGE, without requiring deep changes. In fact, the double-buffer swapping pattern adopted by SAIL is very easy to adapt to most video or audio players, which usually work using a similar buffer-swapping paradigm.

In fact, the software package in which SAGE is distributed by default provides a modified version of *MPlayer*, which includes a custom video output module. Since *MPlayer* video output modules work through an interface that swap in “planes” of data as they are decoded, these data structures can simply be swapped into SAIL for network transmission.

3.6.2 Control messaging

While SAIL is mainly concerned with pushing pixels from applications to receivers, a large part of SAGE’s operation revolves around message exchanges with the *Free Space Manager*.

The FSM exposes a developer-facing layer, called the “Event Communication Layer” (ECL), that allows applications, receivers, and SAGE UI clients (including third-party controllers) to interact with the system using messages.

Acting on user input, clients can send messages to control the FSM and the applications it manages, for instance setting up a new application, moving it from one location of the frame buffer to another or resizing its output region. In return, clients obtain SAGE event messages informing them about the current state of the system and its running applications.

The layer is based on a low-level message exchange protocol on top of raw TCP sockets between the FSM and other components. It supports a very high message exchange rate, in virtue of having very low overhead, but the messages use a simple text-based format and are thus limited to basic unstructured data payloads, enclosed within a fixed message packet format. Moreover, the barebone message format and the simple exchange protocol make the task of keeping track of the whole system’s status burdensome.

3.6.2.A Message format

SAGE ECL messages have 4 fixed-size data fields of 8 bytes, and 1 payload field, all separated by null characters, following the layout seen in Table 3.1.

By convention, there is a distinction between *command* messages (sent from a controller to the FSM) and *event* messages (sent from the FSM to a controller to signal an update to the system or an update between components). This distinction has no concrete impact on the message format however.

The *Distance* and *App code* message parameters are generally unused. Message *Codes* are defined by the SAGE Documentation [50]: commands intended for the FSM are to be found in the 1000–1100 range, commands

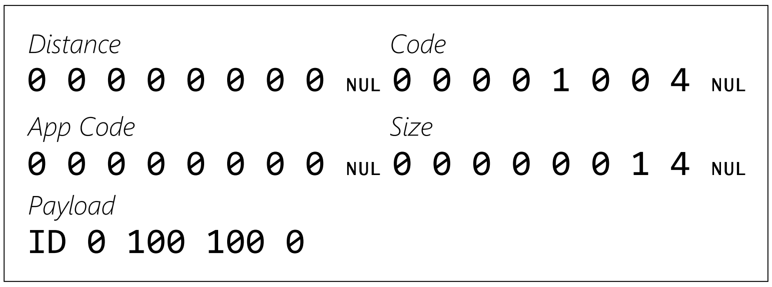
Distance	8 bytes
Code	8 bytes
App code	8 bytes
Size	8 bytes
Payload	*Size* bytes

Table 3.1: Layout of a SAGE message.

intended for application have codes between 31000–32000, while event codes start from 40000. *Payloads* are expressed as a sequence of values, encoded as text strings, and separated by ASCII spaces [50].

For instance, when the user manifests the intent of resizing an application (either by dragging and dropping the window handles from the *SAGE Web Control* interface, by using the mouse wheel in SAGE pointer, or in any other way), a message is sent to the FSM in the form of a command message. The code for resize commands is `RESIZE_WINDOW` (or, in numeric terms, 1004). Payload values differ widely between type of messages, some not containing any payload, some others instead containing long strings of data. In the case of a resizing command, the payload will contain the *Application ID* of the application to resize (seen in further detail in Section 3.6.2.B) and 4 coordinates, specifying the distance between the tiled display's edges and, respectively, the application's left, right, bottom and top border.

A sample resizing message as described can be seen in Figure 3.10. Note that the `ID` payload value will be replaced by the actual *Application ID* value of the target application.



```
Distance                  Code
0 0 0 0 0 0 0 0 NUL       0 0 0 0 1 0 0 4 NUL
App Code                  Size
0 0 0 0 0 0 0 0 NUL       0 0 0 0 0 0 1 4 NUL
Payload
ID 0 100 100 0
```

Figure 3.10: Sample SAGE ECL message of a resize command.

Other supported messages by the protocol include, for instance:

- `SAGE_UI_REG` (1000): signals the presence of a UI controller to the FSM. The FSM will not keep track of active UI clients. However, such a registration message forces the FSM to respond to the UI controller with a list of the running applications, known to the server.

Once the appropriate response is sent by the FSM, an UI client can build its user interface and show SAGE's state to the user.

- `EXEC_APP` (1001): is interpreted by the FSM as an application launch attempt. The payload includes the application name and the command line arguments that need to be supplied to the application on launch.

  The application process is started by the *SAGE Application Launcher*, which usually entails the spawning of a new application process on a machine on the SAGE cluster.

  Once an application process has been started correctly, the Application Launcher reports the success through an event message, using code `APP_INFO_RETURN` (40001), which includes the application's new ID (see 3.6.2.B for more details) and its position on the tiled display.

- `SHUTDOWN_APP` (1002): issues a termination command to a specific application, whose Application ID is specified in the payload.

  The FSM removes the application from its bookkeeping system immediately, also sending an `UI_APP_SHUTDOWN` (40003) event message back as confirmation. An `APP_QUIT` (33000) message is then sent to the application itself. It is customary, for well-behaved SAGE applications, to terminate their process as soon as they receive the quit message. Once the process terminates, the application shutdown process is complete (no additional event message is sent to signal this success, however).

- `MOVE_WINDOW` (1003): moves an application to another region of the tiled display. The message payload contains the target application's ID and the new coordinates to be used.

- `RESIZE_WINDOW` (1004): similarly, this message resizes the draw region of an application on the tiled display. The message payload contains the target application's ID and the new distances from the 4 edges of the tiled display.

- `EVT_CLICK` (31000) or `EVT_KEY` (31007): these messages (along with other message types expressing double-clicks, panning gesture, and so on) are generated by an UI controller and sent to an application using SAIL. The message payload usually contains the coordinates (in application space) of where the click has been performed.

Messages are received by SAIL and delivered to the application code, which will be able to process them using a common *message pump* pattern.

As can be seen from the previous list of message types, SAGE does not provide a real distinction between messages directed to the FSM and messages directed to other components, just as it doesn't formally distinguish between commands and events. Messages of the any kind can be sent indiscriminately to any component, which will receive the message, process it, and—if not interested—discard it. Some messages can be forwarded to the intended recipient, some other messages can be converted into an appropriate message and then routed to the correct recipient.

As an example of the last scenario, when the FSM receives a message with type `SAGE_Z_VALUE` or `BRING_TO_FRONT` (i.e., the command from a controller to push an application to the foreground), the FSM sends out a `RCV_CHANGE_DEPTH` message to all receivers on the system. The first two message types make sense only to the FSM, while the last one is only useful when sent to a receiver.

3.6.2.B Application IDs

As shown in the previous section, when issuing commands to a SAGE application through the FSM, applications need to be identified precisely. The FSM must know which message exchange channel will be used to forward commands and which application exactly will be receiving and handling the communication. That is, it must be easy to find out the IP address and the identity of the target application.

This task is carried out by the "Application ID". IDs are numeric, progressive values—starting from 1—which are ensured to be unique on a single SAGE installation. That is, any application running on a SAGE system can be sure it will be assigned an ID perfectly identifying it during its lifecycle.

Notice that Application IDs are not recycled when applications terminate, thus there is no danger of conflict.

All applications running on SAGE are assigned such a number, which is done by the FSM itself when starting a new application instance. There is no other way to know an ID before launch, nor is there a way to get a specific ID.

Assigned IDs are made known by the FSM asynchronously: after receiving an application launch command (i.e., `EXEC_APP`), the FSM launches the process and adds the new instance to its list of running applications. When the applications has completed initialization and has created a SAIL output surface, an event message with code `APP_INFO_RETURN` (40001) will be sent, containing the name of the application, its output region position, and the assigned Application ID. After receiving this event message, SAGE clients can use the ID to interact with the application.

No safety nor authentication mechanisms are provided for Application IDs: once an ID is known, any user can issue any kind of command to the application.

Chapter 4

Immersive Virtual Environment for SAGE

Over the course of Chapter 3, *Scalable Adaptive Graphics Environment* (SAGE) was presented as a performing and flexible open-source middleware solution for video walls, enabling data-intensive and collaborative visualizations for local and remote users.

In this chapter, the *Interactive Virtual Environment* (IVE) system is introduced [53]. IVE was designed to provide a simple and scalable way of controlling and managing virtual environment systems. The system is also intended for multi-tenant scenarios (like home automation systems with multiple rooms, each one potentially used to provide an immersive experience).

The system presented is built on top of SAGE, and presents a more extensible and abstracted way to coordinate immersive multisensorial virtual environments, on one or more high resolution video walls. As far as SAGE is lacking as a simple to use and simple to manage solution for consumer-oriented virtual reality systems, IVE is designed to close these gaps. The system is intended to fully control one or more SAGE installations, including their start up and configuration.

IVE also allows the creation of simple interactive scenarios, that can be used to control or manipulate the experience, determining what is seen on screen. Also, the system provides a number of friendly APIs that allow interaction with the system's components. These programming interfaces are also used by mobile applications, providing access and control to end-users.

In Section 4.1 an overview of IVE's software architecture and its relation to SAGE is presented. Section 4.2 goes into the details of IVE's implementation, including its messaging protocol used to connect servers to clients (4.2.1) and how it interoperates with SAGE (4.2.2). Finally, in Section 4.3 the experimental setup used to develop and test IVE is be presented.

4.1 Software architecture

According to the scope and goals of the project, the *Interactive Virtual Environment* (IVE) system has been designed with the following main requisites and features in mind:

- Automatically start IVE itself and the virtual environment based on its configuration.
- Manage one or more video walls running SAGE, independently.
- Expose a friendly API for client applications and developers.
- Support easy extensibility, in terms of new sensors and actuators, and in terms of scenarios that can be created.

In order to control multiple SAGE setups, an IVE system is architecturally split up into *logical groups*, one for each video wall. All logical groups are controlled by one central server, which at the same time can be controlled by users through dedicated client applications. Each logical group is bound to an entire, independent video surface, with no intersections nor overlaps with surfaces of other groups.

IVE is structured in a complex master/slave topology, as depicted in Figure 4.1: the whole system is managed by a single supervising *IVE Master*, while each independent display region is controlled by an *IVE Devil* server. On its turn, each Devil may control any given number of *IVE Slave* servers, whose activities and interactions are still orchestrated by the master server.

In detail, the main components of an IVE system are the following:

- **IVE Master**: a standalone server, controlling the IVE system and exposing a high-level communication protocol for clients and end-users.

  It manages the system's state and controls communication channels to all other components. The master will also bootstrap other servers if needed by the configuration.

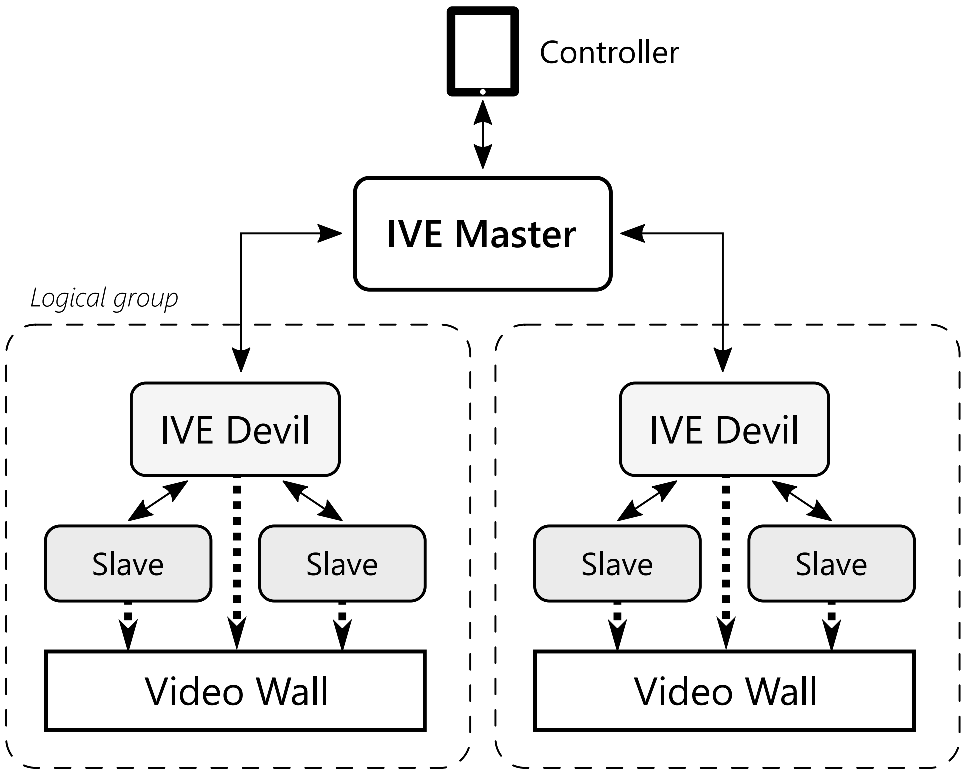


Figure 4.1: IVE architecture overview.

- **IVE Devil**: server overseeing a single logical IVE group, dedicated to an independent display surface.

  The Devil receives commands from the Master and communicates events back to it, thus keeping the system's state in sync among servers.

- **IVE Slave**: is a passive worker server of an IVE group.

  A Slave is directly controlled by the Devil of its IVE logical group, which issues commands to it in order to drive the tiled display.

Each logical group in an IVE system internally runs an independent SAGE system. The SAGE *Free Space Manager* (the component that manages the "virtual frame buffer" drawn onto the video wall) and the receivers of each logical group are configured in order to match the physical topology and the tiled display of the group. See Section 3.1.1 about how SAGE manages output and tiling.

In every logical group there may be a variable number of SAGE components running at the same time. Figure 4.2 shows how SAGE components inside the same group are spread out.

It is important to note that SAGE components from different logical groups do not interact in any way, if not indirectly through IVE. Also, since high bandwidth streaming is needed only to push raw pixel data to SAGE receivers, only the components of the same logical group need to actually be connected to a high speed local network.

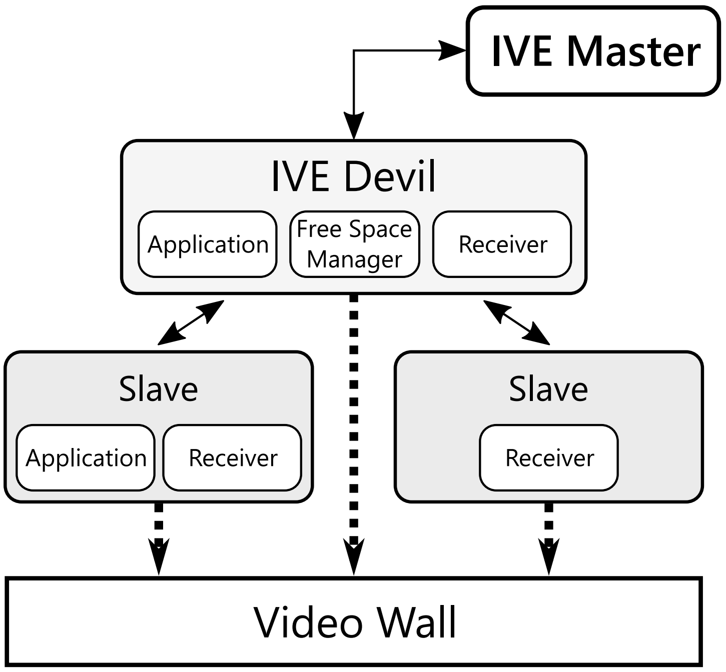


Figure 4.2: Relations between IVE and SAGE components.

Within an IVE logical group, all operations concerning SAGE components are directly or indirectly managed by one IVE Devil server. Notice that, as mentioned before, SAGE components can run on the same workstation or be freely distributed through a cluster of interconnected workstations. IVE Devil and Slave servers, on the other hand, are assumed to run on different physical systems.

As shown in Figure 4.2, an IVE Devil always runs the one SAGE *Free Space Manager* for its logical group. There is only one FSM and only one Devil for each logical group.

Since the workstation on which the Devil runs usually also has a graphical adapter and is connected to the tiled display, the same workstation will also run a SAGE receiver to actually draw onto the screen. If additional receivers are needed—because of how the display is divided up in tiles—those will run on other workstations, each one running an IVE Slave server.

Applications running within a logical group and generating visual data for its display can run either on the Devil or on any other Slave server. The actual workstation executing a SAGE application is ultimately determined by the IVE Devil, according to a load balancing policy described in Section 4.2.5.

The IVE Master is accountable for the high-level control over the whole system. Actual interoperation with SAGE processes is performed by the IVE Devil server, or by the Slave—acting as a proxy for the Devil—for SAGE processes on other machines.

At bootstrap, the IVE Master starts up all IVE Devils needed, one for each logical group. As soon the Devils have completed the boot process and determined their configuration, Slave servers are started, followed by the start up of the needed SAGE processes.

The one-to-many relation between IVE and SAGE components is shown in Table 4.1, also reporting the cardinality (i.e., the number of existing components) of each component.

IVE	**SAGE**
Master	–
Devil	Free Space Manager (1) Receiver (0-1) Application (0+)
Slave	Receiver (1) Application (0+)

Table 4.1: Mapping between IVE and SAGE components.

While a large IVE system may require many machines, running the Master and several other separated SAGE systems, a minimal system can be built on a single workstation. In this case, the IVE Master and the Devil share the same machine. On a single machine, only one SAGE system will be installed, running both the FSM and the only receiver. With only one receiver, no additional IVE Slave is needed. Applications will run on workstation and stream pixel data locally to the receiver, to be drawn onto the video wall.

4.2 Implementation

All IVE components, Master, Devil and Slave, are implemented in Java and run as standalone headless processes running on a standard *Java Virtual Machine* (JVM) instance.

Underneath the IVE software layer, the bulk of the work is done by Devil and Slave nodes, managing their respective SAGE processes following the commands issued by the Master node. All SAGE components also run as standalone headless processes, started and monitored by the IVE software: this includes the FSM (managing the whole frame buffer directly mapped onto the display surface of that particular IVE group), SAGE Receivers (managing tiles of the frame buffer) and all applications generating the output video data. Interaction with SAGE, through standard process management facilities provided by the operating system and TCP sockets, is seen in detail in Section 4.2.2.

Components of IVE can, to a certain extent, manage SAGE's configuration. However, most aspects of how SAGE works and is configured, especially the setup of the video wall and other hardware, need to be hardwired as configuration files by the user. IVE components must be configured in a similar way by the user, particularly in terms of setting the IP addresses of all components composing the system. Even if each logical group needs precise configuration during installation, the IVE Master is capable of exploiting an *auto-discovery* method, described in Section 4.2.4, that allows it to work without preconfiguration.

An IVE system provides means for the end-user to control the virtual environment through client applications. In particular, an Android application for tablets was developed using the APIs exposed by IVE. This controller is also implemented in Java and runs on a standard tablet running Android 4.2 (*Jelly Bean*) or superior (see Section 4.2.6).

4.2.1 Messaging protocol

The three kinds of components in IVE make use of a simple, text-based message passing protocol to communicate. While the overall working principles of the protocol is similar to the one used by SAGE, IVE takes a slightly higher-level and more flexible approach, both in terms of flow, routing and message formatting.

4.2.1.A Message transport

Like the SAGE message exchange protocol, covered in Section 3.2.3, the protocol adopted for IVE distinguishes between messages going "downward", from Master to Slave, and messages going "upward", from Slave to Master. While in SAGE nomenclature the first are known as "commands" and the latter as "events", IVE makes the distinction between "**in**-messages" (messages that go downward, into the inner levels) and "**out**-messages" (messages that go upward, out of the inner levels).

In SAGE there is no concept of routing a message to destination, and messages need to be actively processed by a component in order to be, possibly, forwarded to another component. In most cases, commands and events are sent to the FSM, that does the heavy lifting of processing messages and sending the appropriate message to the intended components.

On the other hand, IVE performs routing of messages to a certain extent: since most messages originate from clients and controllers connected to the Master server, the latter takes care of forwarding in-messages as appropriate, to the concerned Devil or Slave servers. IVE Master servers have full knowledge of all running servers, and can deliver the message directly. Same considerations apply to out-messages: on receiving an update from a Devil or a Slave, the Master can forward it to any connected clients, or give the information back through an API.

The way messages are exchanged between components of IVE and SAGE is shown in Figure 4.3. Dashed lines between IVE components indicate an out-message (traveling up), while continuous lines indicate an in-message (traveling down). Other messages exchanged, between SAGE components and bridging between IVE and SAGE, are SAGE messages (direction is not noted graphically in this case).

In a similar fashion to the message exchanging adopted in SAGE, the protocol used by IVE works across socket-based TCP channels. On start up it is the Master server's duty to open up persistent TCP socket connections to Devil and Slave servers alike. These sockets are kept alive in order to continuously exchange messages. As for SAGE, the maximum throughput rate of messages is quite high. The slight overhead for JSON encoding and decoding is offset by the far lower exchange rate needed by IVE: while SAGE must communicate with receivers and applications frequently for each update to the streaming configuration, IVE sends out far fewer messages.

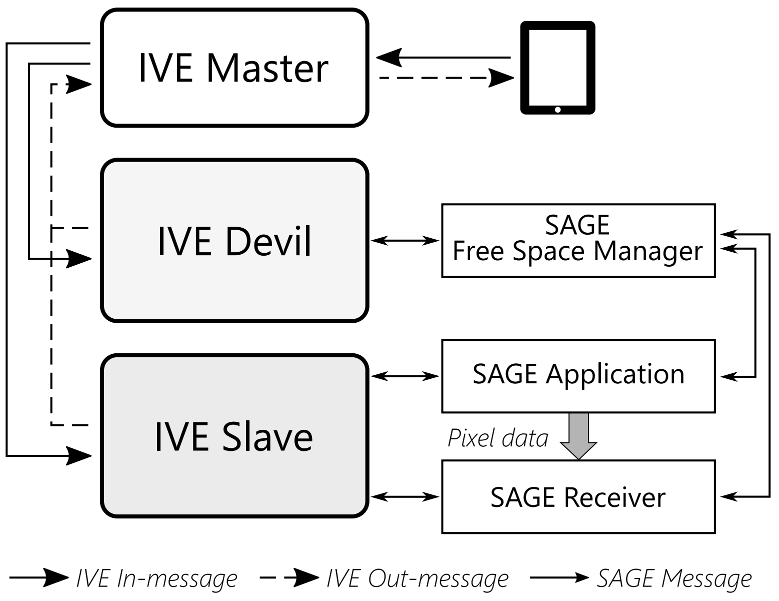


Figure 4.3: Overview of message routing in IVE.

4.2.1.B Message encoding and types

Messages are serialized using the text-based *JavaScript Object Notation* (JSON) format. This allows IVE to eschew the fixed-size encoding used by SAGE, and expose a fully extensible message format.

Choosing this particular encoding also makes the IVE servers easy to debug and develop for: testing messages need not to be painstakingly constructed using binary values, but are based only upon strings of text, visible to the user.

The protocol adopted runs over a simple TCP socket, encoding each message using a text-based scheme. Each single message is separated from the others using a *newline* character. Thanks to this simple scheme, messages are composed only by the textual JSON payload, followed by a *newline*, thus making protocol implementation particularly easy.

One limitation of this protocol however is that messages cannot actually contain any *newline* character. Since IVE messages never contain multiple lines of text—actually, most messages only contain numeric information and are encoded in JSON using no spaces on a single line—this never becomes a real issue.

The JSON payload is represented by one single JSON object, essentially a list of properties and primitive values. The *message type* string is the only required property of the object, and is needed to recognize the type of decoding and processing is needed by the message.

Using legible JSON formating, a sample payload looks like the following:

```
{
    type: "START_SAGE"
}
```

The JSON object can contain other information, formatted as additional properties, in order to pass additional parameters to the message handler.

The main *in-message* types available are as follows:

- `CMD_LOG_IN`: sent by clients to the Master server in order to login for control. On a successful login, the Master responds with an *out-message* of type `LOGIN`.

  User management and login is discussed in Section 4.2.3.

- `START_SAGE`: when received by a Devil or Slave server, this message kicks off the SAGE system (if it isn't already running). Needed SAGE processes (the FSM or the receivers) are started and the IVE server waits for the system to be up and running before processing other messages.

- `SAGE_SHUTDOWN`: when this message is received, all SAGE processes, including receivers and applications, are terminated.

- `SAGE_START_APP`: this generic message includes an "app-name" parameter, determining the kind of application that should be started. Additionally, it can include any number of additional parameters, that will be sent to the application and can determine its mode of operation (for instance the video file that should be played back by a video player).

  The message can be sent by a client to the Master server, which will then forward it to the intended Devil server for execution. How the target server is picked is described in Section 4.2.5.

  When the application is started successfully, an `APP_STARTED` *out-message* is generated, which can be used to uniquely identify the application instance on the IVE system (application identification and tracking is discussed in Section 4.2.2).

  In Section 4.2.1.E the full exchange of messages needed to start an application is described.

- `SAGE_CMD_SHUTDOWN_APP`: this message contains an *ID* of the application to be terminated. The Master server will forward the message to the correct Slave or Master server, which will remove the application from the virtual environment (and kill its related process).

  When the application is terminated, a corresponding `APP_SHUTDOWN` message is sent back.

Once applications are running on IVE, they can of course be manipulated by sending update commands. The following messages can be sent to running applications, applying immediate changes or scheduling smooth animations, which are performed by the Devil server:

- `SAGE_CMD_MW`,
  `SAGE_CMD_RESIZE_W`,
  `SAGE_CMD_ROTATE_W`,
  `SAGE_CMD_SET_ALPHA`: these message types allow controllers to, respectively, move, resize, rotate, or set the alpha transparency of a target application. The application targeted by the message is specified as a parameter. The message will be routed to the correct Devil or Slave server by the Master.

  When the update is performed, a corresponding `APP_UPDATED` *out-message* is generated.

- `DRIFT_ANIM`,
  `ZOOM_ANIM`: these messages allow the Devil or Slave server to progressively change the applications parameters (either its position or its size) in order to simulate a smooth animation of the application window.

  Animations are implemented by scheduling a sequence of timed application updates, sent to the SAGE system. On large SAGE systems and with large applications running on multiple tiles, this can have some performance implications, since SAGE streaming needs to be reconfigured for each application update.

An IVE system also provides controllers with means to query about the state of the virtual environment. This is particularly useful for controllers that connect to a running system and need to setup their view in order to represent the current state of IVE.

These messages mark a decisive improvement over SAGE, which does provide only a very limited—and in some ways unreliable—interface to the system. In IVE, SAGE's states is constantly monitored by Devil and Slave servers, enabling the Master server to reliably respond to status queries.

Also notice that IVE has the concept of a "media library", that is a collection of media files that is located on the same network of the IVE system and can be streamed from any component. Similarly to the SAGE "media store" available to SAGE pointer users (see 3.1.2.D), this collection of media files can be used when starting applications—for instance selecting a video file to be played back by a video player.

- `REQUIRE_LIBRARY`: this message can be sent to the Master server, which will respond with a `LIBRARY` message, containing a list of registered *media items*.

  Media items are identified by a unique *ID* and some additional properties, like a title and a thumbnail image (accessible through HTTP). Items can be of the following type:

  - Video files,
  - Audio files,
  - Static images,
  - Youtube videos.

  All kinds of media items are streaming using HTTP by the respective applications accessing them.

- `REQUIRE_CONFIGURATION`: a message of this type requests a complete view of the system's logical groups and servers. The Master responds with a `CONFIGURATION` message, which contains a list of servers, their information (IP address, role and status), and the list of running applications.

Finally, there is a set of additional messages that apply only to specific applications. These messages can be generated by a controller and will be forwarded to the correct Devil or Slave by the Master. If there is a mismatch between type of message and type of application (for instance, a message intended for a movie player is sent to an image viewer) the message is dropped. Otherwise, the corresponding SAGE command is sent to the application process.

For instance, the following message types only apply to movie player applications (that is, applications that rely on the *MPlayer* application for SAGE):

- `MPLAYER_CHANGE_VOLUME_CMD` : change the audio output volume of an existing movie player application.
- `MPLAYER_SEEK_CMD` : seeks inside the file currently played back by the movie player. The message contains a seek position parameter indicating the position where the playhead should be moved to.
- `MPLAYER_PAUSE` : pauses and resumes playback of an existing movie player application.

4.2.1.C Message routing

An IVE system may span multiple computing devices, from a smartphone running a controller, to the workstation running the SAGE receiver and presenting pixels onto the screen.

While in SAGE there is no facility to understand which process is running where, except tracking processes as they are spawned, IVE supervises how components are started and where they are physically located. Instead of requiring the sender to know where the message's destination node is located on the network, all IVE components are able to route messages to their destination.

In practice, client applications only need to open one connection to the Master server. All messages will be sent to the Master, which will then hierarchically route them to the final destination.

There are two routing parameters, that can appear inside the message payload, which help IVE to route the message correctly. Firstly, the `slaveIp` parameter indicates the IP address of the logical group master (i.e., the IVE Devil) that should handle the message. Secondly, if the message needs to be forwarded to an IVE Slave server, the `subSlaveIp` parameter is used to specify the final IP address the message is sent to.

For instance, when launching a new application, the controller will decide beforehand on which logical group the application will be spawned. Once decided, the `slaveIp` parameter is set to the logical group's Devil server IP address, and sent to the Master. The Master forwards the message to the Devil. On its turn, the Devil determines if the message can be handled by himself. If not, the Devil determines the target Slave, sets the `subSlaveIp` parameter, and forwards the message along its last hop.

The final payload of a message sent to Devil `192.168.1.2` and relayed to Slave `192.169.1.3` would look like this:

```
{
    type: "START_SAGE",
    slaveIp: "192.168.1.2",
    subSlaveIp: "192.168.1.3"
}
```

4.2.1.D Application identification

Applications running inside a SAGE environment are equipped by an *Application ID*, as described in Section 3.6.2.B. This ID uniquely identifies the application instance inside SAGE and allows controllers to interact with it. However, these IDs are only visible to the SAGE system itself and have no particular meaning outside of it.

IVE provides an additional, all-comprising Application ID, which can be used to uniquely identify applications, no matter on which SAGE system they are in fact running. Application IDs generated by IVE are simple integer numbers, and they are ensured to be unique during an IVE session.

The IVE Master server keeps track of all instantiated applications, also keeping a map of all instances, their IVE Application ID, their SAGE Application ID, and the IP of the machine they are running on. (See Section 4.2.2 for more about the interoperation with SAGE.) Thus, when sending a message to an application, controller can send messages only to the Master, providing the target ID as a message parameter. The message will be routed correctly to the intended application.

To ensure that IDs are always unique, they are always assigned by the Master itself when creating a new application.

4.2.1.E Sample message exchange for application launch

To illustrate how the message passing protocol works in detail, the scenario of a user launching a video player application will be shown.

Assuming the user is already connected to the IVE system through their client application, the user will pick to start a video player application. The application will generate the following *in-message*, directed to the Master server:

```
{
    type: "SAGE_START_APP",
    slaveIp: "192.168.1.2",
    appId: 123,
    parameters: {
        "app-name": "mplayer",
        "loop": "true",
        "srcs": [
            {
                type: 3,
                source: "http://192.168.1.1/file.mp4"
            }
        ]
    }
}
```

The controller knows in which logical group the application should be launched, therefore the `slaveIp` parameter is set to the IP address of the intended target Devil server. The `subSlaveIp` parameter is not set instead (see 4.2.1.C).

A new application ID is generated randomly for the message. In this case, the value 123 is used for parameter `appId` (see 4.2.1.D).

Additional parameters indicate the launch arguments for the *MPlayer* process. In the example above, the video player will be launched to play back a single audio/video file, streamed over HTTP, and will loop this single file indefinitely.

When the message reaches the Devil server, the draw region of the application is determined. Then, the draw region is used to determine the best server to run the application. In this sample, IVE determines that the application will mainly run on a secondary workstation in the same logical group, and thus forwards the message accordingly.

```
{
    type: "SAGE_START_APP",
    slaveIp: "192.168.1.2",
    subSlaveIp: "192.168.1.3",
    appId: 123,
    parameters: ...
}
```

The contents of the message are left intact, while the `subSlaveIp` parameter is added, containing the IP address of the target Slave server.

Once the Slave receives the message, it processes the command by registering the application locally and spawning a new *MPlayer* process, with the supplied command lines arguments. The Slave listens for updates from SAGE's FSM, in particular for the SAGE *Application ID* assigned to the new application (in this sample the generated ID is 12).

When the new application is correctly registered by SAGE, the application instance is registered by the IVE Slave as well. A confirmation message, with all the details about the application, is sent back to the Master, which will forward the information to the controller.

```
{
    type: "APP_STARTED",
    application: {
        slaveIp: "192.168.1.2",
        subSlaveIp: "192.168.1.3",
        id: 123,
        appName: "mplayer",
        isSageApp: true,
        sageAppID: 12,
        left: 100,
        right: 100,
        bottom: 100,
        top: 100,
        z: 0,
        alpha: 255
    },
    slaveIp: "192.168.1.2"
}
```

After this exchange, the controller can continue controlling the applications behavior and its lifecycle, by identifying the application through its ID.

4.2.2 Interoperation with SAGE

As described before in Section 3.1, a SAGE installation is composed of several independent processes, that cannot be managed through a single interface. Also, the SAGE system has no high-level understanding of the lifecycle of applications that draw on its frame buffer, nor of how these applications interact with each other and other components. IVE tackles this issue by essentially wrapping each SAGE process by an IVE component, and keeping track of their status.

All SAGE components are launched by IVE as external processes using the system runtime. In particular, for each logical group, the SAGE *Free Space Manager* is launched by the IVE Devil, while receivers and applications are launched by Devil and Slave servers.

Processes that are part of SAGE have two methods of communicating information: either they send messages through the FSM's "Event Communication Layer" (see Section 3.1.2.A), or to the standard output stream (`stdout`). IVE components will thus both read update messages, by opening a TCP socket connection, and intercept output streams, attempting to parse the output for updates or other information.

In this way IVE is capable of providing a complete and coherent overview of the system, even if by default SAGE does not expose such detailed information and has a far more limited vision of its components and the running applications. Commands and status queries exposed through IVE thus enable a much more powerful and rich message exchange than would be possible by using SAGE alone.

For instance, SAGE's *MPlayer* application can be controlled by sending ECL command messages (in order to pause and resume playback, for instance), but the application does not provide detailed updates about its status through event messages. Nonetheless, *MPlayer* writes different status updates directly to its standard output stream, like its playback position inside the file. When the application is launched, the managing IVE component (an IVE Devil or Slave) hooks onto the output stream, parses out interesting information and forwards it as IVE *out-messages*. This means that the IVE Master can keep track of whether a video player application is playing or is paused, or its position within the played back file—based on messages coming from lower-level IVE components—and is thus able to provide a full snapshot of the system's state through its API.

A full map of the system's configuration and details of all running applications, including their metadata (like SAGE Application IDs, needed to send SAGE commands), are stored by the IVE Master.

4.2.3 User management and security

A simple user management system is built into IVE, to provide a basic access control to users. Access control is applied only at the IVE Master level, toward connections from client applications.

Every client connecting to the Master server to send messages to the system, must first perform a login step, by sending a `CMD_LOG_IN` message. The message must contain a username and a password parameter. If the login succeeds a `LOGIN` confirmation message is sent back, and the communication channel with the client is cleared and can be used to control the system.

Notice that user management is limited to a single registered user, with a single couple of username and password set through IVE's configuration file. Also, there is no concept of *roles*: the single user has full access to the whole system.

Moreover, notice also that username and password are sent in clear, just like every other IVE message. The message exchange protocol is thus particularly susceptible to tampering, *man-in-the-middle* attacks and packet sniffing.

4.2.4 Auto discovery

Being intended to work on dedicated installations, SAGE mostly relies on static configuration files for its setup. Instead, IVE is designed to work in an environment where subsets of the system may not be available or may be intentionally turned off. Moreover, all components of an IVE installation are located on the same network, while SAGE takes into account that sources may be remote and stream video through the Internet. Thus, IVE can rely on an auto discovery process in order to detect the available components as they come online.

System start-up proceeds as follows:

1. *IVE Master* and *Devil* processes start as soon as the boot phase of the systems where they respectively reside is completed.

2. *IVE Devil* nodes announce their presence with periodical UDP broadcast messages on the network.

3. The *IVE Master* will detect newly started *Devils*, register them and initiate a communication channel.

Devils are recognized and setup by the *Master* according to the configuration defined by the user during the initial installation. *Slave* servers are started by *Devil* instances as remote processes.

4. *IVE Devils* and *Slaves* start their SAGE processes, including the FSM and the receiver. Since SAGE installations are highly tailored to their hardware setup, these instances depend on preconfigured local configuration files.

5. The *IVE Master* starts announcing itself using periodical UDP broadcast messages on the network.

6. *IVE Controllers* can detect the presence of the *Master* thanks to the broadcast message and initiate a connection to it. After login, the *Controller* can take control over the system.

4.2.5 Load balancing

Applications in SAGE generate a stream of pixel data, that is transferred to a receiver, appointed to present the pixel data on the tiled display. In some cases, it is necessary for an application to split up its data and stream it to multiple receivers. Figure 3.8 shows a case where the application's target region overlaps two tiles of the video wall, controlled by different receivers. When the receivers and the application are located on different physical machines, the application must transfer the pixel data through the network, in order for it to reach the video wall. This can quickly put a high strain on the network, quickly reaching gigabit-per-second bandwidths [90].

IVE is designed to keep a high level overview of where applications run and where they are displayed. When starting an application, the IVE Devil server that receives the request takes into account the target region where the application will be prevalently shown and, when starting the actual SAGE application process, will spawn the process on the nearest machine to the receiver—ideally the machine running the receiver itself.

Figure 4.4 shows that, when an application is running on the same Slave (or Devil, for that matter) server as its target receiver, all data transfer through the network can be avoided. When a part of the target region, albeit small, overlaps on another tile of the video wall, the video data must be streamed from the application to the corresponding receiver, which requires a high-bandwidth data transfer.

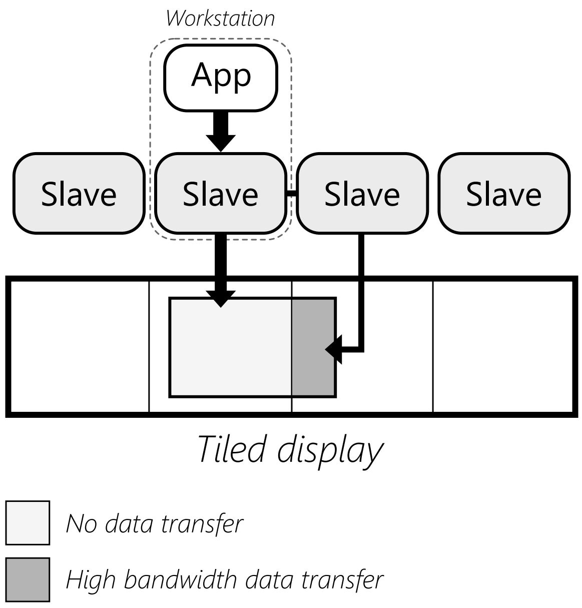


Figure 4.4: Application load balancing scheme in IVE.

At the moment, the load balancing decision only takes into account the initial starting region where an application will be drawn, when selecting a machine to spawn the process. If an application is moved or scaled for any reason, for instance by the effect of a scenario or the action of a user, its draw region may move to another tile. In this case, relocating an application process from one machine to another is theoretically feasible for simple, static applications (e.g. image viewers), but still poses a challenging problem for real-time multimedia sources like videos or rendered outputs.

4.2.6 IVE controller for Android

The messaging exchange protocol used by IVE and described in Section 4.2.1 exposes a quite rich set of interfaces, that allow third-party controller clients to query the state of the system, present a coherent user interface to the end-user, and to control applications. In fact, any device capable of establishing a connection on the same network used by IVE, and capable of exchanging JSON encoded messages through a TCP socket, can be used to control the system. In order to showcase the possibility of controlling IVE entirely from a mobile application, a sample controller for Android tablets was developed.

The application has been designed as a standard, tablet-compatible, application for Android 4.2 (*Jelly Bean*). Thanks to the fact that Android applications can be programmed using Java, most of the IVE messaging code (also developed in Java) was reused for the mobile app without changes.

The application is based on two main components: the front-end *Activity*, showing the state of IVE to the user, and a back-end *Service*, that connects to the IVE Master and keeps the connection alive, continuously receiving updates through a TCP socket.

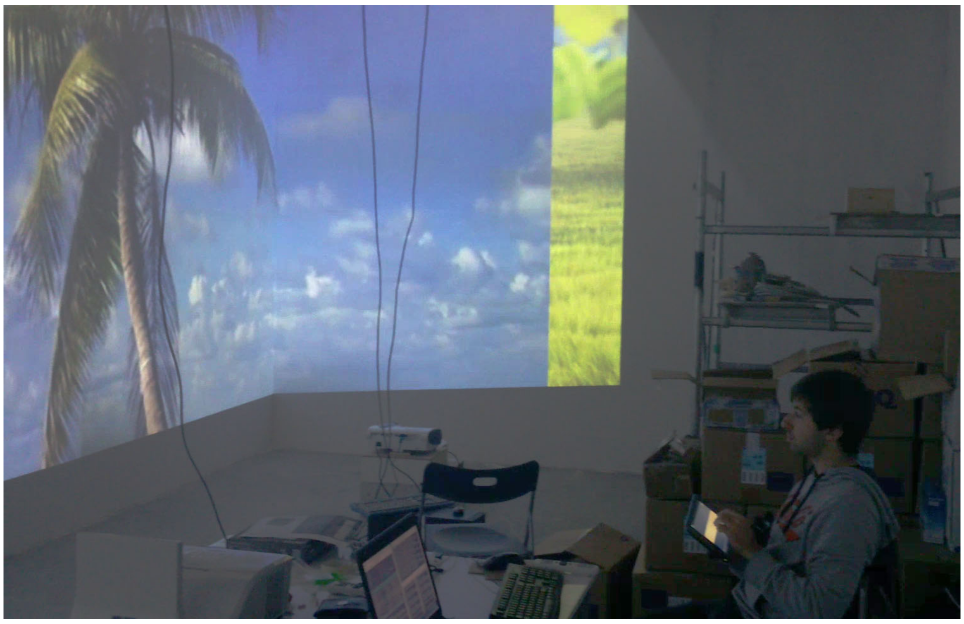


Figure 4.5: A user controlling an IVE setup using an Android tablet and the IVE application.

On start-up, the application looks for a running IVE Master instance, listening for broadcast messages on the local Wi-Fi network. When an IVE Master is detected, the application will automatically connect to it, asking the user for username and password.

After the user has been authenticated (see Section 4.2.3), the application queries the Master for the initial state of the IVE system. After receiving both the configuration, the list of servers and the list of running applications, the application can present IVE's state on screen. Each IVE group's display is shown as a colored rectangle, while running applications are shown as gray windows on top of them.

During operation, applications can be drag & dropped around, resized using touch, started using a menu or controlled by tapping on them. The application is also capable of accessing IVE's media library and its scenario library.

In Figure 4.5 a user of the application is shown, while he alters the position of a video playing application on top of another video application.

4.3 Experimental setup

A prototypical installation of the IVE system has been realized in a dedicated room for demonstration and testing purposes. The main wall of the room measures about 11 × 3 m, while secondary side walls measure 2 × 3 m.

The setup is intended to entirely cover the main surface and the lateral walls of the room with a single complex visualization. To this purpose, 8 BenQ LW61ST projectors where used for the main surface and 2 identical projectors for each side wall, totaling 12 projectors to cover the entire surface. The overall projected frame buffer accounts for 7680 × 1440 total pixels (that is, roughly 11 mega pixels).

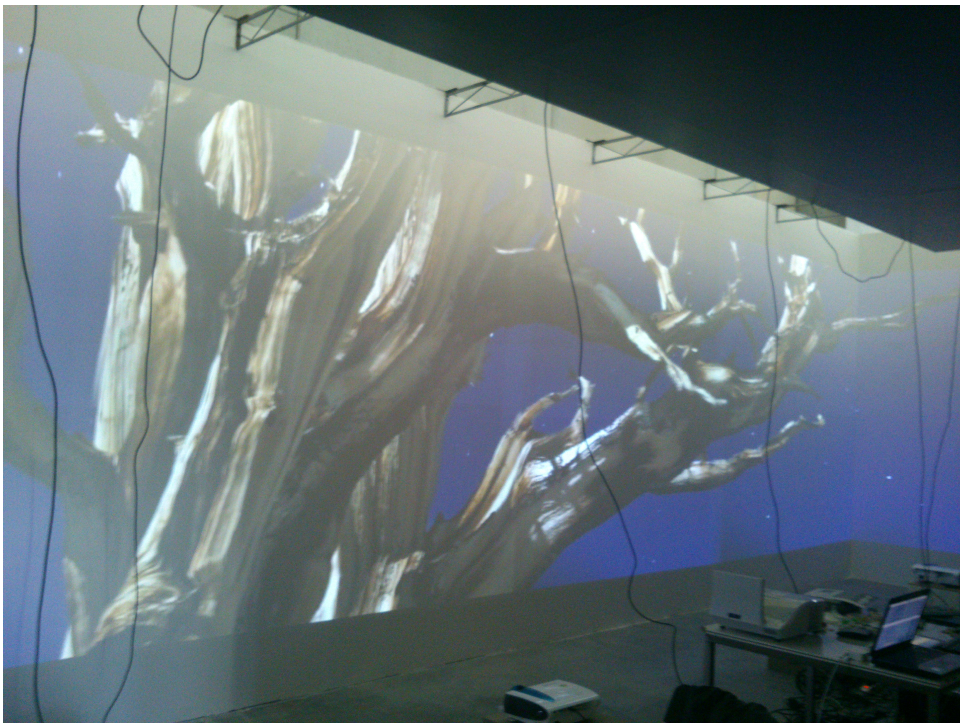


Figure 4.6: An IVE installation running a simple immersive scenario.

The surface is split in three logical regions, each managed by a single IVE Slave node. The workstation managing the main screen also runs the

Master and a Devil server at the same time. (This adopted setup makes IVE run as a *de facto* standalone system, like a single logical group. However, the IVE Master might in fact be located outside the room, or even remotely, while also managing other IVE Devil servers at the same time.)

All IVE nodes are connected by a high-performance 10 gigabit network, which supports high bit-rate raw pixel data passing from one server to another. The network makes use of one Netgear Prosafe XS708E gigabit Ethernet switch and workstations are equipped with Intel X540-T1 network cards. A Wi-Fi access point is also present in order to provide access to the controller running on an Android tablet.

The central workstation running the Master and the Devil has the more onerous workload of the scenario, having to drive 8 projectors while also controlling the other two machines. The workstation is equipped with two NVIDIA Quadro K5000 video cards (each sporting 2 DVI and 2 Displayport video outputs) and an NVIDIA Quadro Sync card[1]. The two secondary computers driving the total of 4 projectors on the sides of the room are equipped with single NVIDIA GTX670 video cards. Both kinds of workstation are also equipped with Intel i7 3770 processors, SSDs and respectively 8 and 4 GB of RAM.

Each machine runs Ubuntu 12.04 LTS, using the Compiz desktop manager and the *LightTwist* plug-in for projection deformation correction and alignment.

An overview of the physical IVE installation in pictures can be seen in Appendix A.

[1]This particular card is needed to synchronize the two video cards and allow them to run the 8 output screens as a single coherent desktop surface on Linux systems. On Windows, on an NVIDIA-approved workstation, the Sync card would not have been necessary.

Chapter 5

Hardware acceleration

The *Scalable Adaptive Graphics Environment*, known as SAGE, has been shown to be a viable solution to drive and manage large-scale shared displays, without resolutions constraints, that enable collaborative work or immersive virtual environment systems, such as the *Interactive Virtual Environment* (IVE), presented in Chapter 4.

These results are supported by the variety of reported installations and real-world applications, leading to the joint project of a persistent distributed visualization facility (i.e., the GLVF, *Global Lambda Visualization Facility*, introduced by Leigh et al. in 2006) grown out of the *OptIPuter* and its related projects [56, 93, 25].

Practical advantages of such systems have been explored at length, for instance as multi-user collaborative environments for educational scenarios as documented by Jagodic et al. [49], or in pilot studies in remote multi-directional conferencing for medical consultation and education, as described by Mateevitsi et al. [64].

However, as previously discussed (see Section 3.5), high resolution pixel streaming entails very high performance requirements, in particular in terms of network capacity. In most cases, memory and transfer bandwidth are the primary bottlenecks of the system.

As such, once the capacity of transferring memory from one component of the system to another is saturated, exploiting advanced hardware capabilities to speed up computation does not bring any concrete benefit to the system. Even if the decoding of compressed files, or the composition of the final rendered image, could benefit from acceleration, the frame rate of images displayed by SAGE is almost exclusively determined by the network's capacity [90].

Since SAGE was first developed and deployed, the technical landscape has changed profoundly. With the advent and popularization of HTML 5, high-performance JavaScript interpreters, WebGL, Canvas with accelerated 2D rendering, and so-called *Rich Internet Application*, Internet browsers have become powerful and ubiquitous rendering tools.

In fact, contemporary browsers, by their nature, provide access to high-performance graphics with easy programmability and full networking capabilities at the same time. Both features were formerly available only to native applications, while nowadays web applications written with HTML and JavaScript are increasingly popular, portable, and far more accessible by a growing community of developers.

The evolution of the SAGE project, which started in 2004, matured into the SAGE2 project during the last years. While keeping SAGE's original foundations intact, SAGE2 adopts the browser, the "cloud", and portable web technology as its new cornerstones.

A detailed introduction and technical overview of SAGE2 will be given in the next section. Because of the peculiar way in which video streams are decoded and presented on screen in SAGE2, two different hardware acceleration approaches are presented. The first exploits acceleration techniques on the renderer's side, just before drawing and composition, and is described in Section 5.2. The second works by decoding videos on the server's hardware, and is discussed in Section 5.3. In the closing section, a sample implementation using real hardware is discussed, together with performance benchmarks, and a glimpse of a modular hardware acceleration scheme using commodity embedded systems.

5.1 SAGE2

The *Scalable Amplified Group Environment* project (SAGE2) is a portable, browser-based, open-source solution for data intensive co-located and remote collaboration. The software is based around modern web technologies, both on the server and the client side, and can be used as a flexible graphics streaming system.

Development of SAGE2 started in 2003 at the *Laboratory for Advanced Visualization & Applications* (LAVA) of the University of Hawai'i at Mānoa and at the *Electronic Visualization Laboratory* (EVL) of the University of Illinois at Chicago (UIC).

Much like its predecessor SAGE, the new system is designed as a distributed streaming system and its main focus is to enable multiple users to interact and show contents on a large display video wall. Many of the original requirements have been dropped, in favor of components which are more affordable and easy to setup, thus also being more approachable for developers and end-users alike. In fact, SAGE2 can be controlled from anywhere (even remotely), documents and content can be shared directly through drag 'n drop, and entire laptop screens can be shared directly through a browser window, on any modern platform and without additional software.

SAGE2's version 1.0 "Ko'olau" was released on the 17th November, 2016.

5.1.1 Architecture

SAGE2 has been designed from the ground-up to follow a flexible and distributed architecture, similar to the one adopted in SAGE, but relying entirely on more modern infrastructure and the capabilities of web browsers. In fact, the SAGE2 architecture is presented by Marrinan et al. as a proof of concept that the web browser runtime environment can be leveraged to drive large display experiences and intensive applications which require very large volumes of data [63].

The system consists of several components, as illustrated in Figure 5.1. At the core of SAGE2 is the *Server*, which takes over a similar role of SAGE's *Free Space Manager*, synchronizes other components, runs applications and stores media files. Any number of *Display Clients* can be connected, actually performing the rendering to the output display, and running most of the application code. Finally, the *Interaction Clients* allow users to interact with SAGE2 via a multi-user user interface.

The SAGE2 Server is built upon Node.js[1], a server-oriented platform for building network applications entirely written in Javascript. Node.js is fully cross-platform and provides built-in platform manager for managing software dependencies. This feature greatly reduces the effort required to install the system—compared to SAGE and its many low-level dependencies—and speeds up development. Display and Interaction Clients are also written in Javascript and run in any recent browser [81]. However, using the latest version of Google Chrome is strongly suggested by developers for compatibility.

Most of the tiling aspects are similar to the ones of SAGE, discussed in Section 3.1.1. However, SAGE2 effectively gets rid of the "virtual frame buffer"

[1]`https://nodejs.org`

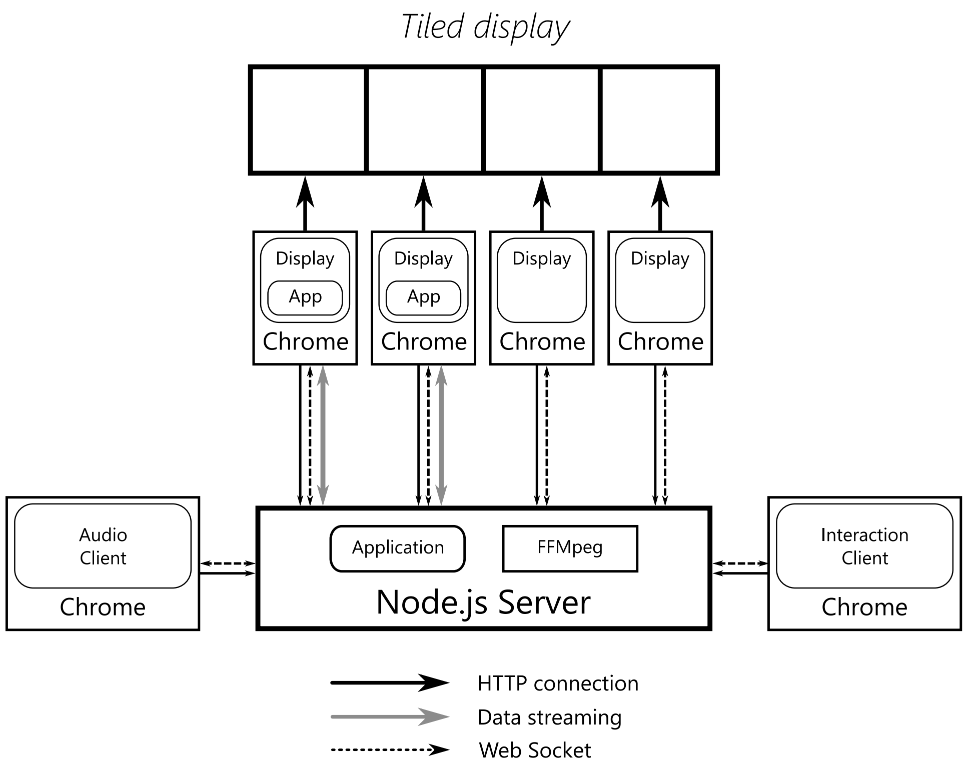


Figure 5.1: SAGE2 architecture overview.

concept. The system still presents one seamless graphical environment, regardless of the number or configurations of the Display Client machines. The layout of such graphical environment is set in a configuration file on the SAGE2 Server.

SAGE2 Display Clients are instances of a web browser that connect to the Server by simply accessing a specific URL through an HTTP connection, with a standard web request. Each Display Client sets the `DisplayID` parameter of the requested URL with a unique ID, mapping it to a specific tile on the output display. The Client will receive an HTML page representing the output to be rendered on that tile.

After the initial HTTP connection, further updates—in both directions—are transmitted using a Web Socket connection opened by the web page back to the SAGE2 Server. The Web Socket is used both to get further updates, to handle user input and to synchronize app and video rendering across Display Clients. Additional resources, including videos to render, images and other resources, can be delivered through HTTP connections to the Server.

An Interaction Client also runs inside a web browser connected to a specific URL on the Server. The web page displayed in this case is similar in purpose and appearance to the *SAGE Web Control Interface* (see page 61). The page opens up a Web Socket connection back to the Server, that allows the user to start or terminate applications, move running applications across screens and to interact with them.

Finally, the SAGE2 system requires one Audio Client, that takes over playback of all audio sources currently on screen. For instance, when a video file is loaded into SAGE2 and played back, its video part is played back by one or more Display Clients (depending on the video's position on screen), while its audio part will be delivered to the Audio Client. This client receives audio data for all media resources played back on the system, and mixes the different streams to the system's audio output.

SAGE2 is also designed to synchronize video and audio playback between the Audio Client and all Display Clients. To that end, the Audio Client also works as a synchronization source, ensuring that playback of video files on Display Clients proceeds in sync with audio playback.

5.1.2 Application model

Applications in SAGE2 also rely fully on the web technologies adopted by the rest of the system.

In essence, an application is composed by a JSON manifest and a bundle of Javascript and optional resource files. The manifest includes some basic information, like title, description, and an icon, that can be used by the system to present the application to the user.

The Javascript code bundled by the application only needs to supply an object instance implementing the app interface, as specified by the SAGE2 API. Being fully written in Javascript, applications can make use of any method available through the language or the web browser environment, including Web Sockets or HTTP requests to SAGE2 and to remote servers.

Application instances are registered and managed on the Server. The Server keeps track of the application's identity, its data, its position, and screen size. However, unlike in SAGE, applications do not run on the Server, nor on any other external workstation: the code of applications runs directly inside the web browser runtime of Display Clients.

The Javascript files bundled with the application are loaded directly by the Display Client and code is executed inside the web browser. However, execution is strictly controlled by the Server, which synchronizes rendering and drawing, thus ensuring that applications show a coherent state across display tiles.

Synchronization is achieved using the constant Web Socket connection between Display Client and Server. In this client/setup configuration, the SAGE2 Server broadcasts instructions to draw a new frame of an application to all concerned Display Clients. Clients respond when the application has finished rendering the requested frame, which on its turn triggers a new request for the next frame.

Applications implement the following interface, which will be called by each Display Client on request by the Server:

- `init(data)`: called once, when the application is initialized and begins its lifecycle on the Display Client. The `data` parameter contains application state data (if provided by the developer) that is shared across instances.

  Applications can set some of the basic properties, like the container item that represents the application inside the web browser. This is done by creating a new *Document Object Model* (DOM) element (e.g., a simple block, a 2D canvas, or any other HTML element), which will contain all graphical elements of the application.

  Additionally, applications can specify a maximum rendering frame rate or set other synchronization options.

- `draw(date)`: updates the application and renders out a new frame.

  This can be done either by altering the DOM, or rendering to an HTML canvas, or by making use of any other rendering facility provided by the browser. Once rendering is complete the application automatically calls back to the Server to synchronize drawing.

  The `date` parameter contains the rendering timestamp: since the Server issues drawing calls, applications must take this timestamp as a reference when performing time-sensitive rendering. For instance, a clock application should always update the time shown using this timestamp. Also, applications showing moving images must use the timestamp to keep pace.

- `event(type, position, userId, data, date)`: signals an input event.

Since input is not handled through the Display Client, but through an Interaction Client, events are brokered by the Server and sent in through the Web Socket connection. When an input event—like a click or a key press—is performed, this event is called and provides the application with the possibility of handling it.

- `quit()`: sent to application instances when the application is terminated. The Display Client will remove the application's HTML DOM element from its surface after termination.

In reference to SAGE's application model (see Section 3.1.2.C), SAGE2 clearly adopts a very different architecture and programming model. Applications no longer are represented by native code processes tangentially collaborating with the SAGE system by participating in the message exchange and by feeding pixel data to the receivers. In SAGE2, applications are closed-off bundles of Javascript code that runs distributed inside various web browsers, while its drawing process is tightly kept under control by the Server.

These boundaries put limits on what an application can do, to a certain extent, and force applications to be rewritten from scratch, especially for SAGE2. As is seen in the next section, this also has different implications on the video streaming model that can be used by applications.

5.1.3 Video streaming model

In SAGE, applications have only one way of pushing video data to the frame buffer: they assemble a pixel buffer and stream it to receivers, which then draw the pixels on the display. While there are some possibilities of interaction with the rest of the system through message exchange, each application in practice runs monolithically, without being really coupled to SAGE.

Things are radically different in SAGE2, where applications run inside a very controlled environment and there is no trace of the "frame buffer" as an output target anymore. While these evolutions mean that developers do not need to directly interact with buffers of graphical data—a welcome change—these limitations also restrain how video and audio data can be streamed to applications.

In the next two sections, two methods of streaming pixel data to the output screen are taken into exam.

5.1.3.A Pull streaming

The first streaming method is also the simpler one: applications in this case delegate the streaming task directly to the web browser.

This is achieved through specific multimedia rendering tags introduced in HTML 5, such as the `<video>` and `<audio>` tags. When one of these tags is created inside the Client's DOM, the web browser is able to directly stream a file through HTTP and render it on screen, without any further interaction with the application's code. In this case the Server will act as a basic web file server, transmitting the requested multimedia file through HTTP, as shown in Figure 5.2.

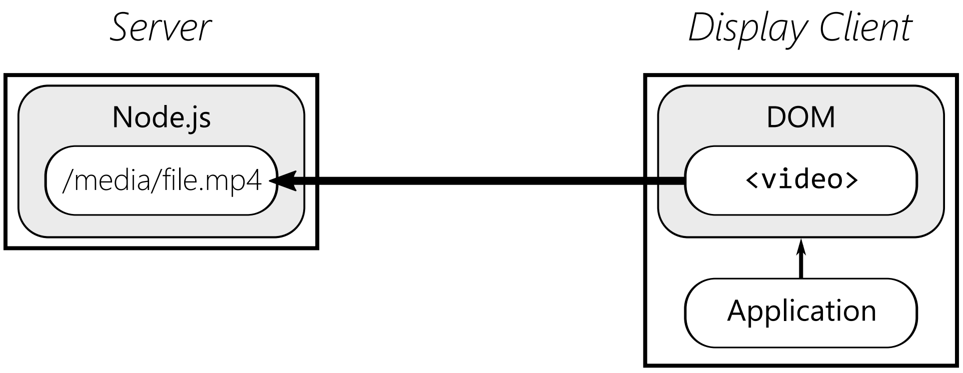


Figure 5.2: The DOM element created by the application directly accesses the multimedia file on the Server, through an HTTP request.

Synchronization is achieved by issuing seek commands to the browser's renderer, based on playback of the same source by the Audio Client (which also uses the same pull-streaming scheme to decode the file and playback its audio stream).

Since the browser takes over the tasks of downloading, decoding, and rendering, this streaming model comes "for free" by using a web browser. Moreover, these tasks are highly optimized in modern web browsers and can be done with quite high efficiency, in some cases even taking advantage of built-in hardware acceleration inside the browser's decoder. Also, the Server experiences almost no computational load for simply serving a file to the Client. Transferring a compressed file requires much less bandwidth than transmitting uncompressed raw pixels.

On the other hand, the same file must be served in its entirety to all Display Clients, which must independently demux and decode the compressed stream, and then present it on screen. This does not depend on *how much* of the video is actually visible: no matter how small the section rendered by a Display Client, its computational load will be the same.

Showing multiple high-resolution videos on the same Display Client can prove to be too hard of a task, even for powerful workstations (decoding and rendering 4K videos easily saturates desktop-class CPUs). Also, videos that span many Display Clients require many transfers of the same file, causing more load on the network. This however is offset by the fact that files are sent in their compressed format[2].

5.1.3.B Push streaming

This streaming method has been added in recent updates to SAGE2, leading up to the 1.0 version. While more complex in many ways, this scheme brings SAGE's original approach of raw pixel streaming back to SAGE2.

In this case, depicted in Figure 5.3, applications create a simple drawing surface on the web browser's DOM. Through the Web Socket interface, the application requests the streaming of a file. Instead of delivering the compressed data to the Display Client, the original file is decompressed directly on the Server, split up into blocks, and then sent through a Web Socket to the Display Clients that need the pixel data. Pixel blocks are then presented using the browser's drawing surface.

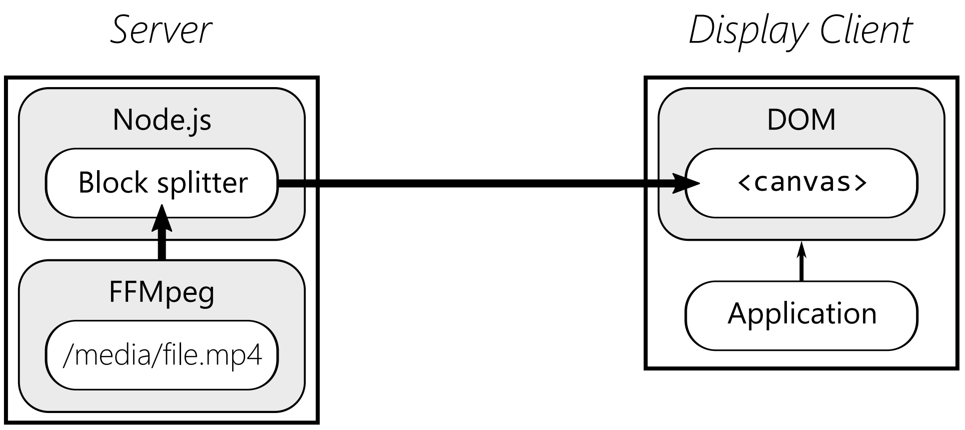


Figure 5.3: The Server decodes and splits up the multimedia file, serving pixel blocks to the applications.

As shown, the Server reads the media source from disk or from the

[2]Data-rates of compressed files vary dramatically, depending on several factors. However, a compression rate of at least 100x can be expected when using H.264 compression. That is, even sending the same file 100 times will still cause less bandwidth occupation than sending it once uncompressed.

network and feeds the data into an external *FFMpeg* process, that performs the actual decoding of the compressed file. The uncompressed data is fed back to the Node.js process, raw frame by raw frame. An internal block-splitting routine takes care of separating the decoded frame into many 128×128 pixel blocks (assuming a full 32 bit color encoding, each block will take up 64 KB of memory). The Server determines which blocks need to be sent to each Display Client and performs the transfer. Clients receive the data and render the full frame once all blocks have been received.

The main advantage of this method is that the decoding process runs only once per multimedia file, leaving only the task of receiving incoming blocks and presenting them on screen to the Display Clients. In some cases, the decoding step can take advantage of hardware acceleration through *FFMpeg*, just like the browser in the "pull" scheme. Moreover, video synchronization is not an issue, since all Clients are automatically synchronized to the latest frame decoded by the Server, using a mechanism that is similar to the one used by SAGE (see Section 3.4.3).

On the other hand, as is the case for SAGE, the required bandwidth on the network is far higher than in the previous scheme. If many high resolution videos are decoded and streamed at the same time, the computational capacities of the Server and the network's bandwidth capacity can quickly be exceeded. Furthermore, Javascript and the web browser runtime can be inefficient when working with large buffers of data, when compared to native code. Both splitting the decoded frames up into blocks and copying them from network to the browser's drawing surface can limit the system's performance.

5.2 Renderer acceleration

When using a "pull" streaming model in delivering video to the output display, described in Section 5.1.3.A, the bulk of the work is actually performed by the Display Clients and their web browsers. In fact, the browser instance on each Client must perform the data download through HTTP, demux the file, decode the video stream and then present it on screen, for every video present on the Client's tile.

Particularly because the full file must be transmitted and decoded, no matter how little of the decoded file is really needed, reducing the decoding cost can improve the load on the Client considerably.

Since Google Chrome is the suggested web browser for using SAGE2, in the following sections hardware acceleration will be discussed taking *Chromium*, the open-source web browser on which Chrome is based, as a reference.

5.2.1 Chromium architecture

The *Chromium* project is an open-source, cross-platform web browser, initially released in 2008 and currently developed by a large community. It is arguably one of the most feature-rich web browsers available, and is currently released in several proprietary variants, including Google Chrome, CEF (*Chromium Embedded Framework*) or Opera.

Chromium is based on a multi-process architecture. The main *shell* offers the web browser experience, while individual tabs and windows contain the core web renderer provided by Chromium, hosted inside external processes for security and stability.

Video decoding in Chromium relies on third party decoders, which are built into the web browser at build. Support for the main encoding formats is provided by *FFMpeg* and *LibVPX*. The first library is one of the most popular multimedia encoding and decoding libraries, also released as open-source software. The second library was developed at Google, as the main reference encoder and decoder for *VP8* and *VP9*. These two formats are Google's custom video encoding schemes, that were created as a patent-unencumbered alternative to H.264.

When required to render a media file, the decoder will attempt to detect the file's type—either by guessing from the extension, the source's media type as specified by the HTTP headers[3], or by demuxing the initial parts of the file. If a compatible video stream is found, the best matching decoder is loaded and used by the web browser.

Chromium makes use of a very abstract interface to the decoding process, since it relies on different decoders in the back-end. In essence only three operations are provided: passing data into the decoder, waiting for a frame to be decoded, and receiving back raw frames. These operations are repeated continuously in order to present video on screen, until playback is stopped or the stream ends.

Internally, decoding libraries can adopt a very different decoding model, or interface with another layer of decoding components. *FFMpeg* may in

[3]A *media type* or *MIME type*, is a two part identifier for file formats used when transmitting content through the Internet. It is notably used by HTTP, in its "Content-Type" header.

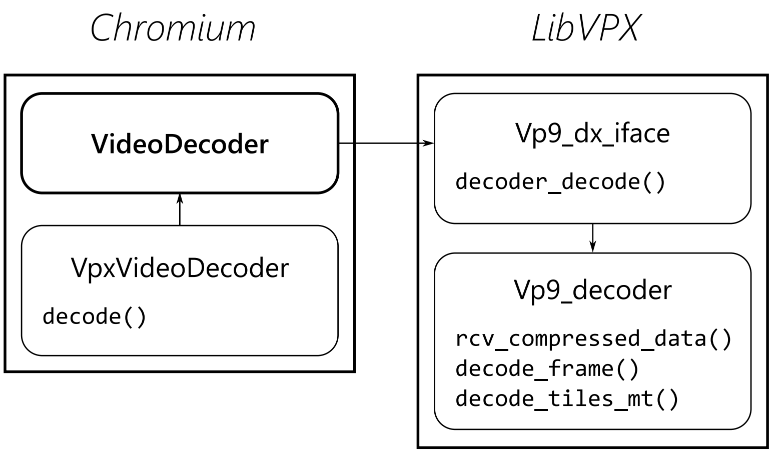


Figure 5.4: Architecture of the video decoding components in *Chromium* and *LibVPX*, showing the control flow required to decode a single frame using the *VP9* decoder.

fact provide many different decoder implementations for the same encoding format, which are selected based on compilation and runtime options. In a similar fashion, the *LibVPX* library will demux the WebM input stream and then select the appropriate video decoder based on compilation options and stream characteristics. Also, video decoder libraries can account internally for multi-threaded or hardware accelerated decoding, which is completely transparent to the web browser.

In Figure 5.4 a sample control flow across Chromium and LibVPX's *VP9* decoder is shown, that is used by the browser in order to decode a single frame of a WebM/VP9[4] video file.

Since the container file passed in by Chromium wraps a VP9-encoded stream, *LibVPX* ensures that all decoding calls from the browser are passed in to the internal VP9 decoder, as shown.

As mentioned before, decoders can perform their internal operations using any policy. In fact, the function `decode_tiles_mt()` in *LibVPX* mentioned in Figure 5.4 does make use of multiple threads internally when decoding the frame data. These decoding threads are kept alive during the whole decoding process, and terminated once the decoder isn't needed anymore.

[4]WebM is a multimedia container format based on the *Matroska* specification. WebM supports the VP8, VP9 and upcoming VP10 video stream encoding, all of which are released as royalty-free formats by Google.

5.2.2 Video decoder pipeline

In this section and the following, the VP9 is taken as the reference video encoding format, and the *LibVPX* decoders are taken as reference implementations thereof. However, most points discussed equally apply to many other video format and the decoders in *FFMpeg*. In fact, at a high level, most recent video formats and their decoder pipelines have a similar structure.

LibVPX's VP9 decoder implementation is taken as a reference primarily for being implemented in a smaller code base, thus allowing faster and easier development for the proof of concept implementation reported in Section 5.4.

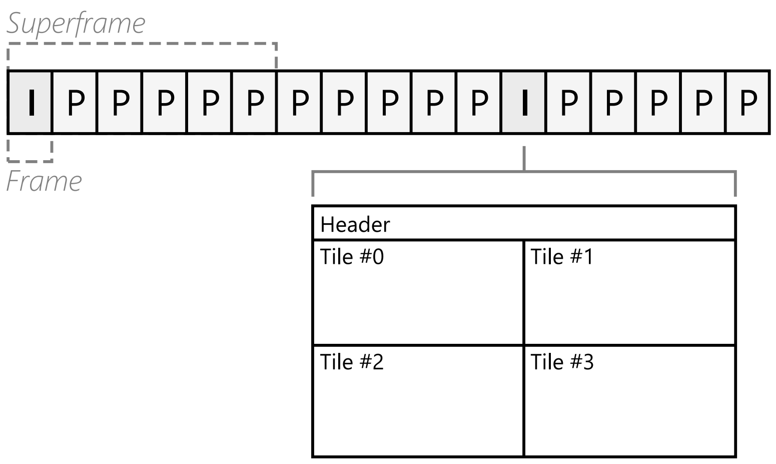


Figure 5.5: Sample layout of a video stream encoded using the VP9 format and the data layout of a single `I`-frame.

A compressed VP9 video stream is generally composed of header, followed by a sequence of frames. In order to exploit temporal compression, only an exiguous number of frames is encoded fully inside the stream. Such frames, named `I`-frames (as in *inter*-frames), are represented using an encoding similar to JPEG[5]. That is, frames are reconstructed by applying a *Discrete Cosine Transform* (DCT) to blocks of source data, thus obtaining a frame of pixel data. Other frames, called `P`-frames instead (as in *predicted*-frames), only represent differences between the last fully-decoded frame and the next one.

Some encoding formats, like H.264, may also use additional kinds of frames.

[5] *Joint Photographic Experts Group* (JPEG) is the most widespread digital image lossy encoding format.

Groups of frames can be grouped into larger chunks of the byte stream, called "superframes". Each superframe may contain up to 8 frames, allowing the encoder to save some bytes by reducing the frame header.

As shown in the sample VP9 byte stream layout in Figure 5.5, each frame is structured into a header and into multiple tiles. The number of tiles usually varies from 1 (for low resolution files) to 8 (for 4K resolutions or higher). Each tile does share the header information with other tiles, but has no data dependency on any other tile in the case of `I`-frames. Conversely, `P`-frames clearly have a data dependency on previously decoded frames.

The VP9 decoder adopts a multi-threaded approach in which, after decoding the format of a frame and its header, each tile is assigned to a worker thread for decoding.

5.2.3 Decoder acceleration

Real performance gains obtained through hardware acceleration are hard to estimate and often are hindered by counter-intuitive factors or dependencies that are not evident in sequential code. In particular, adapting a video decoder to fruitfully making use of the hardware available is not an easy task because of the large amount of memory transfers involved. Even if the computational aspect of video decoding is an ideal task for many dedicated processors, time spent copying video data can—in some cases—negate any time gain. In fact, for instance when decoding lower video resolutions, far better performance can be obtained by doing all work in CPU.

Moreover, implementing a whole video decoder, for any modern encoding format, capable of making use of hardware acceleration, is a daunting task because of its inherent complexity.

In order to perform an evaluation of the achievable gains, focus was put on a single part of the entire decoding pipeline. Intuitively, following Amdahl's law, the decoder segment with the largest expected data parallelism should be able to bring most performance gains when executed on multi-core hardware [2].

An evaluation of the different parts of the VP9 decoder was done, timing each individual segment of code and accumulating the ratio of time spent in strictly sequential code parts against time spent in code that can be parallelized.

Results in Table 5.1 show the ratio between inherently sequential and parallel code section.

Frame type	Sequential	Parallel	Prediction	Compensation
I-frame	8%	92%	–	100%
P-frame	36%	64%	84%	16%

Table 5.1: Ratio of strictly sequential and parallelizable code in the VP9 decoder for each frame type.

The “prediction” column indicates the amount of time spent reconstructing the frame using data from other frames. By their nature, work of this kind is only needed when processing P-frames. Prediction is done by applying a *convolution filter* on the reference frame, thus producing the final image data. In particular, a convolution filter pass comprises a matrix multiplication, between source pixel data and a filter matrix determined by the encoding format.

The “compensation” column indicates time spent compensating for errors during the prediction pass. Essentially, compensation is done by decoding a frame that contains the difference between the reconstructed image and the final image data. As such, this pass requires the decoder to perform *Discrete Cosine Transforms* (DCTs) to create the difference frame, just like decoding a single image. I-frames, not having any predicted component, are decoded only through work of this kind.

Both kinds of work load, matrix multiplications and cosine transforms, are particularly suited for dedicated hardware.

Even if the I-frame decoding step exhibits more parallelism and thus more chances to exploit hardware acceleration, the ratio between I and P-frame count in video streams must be taken into account. While in practice this ratio depends on the encoder, the bit rate of the stream, and the kind of video source, the widespread x264[6] encoder—for instance—usually makes sure that the ratio is in the 30–300 range (for 30 frame per second video streams) in favor of predicted frames. The impact of P-frames on the overall decoding time is thus far higher.

5.3 Server acceleration

Video decoding hardware acceleration in SAGE2 can also be applied server-side, when considering the “push” streaming model seen at Section 5.1.3.B. As previously discussed, in this case the server directly accesses and de-

[6]Popular free software library for encoding video using the H.264 format. Widely used by many software applications and services, including Youtube.

codes the video stream for each file played back on the system.

The process of decoding the compressed stream and splitting it up into blocks is a good candidate for harnessing advanced hardware capabilities. In fact, the *FFMpeg* library SAGE2 makes use of—just like the Chromium web browser does as well—already offers hardware acceleration on some specific platform and runtime combinations. Thus, the same acceleration considerations that apply to the web browser can equally be applied server-side.

Unfortunately, the “push” streaming model had not been added to the SAGE2 project at the time when hardware acceleration was being explored, and therefore the hardware acceleration proof of concept discussed in Section 5.4 only references the web browser decoding process within the “pull” streaming model.

5.4 Proof of concept implementation

In order to verify the impact of hardware acceleration on SAGE2's performance in rendering high resolution video, a proof of concept acceleration test bench was built. The hardware acceleration design adopted derives from the “pull” streaming model discussed previously in Section 5.2.

In this model, the compressed video stream is entirely delivered to the Display Client web browser instance. The browser passes the data on to the selected decoder, based on the stream's data type, and receives raw frames back.

5.4.1 Hardware

For the proof of concept, a multi-core *System on Chip* (SoC) evaluation board has been used: the Texas Instruments Keystone II 66AK2H12 (Figure 5.6), equipped with a quad-core ARM Cortex-A15 processor and with 8 TMS320C66x high-performance *Digital Signal Processors* (DSPs). Both processing units work at a nominal frequency of 1.2 GHz. They have access to 2 GB of RAM, through a shared memory access model.

The Keystone II board's DSPs can be programmed using two alternative frameworks.

The *Open Computing Language* (OpenCL) is specifically targeted for programs executing on *heterogeneous* platforms, that is, computing platforms composed by multiple kinds of processor, just like the Keystone II.

Open Multi-Processing (OpenMP) instead is an open specification for

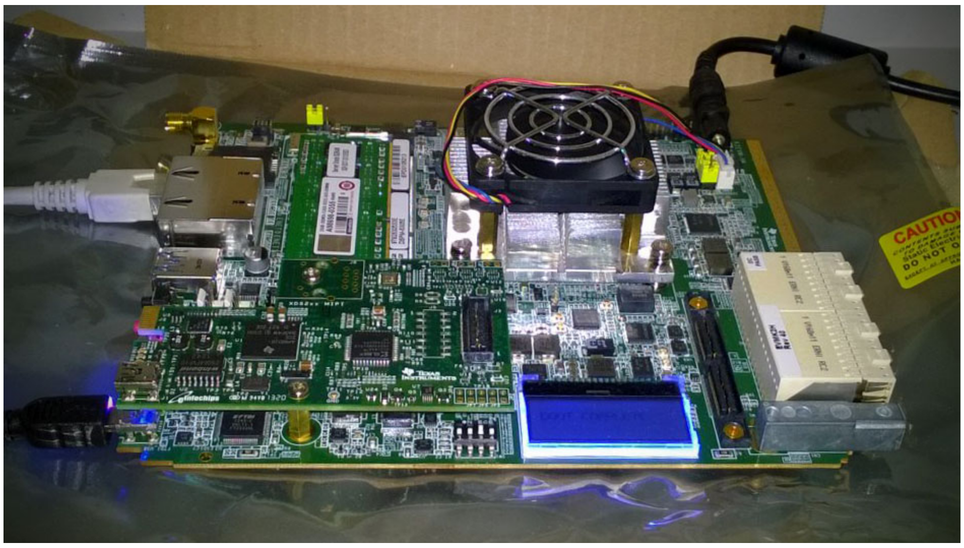


Figure 5.6: The Texas Instruments Keystone II 66AK2H12 board.

an API, that enables programmers to easily harness shared memory multi-processing constructs in most platforms and in most languages (C/C++ foremost). Even if OpenMP is intended for *homogeneous* multi-core systems, a subset of the OpenMP 4.0 specification defines the OpenMP "Accelerator Model" that enables execution on heterogeneous SoC as well.

The Texas Instruments *Software Development Kit* (SDK) allows developers to make use of both frameworks. While OpenCL requires developers to be completely aware of the system they are working on, accurately splitting CPU code and code that runs on the accelerated DSPs, OpenMP adopts a simplified model that allows developers to simply mark regions of C code to offload to the accelerators. The marked code will be converted to OpenCL during compilation (i.e., OpenCL computation "kernels" that can be executed by the accelerator), while loading the code and copying the memory will be taken care by the OpenMP runtime.

5.4.2 Implementation

The *LibVPX* VP9 decoder has been taken as reference for the previous discussion in Section 5.2 and is also used as a starting point for the proof of concept hardware accelerated decoder. A modified VP9 decoder was implemented inside Chromium, running on the TI Keystone II board, in order to evaluate the potential performance gains in a realistic scenario.

As further mentioned in Section 5.2.3, full hardware acceleration cannot be obtained by only offloading parts of a decoder, but would require a major reimplementation. In the scope of this work, the alterations to the original VP9 decoder focus on the parts with higher prospected performance gains. Based on previous discussion, it was deemed most convenient to add hardware acceleration to the "image prediction" step of P-frames.

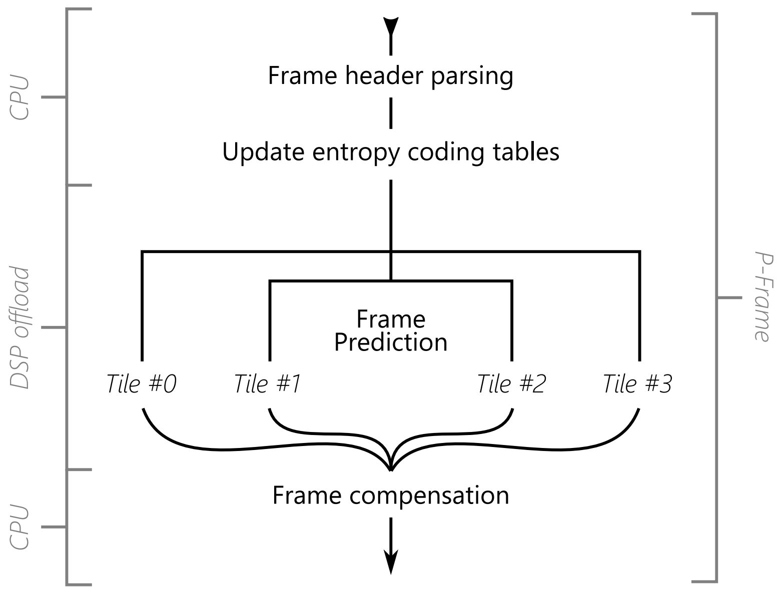


Figure 5.7: Control flow of hardware accelerated P-frame decoding.

The OpenMP API was used to offload part of the original P-frame decoding code on the DSPs installed on the board. Shown in Figure 5.7 is an overview of the control flow in a single frame decoding pass.

The first steps, including frame header parsing and updating of internal data structures, must always be performed sequentially. Likewise, the final step—which includes frame compensation and any additional image processing—is also performed sequentially in the original implementation because of tight data dependencies.

The central step—which is also the more expensive one computationally—can exploit the natural data parallelism available in this decoding phase. Exploiting the tiled structure of the frame, each tile can be directly offloaded on a DSP using task-level parallelism. Each tile is assigned to an OpenMP task. When all tasks complete their assignment, control flow is joined again.

Memory copies are performed at the beginning and at the end of the DSP offload section. Using OpenMP APIs, all memory used to store frame buffers is directly allocated on memory shared between CPU and DSPs, in order to minimize the amount of data that must be copied at each frame.

5.4.3 Benchmarks

Benchmarks of the implemented system have been performed by instrumenting the VP9 decoder with high-resolution timers. The final achieved frame rate has been measured in a real-world scenario, setting up the Chromium browsers as a SAGE2 Display Client and using the performance counters built-in to Chromium to collect results.

Rendering performance is collected as *inter-frame* times, that is, the amount of time elapsed between a decoded and rendered frame. Inter-frame time can be easily converted to a frame rate expressed in Hz:

$$f_r = 1/t_{interval}$$

The minimum acceptable update frequency threshold for smooth video rendering is 30 Hz, that amounts to an inter-frame time of 33 ms or less.

The first results shown in Figure 5.8 have been collected by running the standard VP9 decoder on the ARM Cortex-A15 quad-core CPU. The vertical red bar indicates the 33 ms threshold for smooth video. As can be seen, decoding is perfectly smooth for video resolutions up to 720 vertical pixels, since the distribution curves are largely behind the smoothness threshold, while it degrades sharply for Full-HD videos (1080 vertical pixels). In fact, with 1080p videos, the decoding frame rate appears to be very unstable, often reaching 100 ms per frame or more.

In Figure 5.9 a similar benchmark is shown, using a VP9 decoder compiled with support for ARM NEON[7] instructions. In this case, most inter-frame times for 1080p videos fall below the minimum acceptable threshold, as shown by the purple curve. However, the curves for videos with even higher resolution (1440p or 4K) are centered over the threshold, indicating stuttering playback.

In Figure 5.10 the comparison between CPU decoding without NEON support and DSP offload is shown, also in terms of inter-frame times (error bars indicate the range of times registered). The horizontal red bar again indicates the smoothness threshold.

[7]The ARM NEON is a general-purpose *Single Instruction Multiple Data* (SIMD) instruction engine. It offers an instruction set working on 64 or 128 bit vectors of data for media and signal processing applications.

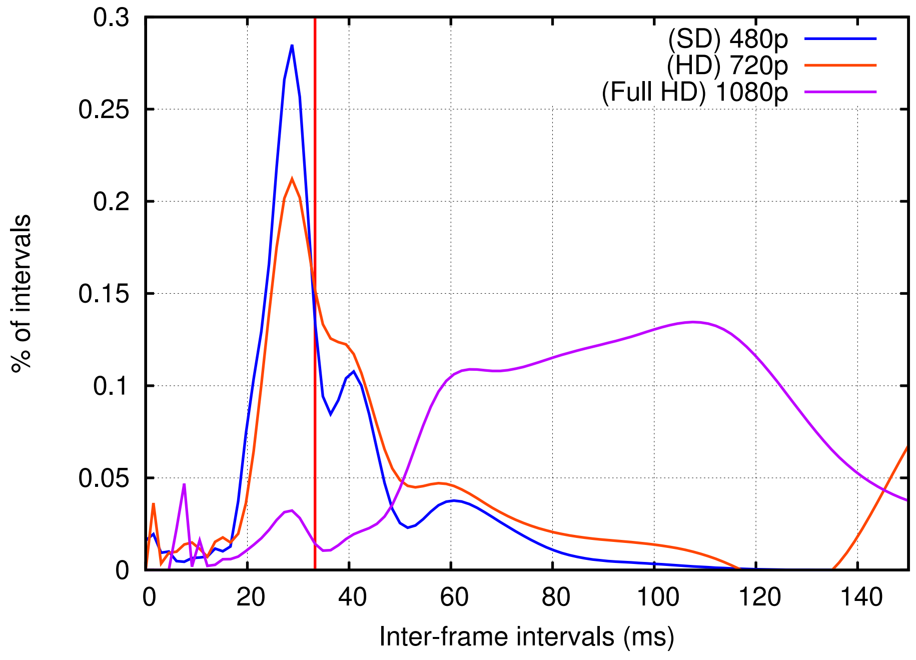


Figure 5.8: Distribution of inter-frame intervals for CPU decoding, using the standard VP9 decoder, for 3 categories of video resolution.

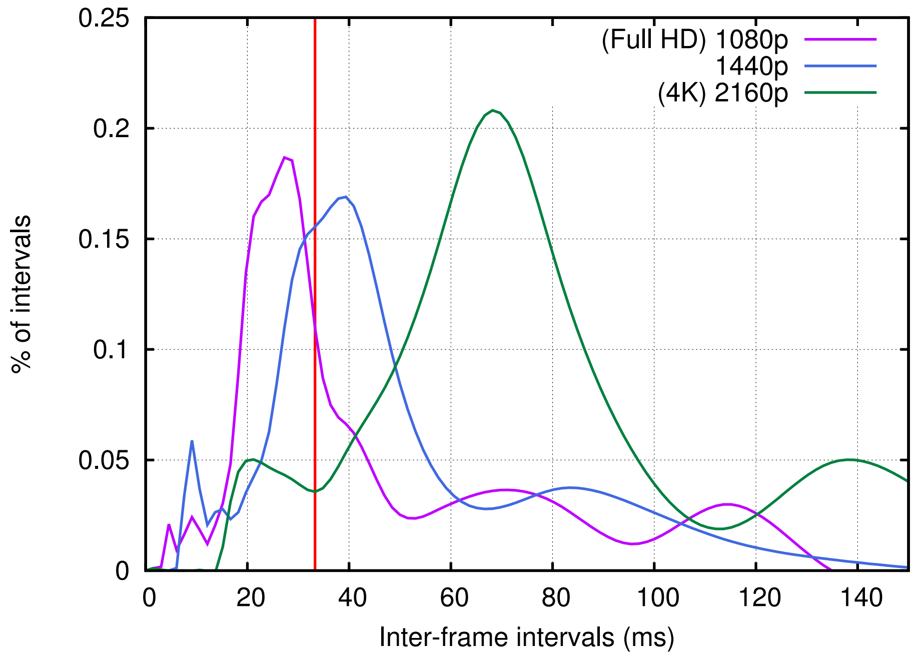


Figure 5.9: Distribution of inter-frame intervals for CPU decoding, using VP9 compiled with ARM NEON instructions, for 3 categories of video resolution.

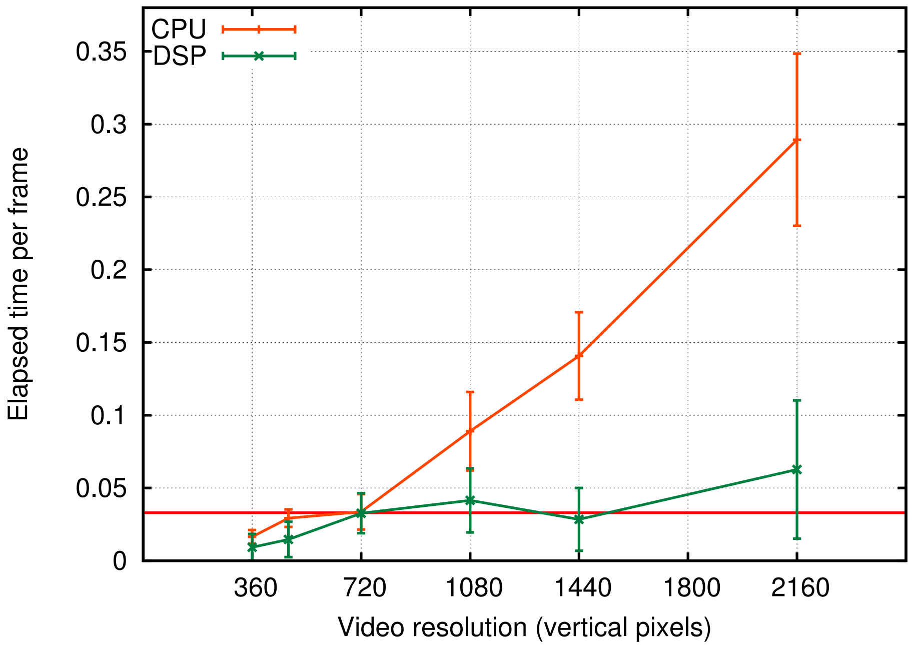


Figure 5.10: Average inter-frame intervals as function of video resolution, for CPU (non-NEON) and DSP-based decoding.

Without NEON support, the quad-core CPU provided by the Keystone II can only decode up to 720p videos with acceptable performance. Instead, when using the DSPs, the average inter-frame times collected stay below the 33 ms threshold even for 1440p video files. 4K video files are decoded with an average rate of 15 frames per second.

Given the limited scope of hardware acceleration that could be implemented using OpenMP directives on an existing heavily optimized decoder, it can be envisioned that the performance gains achieved by a fully hardware accelerated video decoder should be able to reliably decode 4K videos.

5.5 Modular acceleration with embedded systems

Advances in multi-core SoC technologies have opened up a world of specialized hardware boards with low-power requirements but very high performance for specific tasks [106].

As argued by Jo et al., among others, there are plenty of possibilities to exploit the capabilities of such systems, by fully exploiting the inherent parallelism of video decoders [52, 67]. As demonstrated in the previous section, performance improvements through hardware acceleration can be harnessed through OpenMP and are fully applicable to a decoder running inside the Chromium web browser, on an embedded SoC system with heterogeneous hardware accelerators. This can greatly improve SAGE2's capability of decoding and presenting high resolution video sources on large displays.

It can be envisioned that, paired together with SAGE2's "push" streaming model described in Section 5.1.3.B, multi-core embedded systems with high-performance accelerators could be used as dedicated decoding nodes on a distributed large display system. Instead of performing decoding and block-splitting on the Server, these tasks could be dynamically assigned to dedicated embedded systems. These embedded processing modules could be added to a SAGE2 system when needed, augmenting its flexibility and scalability, and automatically power off when no video decoding is needed.

In fact, considering the low computational needs of SAGE2's Server, it too can be handled by a low-power board. One processing decoding module can be user for each streamed video, thus also making the process of designing and provisioning resources for a VR system easier.

Managing the system is a task that can be taken over by a high level controller, much alike IVE discussed in Chapter 4, that would be able to dynamically reconfigure the system and allocate resources based on the experience to achieve. Scaling the VR environment in order to support more or larger videos could be as easy as adding a small-scale module to the network.

Chapter 6

Conclusions

In the first chapters of this thesis, a review of large-scale visualization systems has been outlined, discussing the rationale and purpose of these technologies. Target applications are many and diverse, including usage as visual analysis tools, as cognitive aids for research, as immersive art experiences, and of course as entertainment systems.

Three different, albeit interconnected, technologies for the management of large scale displays have been presented. Each of these technologies presents a glimpse on a different approach to the issue, and offers different features to system integrators, developers, and end-users.

SAGE has been described in depth as a complete and flexible graphics streaming system. Its features and its serviceability have been discussed at length, substantiated by the number of running installations worldwide. However, the lack of a common usable control interface, both for users and third-party applications, and its notable performance requirements have also been detailed.

The IVE system has been presented as a high level management overlay to one or more SAGE installations, in order to overcome some of the aforementioned limitations. It offers additional usability and flexibility in configuration, and allows better control for end-users. By design, it has a deeper knowledge of the system's topology and its state, and it has the means of interpreting user commands in the context of a peculiar scenario. This additional information gives IVE the ability to improve on the SAGE experience, allowing better control, configuration and load balancing.

SAGE2, as a direct evolution of SAGE's original concept, presents several innovations in terms of adopted technologies and in terms of vision. Far higher ease of configuration, installation, and development make it a very alluring choice both for academic research and production deployments. This notwithstanding, it arguably represents more of a refinement than a dramatic reformation. Many friction points concerning management, control and performance bottlenecks stand unchanged.

As discussed in the previous chapter, SAGE2 architecturally appears to be well-suited for large display virtual environment composed of several low-power embedded systems, managed by a high level controller. Much alike IVE, the controller would be able to supervise the system with higher awareness of its context. This would allow it to present a coherent programmable interface, while performing accurate load balancing and resource allocation. Also, as previously demonstrated, the system also presents large opportunities to exploit hardware acceleration, potentially allowing it to benefit from higher performance and lower power consumption using fine-tuned hardware and software solutions.

Immersive large scale displays present a set of very challenging and interesting problems. Not only in terms of distributed system architecture and design, but foremost as examples of performance and scalability issues—network and memory capacity, computational load, graphical fill-rate, and synchronization are only few of the topics that come to mind. As mentioned before, such systems present an interesting test-case and benchmark for high-performance embedded systems. On the other hand, they also constitute stimulating and forward-looking scenarios for user interface development and usability studies.

Many solutions discussed in this thesis merely cover a limited spectrum of the variety of challenges mentioned here. Even if the inherent bottlenecks and issues of a large display system cannot be addressed completely, of course, full understanding of the fundamental problems at hand make any of the presented solutions a workable basis for real-life installations.

Appendix A

Tour of the ArtRoom

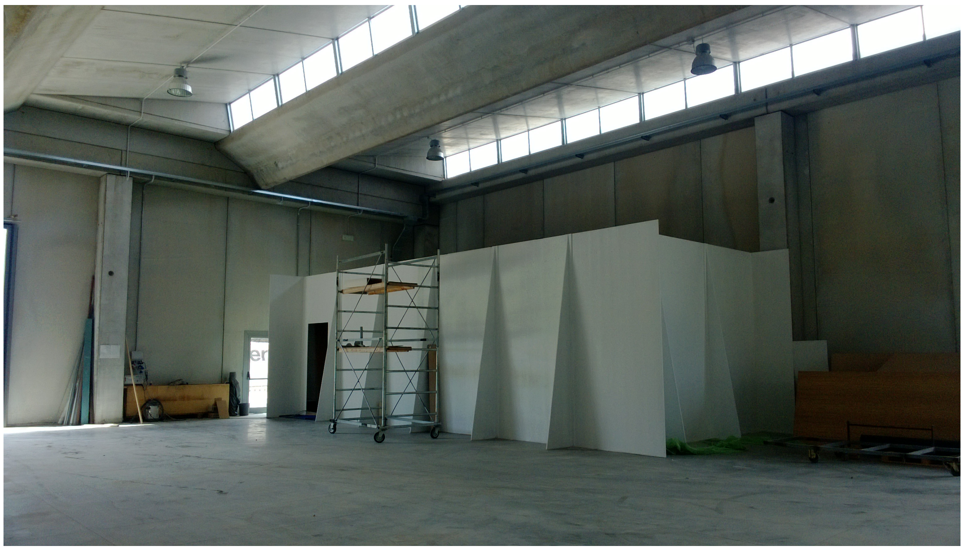


Figure A.1: The *ArtRoom* installation box from the outside.

Figure A.2: The empty location where the *ArtRoom* is installed.

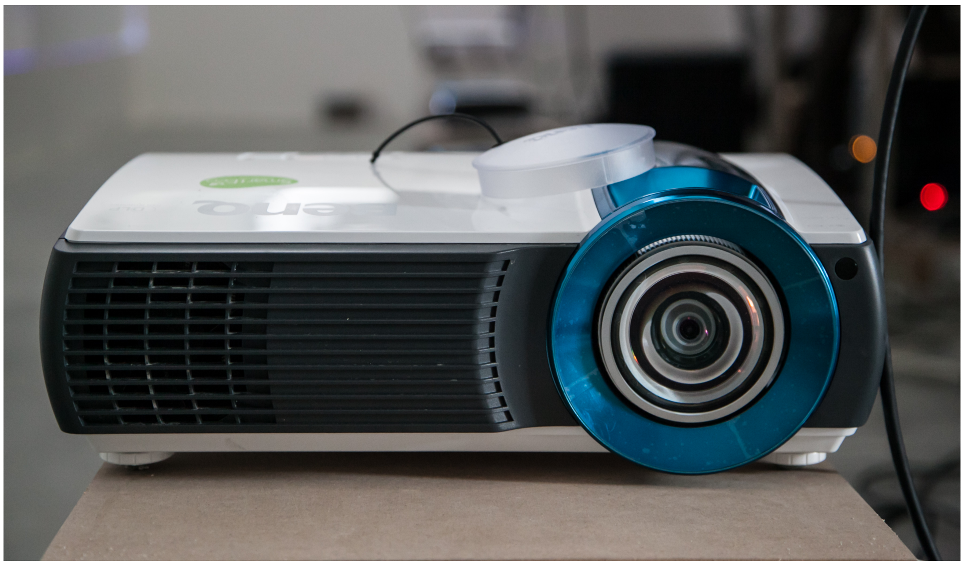


Figure A.3: One of the BenQ LW61ST projectors running the *ArtRoom*.

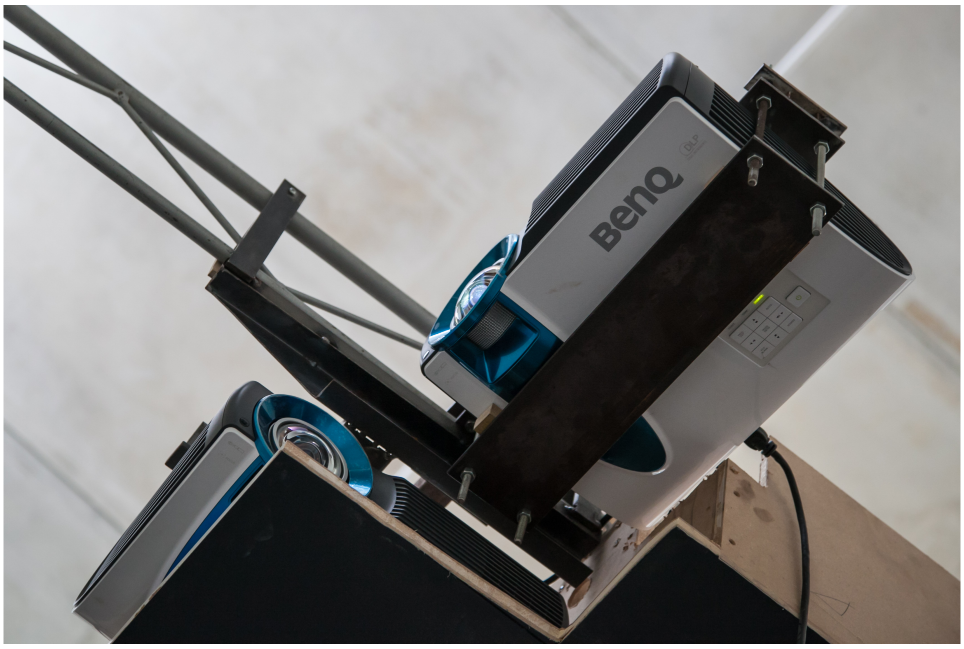


Figure A.4: Hanging projectors are held by iron brackets custom-fitted to the device. At corners, an overlapping bracketing system is used in order to cover both sides of the room. Care must be given not to cover up plugs of any projector (power and video source).

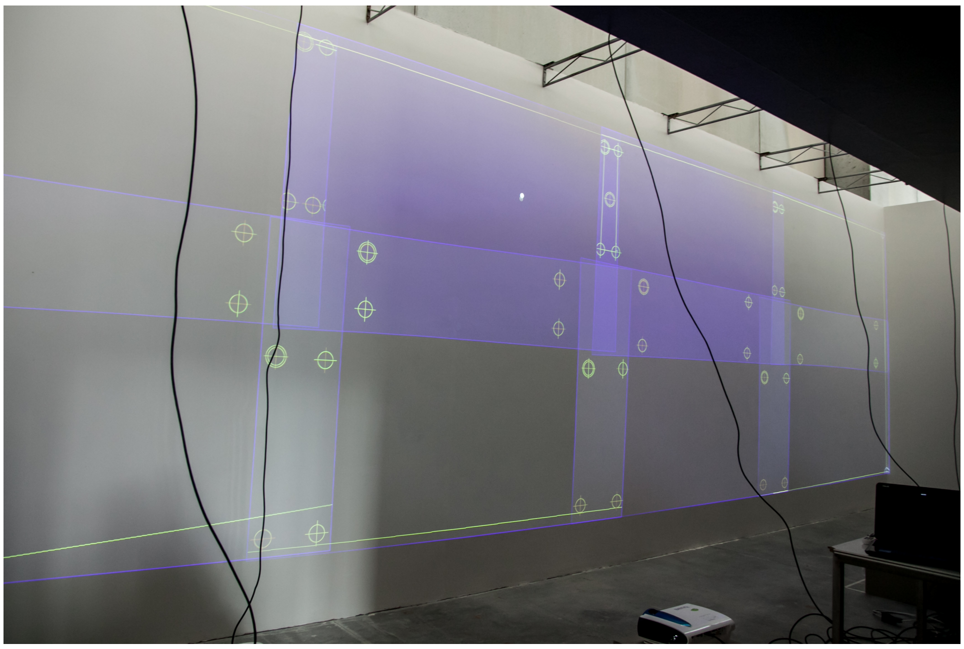


Figure A.5: Screen alignment phase: the overlapping targets determine how the output image must be distorted in order create a coherent single picture.

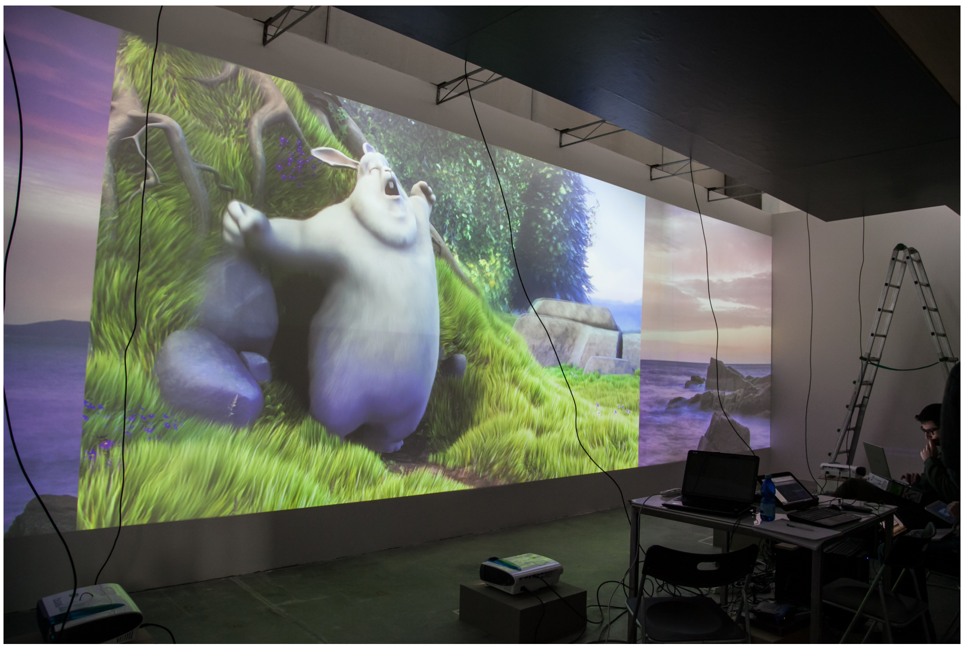


Figure A.6: Playback of a sample video on the main frontal surface.

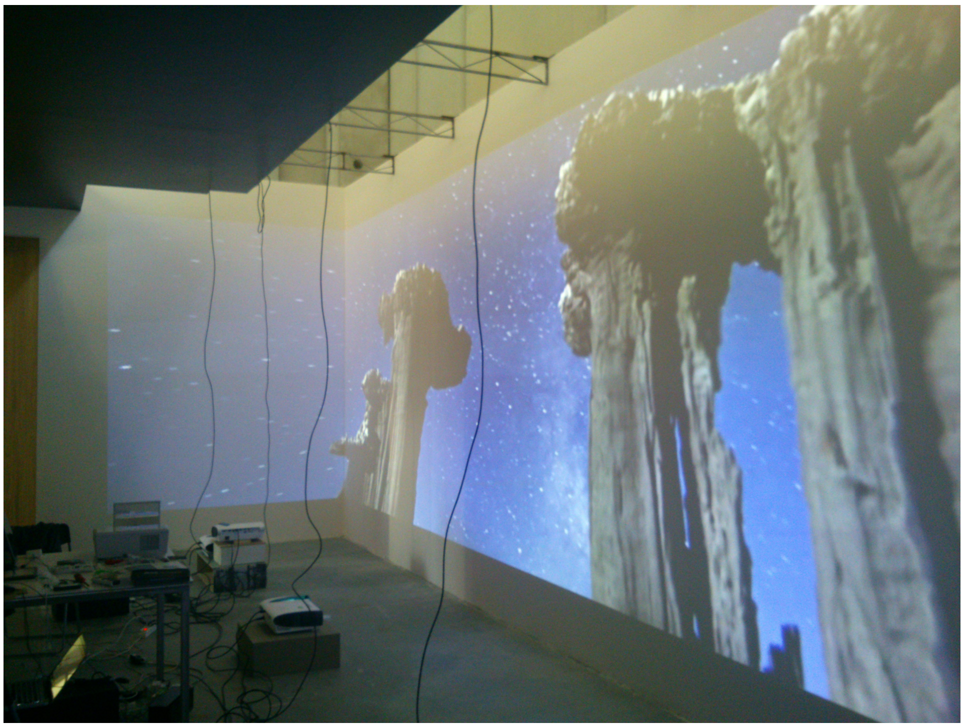


Figure A.7: A sample immersive scenario, projected on all surfaces of the *ArtRoom*.

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