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Spatial User Interfaces for Large-Scale Projector-Based Augmented Reality

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Spatial user interfaces (SUIs) let users freely interact with both 3D virtual information and traditional 2D workstation application information. Spatial augmented reality (SAR) employs projectors to directly illuminate physical objects with perspectively correct computer-generated information in real time (see Figure 1). SAR requires unique techniques to support interaction with 2D and 3D virtual information associated with physical objects. This article explores how SUI concepts can help define appropriate user interface techniques to support this emerging area of augmented reality (AR).

AR is a powerful way to present information. It enables the presentation of just-in-time information and in situ data visualization. Both these attributes provide an easier way to understand information in the context of the real world. Although most AR research isn't restricted to visual information, it has focused on augmenting the user's view using head-mounted displays (HMDs), handheld devices such as phones and tablets, and projectors (SAR).

SAR systems can alter objects' visual surface properties, such as colors, textures, small changes to geometry, shininess, and transparency. Annotations such as instructions can be projected directly onto the objects' surfaces when and where they're required. Users don't have to wear or carry equipment, such as an HMD or a handheld display. Additionally, SAR scales well to allow collaboration and offers affordance with the objects' physical presence, further increasing the realism and perception of the projected content.

However, SAR has these major limitations:

- SAR can only project onto physical surfaces in the environment and can't show virtual information in "midair."
- Projecting in outdoor environments is limited by the projector technology's brightness.
- SAR systems require a geometric model of the environment, which must be known ahead of time or calculated.

Within these limitations, a number of novel SUI techniques and applications are possible.

SAR Display Techniques

SAR has its roots in the vision outlined by the Office of the Future, in which all surfaces, such as the walls, desks, and floor, are potential displays.[1] Using cameras and structured light, this approach captures 3D models of people and objects in the room in real time, allowing for 3D telepresence.

Most SAR systems build on these techniques and those introduced in *shader lamps*.[2] Shader lamps extend SAR to not only augment surfaces with information but also change their appearance entirely. By projecting textured images onto plain white objects, you can create a variety of visual effects. For example, you could make the object red or make it look like it's made of stone or covered in metal sheeting. Additionally, you could render this object under different virtual lighting conditions, such as a spotlight or fluorescent lighting or with an environmental lighting map. The object doesn't have to look realistic; you could use nonphotorealistic rendering effects to create a cartoon appearance.

Projecting graphics spatially aligned to physical objects requires a calibrated projector and a 3D understanding of the environment. This involves calculating the projector's horizontal and vertical fields of view, principal point, focal length, and position and orientation. Calculating the intrinsic parameters requires finding correspondences between projector pixels and known 3D locations in the physical world. You can automate this process

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using cameras with structured-light algorithms.

As Figure 1 shows, projectors in the ceiling controlled through our SAR system can alter the visual material properties of large objects such as an automobile. This image shows a wireframe and test textures to confirm the projector alignment. We use six projectors to project onto all the vehicle's sides, with projector overlap to reduce users' shadows. As we'll show, such an SAR system can also provide visual layouts of large workstations for prototyping and provide in situ information in a workspace.

Unlike other forms of AR, many SAR applications don't need to track the user's viewpoint to render suitable graphics. However, tracking the user allows more advanced view-dependent rendering effects, such as accurate lighting models. It also allows rendering virtual geometry that doesn't match the physical object, such as virtual holes in a surface. One technique for view-dependent rendering is recursive ray tracing.[3] Ray tracing allows for view-dependent rendering effects on geometry of any shape, avoids aliasing problems, and produces photorealistic effects. However, the rendering is restricted to a single viewpoint. Techniques such as active shutter glasses might improve this situation; another approach is to let users toggle the view-dependent effects when necessary.

The virtual environment (VE) closest to SAR is probably the CAVE (Cave Automatic Virtual Environment). Both SAR and CAVE systems employ projectors as the primary display technology. The Allosphere, a 10-m-diameter spherical immersive enclosure, is a great example of a state-of-the-art CAVE.[4] When SAR environments and CAVEs employ nonstereoscopic projection, multiple users can view the virtual information.

The main difference between the two approaches is that SAR projects directly onto the physical objects of interest, whereas CAVE projection screens are simply surfaces acting as windows into a virtual world. Another major difference is how users interact with virtual information. Imagine you wanted to view a table. In a CAVE, this would be like being in a glass box that might teleport around the shop, but the table would always be behind the glass walls. Stereoscopic CAVEs let virtual objects appear in front of and behind the projection walls. This approach has limitations; for example, a virtual table can't be rendered between two users facing each other.

In contrast, SAR projects the virtual information onto an actual physical object anywhere in the environment. Users can touch the table, arrange a place setting, and even pull up a chair and sit down. Multiple users can view and interact with this information, such as having the table between them. However, this information can't be rendered in stereo; stereoscopic projection of SAR information is an open research question.

Figure 1. Spatial augmented reality (SAR) can change the appearance of large artifacts and can be viewed from all angles. In this case, the SAR system is projecting a wireframe and test textures to confirm the projector alignment.

The Research Opportunity

Because SAR is a relatively new branch of VE research, there's a lack of good user interface technology. Whereas the keyboard and mouse are ubiquitous for desktop PCs, they're not suited to large, immersive SAR systems. These systems require SUIs that let users freely move around and experience the augmentations from different angles and positions. Except for very large, building-scale SAR systems, users can touch and interact directly with physical objects and the information projected onto them.

Decoupling the display from the user makes SAR a promising technology for collaborative tasks. Collaboration is limited only by the number of people who can fit in the available space, not by the amount of equipment available. All users can see exactly the same augmented information. Projector-based displays don't require users to cover their faces with HMDs, which would make them unable to read each other's facial expressions.[5]

The physical nature of SAR environments supports *passive haptic feedback*; that is, the physical surfaces are touchable. This greatly enhances the users' understanding of the presented information. Also, SAR environments support all natural depth cues because the projected information falls onto the physical objects. SAR systems can accommodate full-scale, room-size physical objects. Large wall displays, semi-immersive VR, and

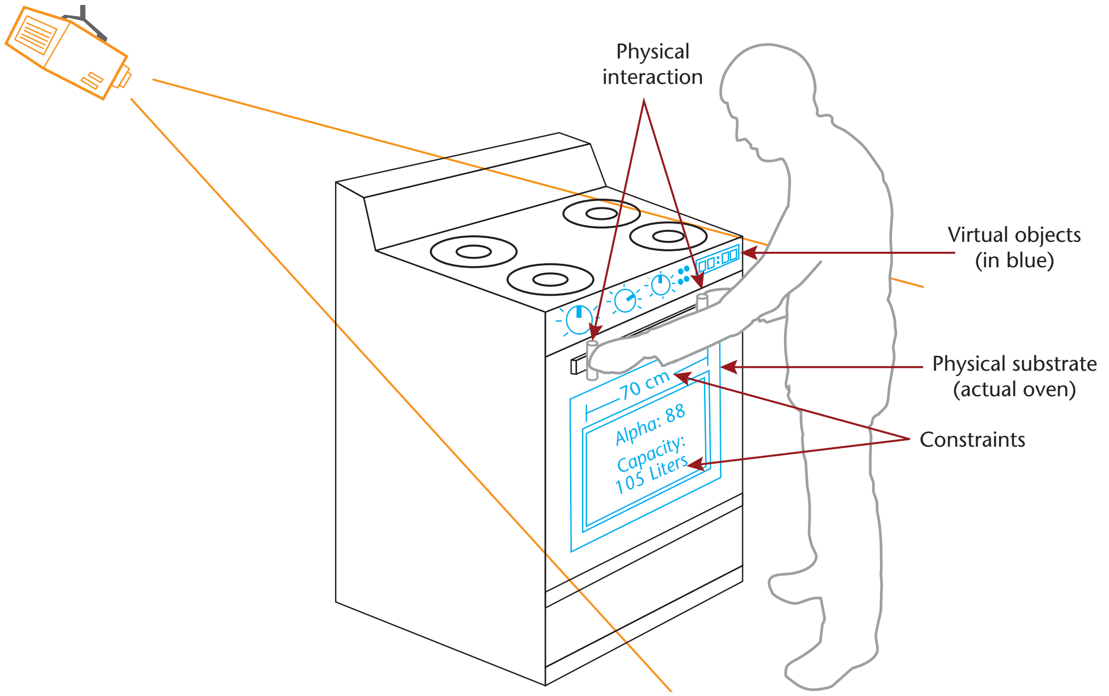


Figure 2. Designing fine details of an oven using SAR and an approximate physical object. Projectors enhance the object's appearance with virtual information (such as the door, dials, and timer). (This figure is based on a drawing by Neven Abdelaziz Mohamed Elsayed.)

desktop displays partially support passive haptic feedback through indirect props, as Ken Hinckley and his colleagues demonstrated.[6]

Many VE user interaction techniques don't map well to SAR. In SAR, all virtual information must be displayed on a physical surface. It's impossible to draw virtual information in mid-air with an SAR system. A key technique in VEs is the presentation of user interface controls in free space, such as floating menus. A second technique is to provide screen-relative information. This information isn't registered to the 3D virtual world or the physical world; it's provided as 2D information directly on the display device.

Another important requirement for SAR is precise, low-latency tracking. This is because noticeable artifacts occur when a user moves a physical object that's being projected onto. When the viewer is using an HMD or handheld display, tracking errors appear as virtual information drifting around physical objects. With SAR, tracking errors can cause the projected information to appear at the wrong location in the real world. For example, the projected light could miss the object in a user's hand and appear on a different object, the wall, or the floor.

These SAR characteristics highlight the requirement for specialized user interface technologies. This provides an exciting opportunity to rethink the user interface in the context of SAR. Consider designing controls for an oven (see Figure 2). Using a physical mock-up for the oven's basic shape, projectors enhance the appearance with virtual information (such as the door, dials, and timer). Tangible interaction tools let the designers manipulate the virtual information. Any interaction and presentation should ideally conform to the constraints imposed on the model and on the SAR system's SUI. For example, the virtual shape should respond appropriately when the engineer changes the door size and should be constrained to appropriate areas on the mock-up.

A tighter coupling between virtual and physical artifacts lets users gain spatial reasoning and understanding by physically touching the artifacts while letting them modify the underlying virtual information. Current CAD systems use standard computer monitors, requiring users to have a high level of spatial-reasoning skills to mentally visualize the full artifact while creating, modifying, and analyzing designs. So, users must have years of training and experience to build their spatial-reasoning capacity. To overcome a user's spatial-reasoning limitations, physical models or prototypes are built to assist the design process. But these are often time-consuming and costly to produce and offer limited flexibility. SAR combines the virtual representation of the design with a physical prototype to enhance the understanding of the design. However, SAR user interfaces require improvements to let users record, interact with, and understand the design.

Developing SUIs

Here we describe three promising approaches for developing SUIs for SAR systems: *tangible user interfaces* (TUIs) and physical props, *physical-virtual tools* (PVTs), and *ephemeral user interfaces.* These approaches build on each other to show how SAR exploits information presented to the user to provide an SUI in the physical world.

This section doesn't provide an exhaustive review; many other possible techniques exist. For example, other potential techniques include employing an additional handheld device as an auxiliary display and interaction surface, hand and body gesture systems, voice interaction, and multimodal techniques.

Tangible User Interfaces and Props

Because SAR freely lets users interact with the physical world, we see the use of physical objects as part of the user interface as a logical direction. The objects not only can help with interactions but also can act as display surfaces.

With TUIs, users employ physical handles attached to virtual objects; manipulating the handles affects the objects.[7] TUIs aim to provide more natural ways of interacting with computer systems. They're a natural fit for SUIs. As we mentioned before, SAR users don't have to wear or hold the display technologies. So, they can hold and employ six-degree-of-freedom tracked physical tools. Key to these SUI technologies is the users' ability to understand and express themselves on life-size artifacts and to physically touch them.

Hunter Hoffman and his colleagues showed that the ability to touch physical objects enhances virtual experiences' realism.[8] Colin Ware and Jeff Rose showed that using physical handles for virtual objects improves users' ability to perform manipulations such as rotating virtual objects.[9] Although these experiments focused on VR applications, the results support the concept of physical-interaction techniques for SAR. SAR doesn't inhibit users' sense of proprioception because they still can see the physical world. Also, because SAR frees users from having to hold a display device, their hands are available for more complex bimanual interaction techniques.

Brett Jones and his colleagues developed techniques for structuring SAR interaction with physical objects.[10] The combination of physical objects and projected information provides an immersive, tangible experience. Jones and his colleagues explored users interacting with everyday objects arranged as an interaction surface, with the system employing interactive surface particles. Users build their own physical worlds as arrangements of the physical objects. Virtual information is mapped onto their physical construction. The users then interact with the content using a stylus.

Jones and his colleagues developed a set of surface-adaptive GUIs—for example, a radial menu. With this menu, the user selects by physically pointing at a point on the physical object. A set of surface particle sprites radiate from this point and progress outward to a determined distance along the surface. The menu itself adapts to the physical object's contours. This is a clear example of how, in an SAR context, a concept such as a menu must be redesigned in not only appearance but also function.

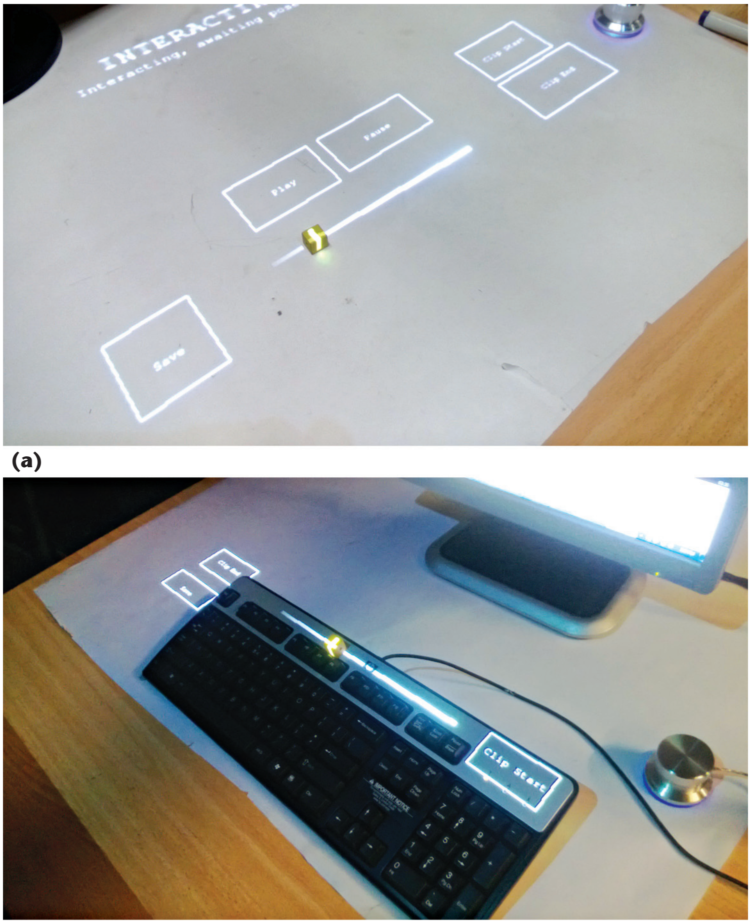
Physical-Virtual Tools

PVTs build on the physical nature of TUIs and address the characteristics of SAR we described earlier.[11] These SUIs consist of physical tools augmented with additional projected information. This is invaluable in a large-scale SAR system, where there's no fixed location suitable for a traditional user interface. Like props, PVTs exploit both our natural ability to operate manual tools and the proprioception cues during the tools' operation to enhance virtual interaction.

PVT user interfaces differ from props and previous TUI research in several ways. Most important, PVTs are for performing specific interaction tasks with a system. Props, on the other hand, are typically physical stand-ins for virtual objects.[12] TUI and prop-based systems either show additional state information and GUI controls at a fixed location on a display or project them onto a tabletop. This approach works well for VR systems and tabletop TUI applications. However, it's unsuitable for a large immersive SAR system because users might need to interact with the system from many different locations or because the system might need to support multiple users. So, in a PVT system, information that would usually be placed in a traditional GUI is instead projected onto the tools themselves. This places information close to where the user is working, avoids the need for additional screens, and naturally supports multiple users without extra infrastructure.

Projecting state information onto tools enables tool virtualization—overloading a tool with multiple functions and attributes. For example, a pen could have several colors and brush styles. A virtualized tool has information, such as its current state, projected onto it. For example, a stylus tip could have the current color projected onto it. Or, the system could change a multipurpose tool's

Figure 3. A physical-virtual-tool user interface for an airbrushing application. The user holds the stencil tool in his or her left hand. The system projects the controls onto the device, indicating the current mode and available modes. The airbrush tool, held in the right hand, has the spray angle, paint color, and brush type projected onto it.



(a)

(b)

Figure 4. Two examples of ad hoc controls, in which the wooden cube is the handle for slider interaction. (a) Video-editing controls on their own. (b) The same controls supplementing the existing standard controls.

appearance to convey its active mode. Rather than providing only a single tool for all interaction, the system provides a set of tools based on the kinds of tasks the user needs to accomplish and the necessary interaction methods. Figure 3 shows an airbrushing application using a PVT user interface with overloaded tools.

Ephemeral User Interfaces

Human–computer interaction is moving from GUIs to SUIs that employ direct manipulation and are consistent across devices and spaces. Away from dedicated TUI systems, we all still utilize the unique physical affordances of everyday objects as part of our interactions with other people and systems. This use of arbitrary objects in novel ways provides a new method for digital interaction, leading to ephemeral SUIs. Given the unplanned and chaotic nature of the real world, it's appealing to empower users to be able to create SUIs on the fly from the resources available and applicable to the users' context, as suggested by Steven Henderson and Steven Feiner's "opportunistic controls."[13]

Besides simple applications such as using physical objects as proxies for digital content, such SUIs take a number of forms. Users might seek to use physical objects as a proxy or token or a physical control for existing content in SAR. For example, users might pick up a marker and angle it left or right and up or down as an improvised joystick to control 3D content. Or, they might be exploring a problem-solving scenario and wish to apply any number of logical constraints to indicate explicit relationships within and between entities in the system.[14] Figure 4 illustrates two examples of ad hoc controls, in which the wooden cube is the handle for slider interaction.

Given that the users exist in the SAR environment, any new content and functionality must be authored appropriately. Such SUIs should fade into the background, with the users unaware of their existence. Users should be able to immediately pick up an object and use it to interact with the system without a second thought. Ideally, users could use their normal physical interactions in the system to author new content and functionality.[15]

The continual advancement and commoditization of the required hardware for managing ad hoc environments means support for such capabilities is no longer a hardware issue. Sensing technologies such as the Microsoft Kinect mean that the required tracking and interaction systems are now pervasive and untethered from the interaction devices. This lets the technology track interactions within the same large-scale volumes that SAR is projecting in. If users know what functionality the system is capable of, they should be able to employ that functionality in a task- and context-appropriate manner. So, the software now enables extensibility for the ad hoc creation of novel tangible and touch-based interaction. Dedicated input devices will always have a place. However, the importance of enabling the user to create (at a minimum) low-fidelity input devices as required for the current context can't be underestimated, if only for peripheral interaction.

Application Domains

Here we discuss application domains particularly suited to SUIs for SAR. Owing to the large scale of the environment and the artifacts the user interacts with, SUI technologies are a natural fit for SAR.

Industrial Design and Architecture

Integrating SAR technologies into design processes can enrich industrial design. Designers require a rich set of tools to let them both haptically and visually understand their designs (see Figure 5). Industrial design already extensively uses physical models and prototypes, making it especially suited to SAR. The goal is to integrate interactive SAR technology early during design. An expressive SUI that lets designers directly interact with virtual designs is critical; PVT techniques are one way to achieve such interaction.

SAR lets designers visualize their concepts in great detail, with a more flexible modeling environment than current techniques provide. Current industrial design requires designers to rebuild and often restart their prototype designs numerous times during development. For example, consider a physical mock-up of a car dashboard in which the designer is placing air conditioning controls. Assume the requirements suddenly change because a GPS display has been added. This is a significant change to the physical mock-up that requires redeveloping a fundamental feature of the design, involving either significant changes to the initial mock-up or a new mock-up. By using SAR and SUI tools, the designer can visualize the new design and appearance without constructing a new prototype.

So, how can designers express design changes in the combined physical and digital spaces? One approach is to use handheld PVTs. The tracked tools allow for comprehensive simulation of the target devices. For example, with a PVT, the designer might select buttons for operating the air conditioning system and place them directly onto

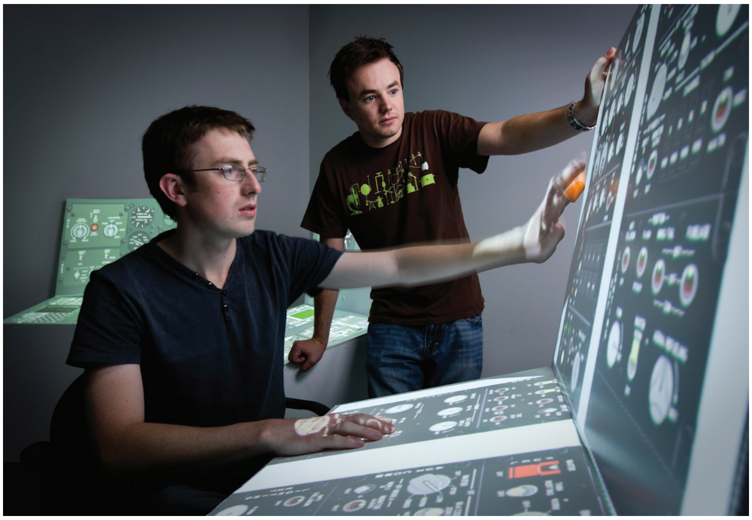


Figure 5. Designing the layout of control panels in an immersive SAR environment. The goal is to integrate interactive SAR technology early during design.

the prototype. The mock-up's appearance can transform to show the design's fine-grain details. Designers can then easily relocate significant features, such as the air conditioning controls, or change the entire surface color at the touch of a button.[16] SUIs let users make these changes in situ with a prototype by enabling them to move freely in the design space.

SAR can also incorporate TUI elements to enhance the fidelity and tactile aspects of prototype user interfaces. Tim Simon and his colleagues developed a set of generic physical buttons to support designers developing SAR-based prototypes.[17] With those buttons, designers can dynamically position controls, and the SAR system can project details on the buttons. The buttons have RFID tags that are read by a wearable glove sensor system to emulate button activation for simulating prototype functions. Industrial designers' requirements guided the system's design, and an expert review of the system evaluated its usefulness and usability. The performance evaluation conducted with the RFID controls showed they can be a supportive tool in the design process.

The SAR enhanced design process is a unique opportunity for SUIs owing to the varied expertise of people who can be supported. In the automotive example we described, the design process has numerous stakeholders; each will interact differently with the artifact. Designers will be interested in form and will require editing tools such as T-squares, detailing brushes, and flipbook collections of instruments.[18] Process engineers will be interested in how the product will be manufactured, will require different information, and will require SUI tools to support task ordering and part placement in the workshop. Specialized tools will

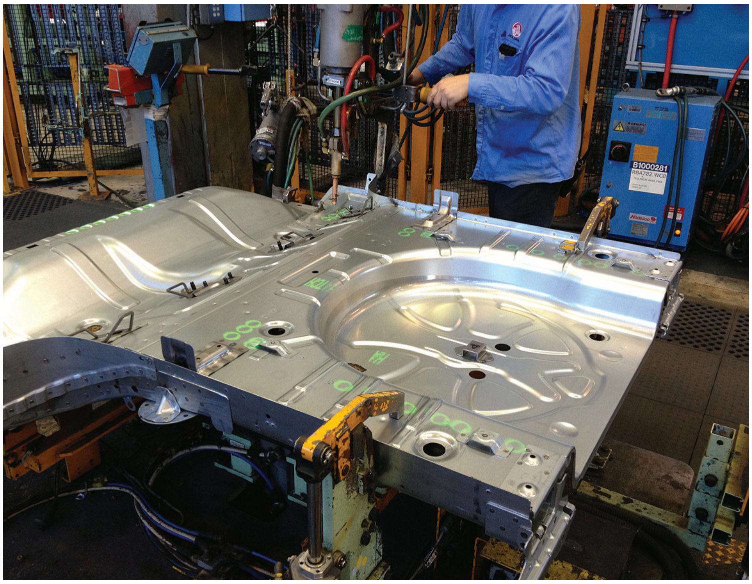


Figure 6. SAR annotations indicating locations for spot welds in an industrial scenario. CAD models are loaded into the SAR system, making this approach fit within existing engineering processes.

let them modify high-fidelity CAD data directly on the dashboard. Marketing personnel will need to compare their companies' products with competitors' products. Finally, customers will want to be part of the design process and experience the final product. They'll be able to sit in front of the dashboard and view different designs. They'll also be able understand the placement of different design elements by viewing them from the driver's seat and emulating operation with the controls.

Manufacturing and Training

SAR is useful for in situ instruction in certain manufacturing and training scenarios. In these situations, there's a significant advantage when users aren't wearing or carrying any display technology. This is particularly true when users need their hands free to focus on their primary task, such as in spot welding. An important aspect of the problem is designing SUIs to support interactions that aren't cumbersome or interfere with the user's task.

A compelling example is the automotive industry, which has employed SAR in different forms. Björn Schwerdtfeger and his colleagues used laser projectors to annotate weld locations.[19] Safety is a concern with laser projectors owing to reflections off metallic surfaces. However, it's now possible to create industrial SAR systems with much more flexible and inexpensive natural-light projectors. Jianlong Zhou and his colleagues used such projectors to indicate the position of spot welds for inspection.[20] Referring to blueprints for weld locations and visual inspections are common techniques. An SAR system uses dynamic visualizations to assist users by directly projecting visual cues over spot-weld locations (see Figure 6). This implementation loads the existing CAD models into the SAR system, making this approach fit within existing engineering processes.

The major challenges involve creating engineering systems suitable for industrial environments and integrating them with existing automation systems and processes. The environmental conditions of research labs and factory floors differ considerably. Deploying projectors and computer systems onto the factory floor requires protecting them from dust and moisture, providing mechanical reinforcement to protect the fragile optics, and ongoing maintenance. Regarding the automotive example, this form of SAR presentation of instructions could be extended to tasks other than spot welding, such as placing parts or applying adhesives. SAR's flexibility allows for a range of tasks. A critical issue is the presentation of information that's appropriate for the worker's level of experience.

For spot welding, SAR would make an excellent on-the-job training tool, not only showing the welds' correct location but also the order of operations. Experienced welders might only require annotations for more difficult welds or to find a missing weld. Welder training might also occur offline, including full multimedia presentations. The system would use audio to explain the task's overall structure. Projected instructions and annotations would let welders quickly understand the tasks in the correct order. This information would be much more in depth and complete than the information provided during operations. Finally, welders could perform simulated welding with the operational SAR information, with the associated SAR system cameras determining whether they were performing the task correctly.

The authoring of these offline training materials would require SUIs to specify and construct the presented material. These materials might be assembled on a traditional workstation but would need to be refined on the factory floor. These refinements would have to be performed quickly and accurately in situ with the piece to be welded. Special techniques would be needed for information placement, the pacing of instructions, drawing annotations, and entering text. The fusion of traditional media with this 3D task would also require SUI techniques.

Process improvement also shows great potential for spatial interfaces and SAR systems on the factory floor. For example, operators play a critical role in process improvements during production that are difficult to recognize during engineering design. For instance, an operator might identify a weld location that's causing intermittent machine failures or slowing down a work cell. An SAR system, in conjunction with a spatial interface, can capture such process improvements and communicate them to designers.

To allow this capture and communication, specialized authoring tools must be developed for both process engineers and line workers. During this authoring, only tracking infrastructure would be required. No tracking would be required during operation, and the system could be calibrated with a simple camera. To support this authoring, temporary six-degree-of-freedom tracking systems must be engineered. The SUIs could be supported with specialized tools. These input devices would support both direct manipulation and command entry for tasks such as specifying the order of welds.

Because the temporary tracking systems might not be precise or accurate enough to meet engineering tolerances, another challenge would be the precise position of instructions. The ability to specify exact dimensions or constraints relative to the parts CAD data is one possible approach but would require significant development of SUIs.

Information Presentation and Entertainment

SAR is a compelling candidate for information presentation on physical objects. Many viewers can see the projected information simultaneously. The display equipment can be mounted permanently out of reach, making SAR suitable for art installations and museums. Researchers have used SAR to overlay computer-generated information on paintings.[21] The implemented effects include overlaying earlier versions of works, color correction based on ambient light, presenting information about the work, and changing the appearance to give the illusion of different materials.

One example of SAR for entertainment is IncreTable, a table-top mixed-reality gaming system.[22] IncreTable allows interaction between physical objects, such as dominoes and user-controlled robots, and virtual objects projected onto the table. Users interact with it by using a tracked pen or moving physical components.

Theatre and installation art is another exciting area suited to SAR. Half Real demonstrated the use of SAR in interactive theatre (see Figure 7).[23] The production used projected sets, tracked actors to produce reactive environments, and audience interactivity. A major challenge limiting the adoption of SAR in entertainment settings is the lack of content creation tools and consumer-level software.

Figure 7. Half Real is a theatre production that featured projected environments, actor tracking, and audience interactivity.

SAR user interface and application design is an exciting research area still in its infancy. SUI concepts, such as movement in 3D space, combining 2D and 3D information, and natural interactions, are critical for SAR user interfaces' success. SAR could greatly improve processes in many application areas in which physical objects are common.

How will people employ SUIs as the technologies advance? We believe SAR systems show great potential for domains such as design, training, education, defense, and healthcare. Industries such as medicine and aerospace have already been revolutionized with CAD systems. These systems will likely incorporate SUIs to further advance their capabilities.

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