Signal Rich Art:
Enabling the vision of Ubiquitous Computing

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ABSTRACT

Advances in networking and mobile computing are converging with digital watermarking technology to realize the vision of Ubiquitous Computing, wherein mobile devices can sense, understand, and interact with their environments. Watermarking is the primary technology for embedding signals in the media, objects, and art constituting our everyday surroundings, and so it is a key component in achieving *Signal Rich Art*: art that communicates its identity to context-aware devices. However, significant obstacles to integrating watermarking and art remain, specifically questions of incorporating watermarking into the process of creating art. This paper identifies numerous possibilities for research in this arena.

Keywords: digital watermarking, steganography, Ubiquitous Computing, Human Computer Interaction, context, art, interaction

1. INTRODUCTION

Advances in computing, networks, devices, and sensors have brought us to the cusp of realizing the promise of Ubiquitous Computing: a world where the power of computing is integrated with the human environment, enabling us to engage fully with the world around us.[1,2] Today, however, our progress towards this vision is impeded by computers, networks, and digital devices that are largely unaware of their context and disconnected from their environment. Making machines context-aware is a significant factor in moving forward into Ubiquitous Computing (Figure 1).

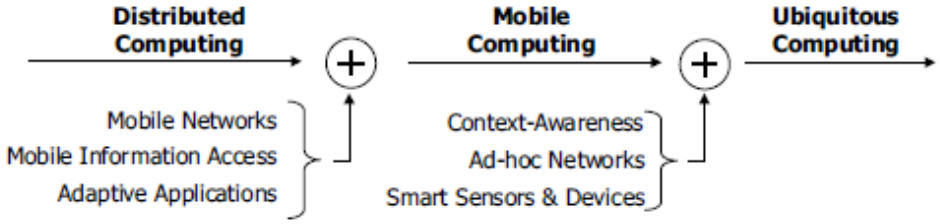

Figure 1: Context-awareness is required for Ubiquitous Computing [3]

A significant component of our contemporary environment that remains beyond the reach of our devices is art, that uniquely human form of expression.[4] Art in this context includes all forms of creative communication — not only traditionally expressive arts such as painting, music, sculpture, and dance, but also commercial arts such as movies, television, commercial photography, graphic arts, industrial design, etc. We are constantly surrounded by this type of art in the form of magazines, posters, TV commercials, movies, TV shows, popular music, etc. Even everyday objects such as drivers' licenses, packaging, and manufactured goods have significant artistic elements.

Across the range of many embodiments, art lifts the spirit and informs much of the context of human decision-making. Facilitating reliable identification of art by digital interfaces can significantly simplify access to network services and amplify our decision-making capabilities. Historically, however, art has been a static representation of its originator's vision, frozen at the moment of creation and communicated unidirectionally to the audience. The originator (artist or sponsor) of a work has lacked a means by which to engage the audience beyond the initial presentation of the work. For

example, a photograph in a magazine provides no opportunity to immediately engage the audience in further exploration. Even a multi-media work like a TV advertisement is a discrete, one-way communication.

Suppose, however, that the photograph and TV commercial could communicate directly with digital devices — more specifically, with smart phones and other mobile devices. Suppose that such devices could recognize and identify art, enabling a photo, a commercial, or any work to trigger a response and engage the audience. The object-device communication reveals an important aspect of the user's context. Sensor input and other knowledge of context would allow the increasingly omnipresent network and device to tailor a response to engage the user in unprecedented ways.

These new experiences would be enabled by art that carries its own identity in a form that's detectable by digital devices' sensors – primarily microphones and image sensors. Such self-identifying art is called *signal-rich* — it contains a digital signal that can communicate its identity to a context-aware digital device equipped with sensors. By virtue of this communication, Signal Rich Art becomes part of the internet of things.[5] Instances of art become extensions of and portals to the online world. *Network attributes* can be associated with each instance of art to specify the range of experiences available to the audience.

The implications of enhancing art in this way are potentially profound. Our everyday environment would be full of works of all kinds that can identify themselves and thereby, at the user's discretion, initiate a response to enhance the user's experience and help achieve the user's goals. Each work of art will become a virtual hyperlink to multimedia information and services in the Internet of things.

Such an environment is alive with possibilities to be discovered and explored. It's a place where you can set your device to "Tell me what's out there" and see what happens. Or you can ask your device to identify a specific art work and help you explore its unique possibilities, which could be anything from a discount coupon to an art history lesson.

In this place, the opportunities for engagement can be of tremendous benefit to both the originators and the consumers of art. The impact of art is no longer bounded in time and space and media, but can expand in all these dimensions for the enrichment of all participants.

Self-identifying art can be achieved via many technologies, such as RFID, barcodes, fingerprinting, and watermarking. Each of these technologies has applications in the identification of objects and art within a broad range of specificity and confidence. RFID, for example, is used for tracking valuable objects, timing races, and identifying animals. Barcodes are commonplace as product identification in retail environments. Fingerprinting works well in some contexts such as music and image identification, particularly when applied in specific domains.

However, digital watermarking's characteristics make it a particularly important means of establishing digital identities for artwork: Watermarks have no materials cost, require no real estate in the artwork, and are unobtrusive, malleable and not bound to specific representations or forms, allowing great flexibility in how they are integrated with art. They are robust to noise and manipulation and are currently used to uniquely identify billions of instances of art for millions of digital devices.

These qualities enable a common mechanism for the recognition of art — a mechanism with the potential to dramatically simplify the development and deployment of context-sensing components across the spectrum of devices envisioned in the Ubiquitous Computing landscape. Ultimately, a watermark detector can be considered a Logical Sensor that utilizes physical sensors, other contextual data, and inference to identify signal-rich objects and provide relatively real-time intuitive access to network services in the user's visual and auditory environment that can be ad hoc or enduring, experienced at the moment, time- or place-shifted, or shared with others.

2. DIGITAL WATERMARKING

Digital watermarking enables embedding into a wide variety of works a signal that is detectable by digital devices but can be made imperceptible in normal use. When detected, this signal can trigger whatever actions are specified by the media creator or marketer, ranging from a simple confirmation of the validity of the identified media to initiation of an ongoing multi-media engagement with the audience. Robust watermarks can survive common media manipulations

including digital-to-analog and analog-to-digital conversion. Such robustness makes it suitable for embedding in various forms of media.

Since the early 1990s, watermarking has grown from an area of fundamental research with an average of only two or three papers published annually[6] to a technology that is widespread across all media types, required by numerous standards, and accelerating in its adoption (Figure 2).

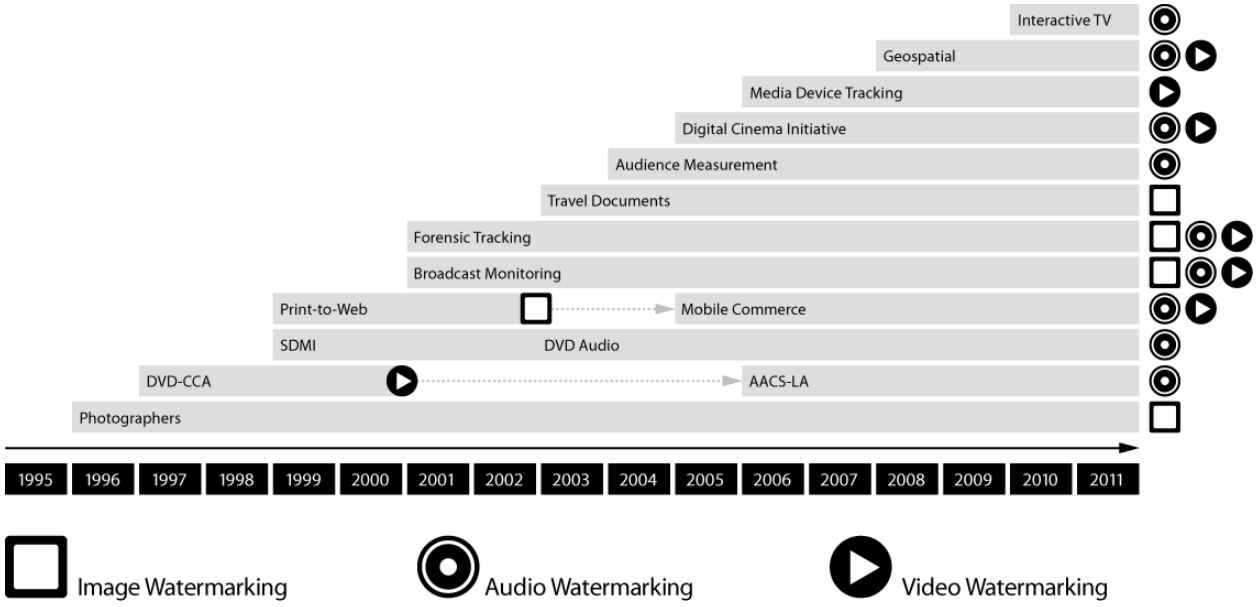

Figure 2: Commercial Adoption of Watermarking

Starting in 1996 with the first commercial deployment of digital watermarking for copyright communication and licensing of digital images for photographers, interest in watermarking quickly moved to print, video, and audio applications. Three years later multiple standardization efforts were underway for video and audio, and the volume of papers being published had dramatically increased. Digimarc's work with Central Banks on counterfeit deterrence progressed in parallel, pioneering the print space. As the years passed, leading suppliers in the IT and CE industries increasingly became stake-holders in the future of watermarking.

Building on this momentum, high-profile initiatives within the content community resulted in the creation of numerous standards that require digital watermarking. These include the Digital Cinema Initiative for movies, the Advanced Access Content System standard for Blue-ray disks, and the DVD Audio standard.

Less visible, but equally impactful, was the adoption of watermarking to protect travel and identity documents. More than half of all Americans carry drivers' licenses that contain one or more watermarks.

Outside of the forensic and DRM fields, watermarking supplanted paper diaries as the industry standard for audience measurement in television and radio, guiding programming decisions and tens of billions of dollars of advertising. Digital watermarks are now embedded in the vast majority of television and radio broadcasts in the United States. Audio watermarks are the basis of the well-known TV and radio audience measurement capabilities of market leaders Nielsen and Arbitron.

A significant and largely untapped market for watermarking is the enhancement of experiences for the media consumer. The earliest initiative in this space was Digimarc's MediaBridge, showcased in the late nineties as a means of linking magazine content to related materials and opportunities to purchase goods and services on the Internet.[7] The initiative lost momentum when the Internet bubble burst and web cameras failed to achieve critical mass. Web cameras provided the integral sensor link between the watermarked content and the Internet services.

With the surge in availability of sensors in mobile devices, such connections have become viable, not only from print but from all forms of media. Notably, Digimarc, Nielsen, and ABC recently conducted a nationwide pilot of providing synchronized services on viewers' iPads via detection of audio watermarks present in the television broadcast. Such synchronized services aim to heighten viewer engagement by providing a richer viewing experience, including character and actor bios, polls, audience feedback, sports statistics, etc.

Early glimpses of such new experiences and the massive proliferation of sensors in digital devices are sparking considerable interest among business in the potential value chain for watermark-enhanced media. The authors believe that this interest will generate significant profit opportunities whose growth will accelerate in time and scale as the market and technology trends rapidly mature and converge, providing a rich environment for applied research and exploration of new usage models.

2.1. On the Cusp

Recent developments in computing and communication are driving new fields of research as watermarking technology migrates from the research laboratory to significant new applications in the market. In particular, we are seeing the evolution of powerful mobile devices that are increasingly equipped with sensors. This has resulted in the creation of numerous applications that employ these sensors to guide the provision of valuable services to their users. This evolution will ultimately lead to devices that will see, hear, and know more and more about their location, orientation, user, and other elements of context. And as connected devices, they can employ this awareness to provide their users with a highly interactive, personalized, intuitive computing experience.

Today, these capabilities are employed in limited and isolated ways, but the capacity exists for creating a broad and integrated ecosystem supporting greatly enhanced benefits from employment of the sensors. A significant ingredient in enabling these novel benefits is reliable object identification. Digital watermarking can play a key role by making object recognition in many situations more reliable, faster, and more economical than alternative means.

Watermarking can be a cost-effective way of embedding a latent signal in almost any type of printed materials. Unlike RFID chips, watermarks do not emit or absorb any form of energy. The proximity requirements for detection provide a measure of privacy and user control. In contrast to barcodes, watermarks do not occupy any of an object's valuable real-estate or impact an object's design aesthetics. Similar comparisons can be made regarding audio, video, and other media objects.

Leveraging watermarking in this capacity spotlights a number of new applied research topics, many of which call for collaboration among researchers in the fields of Ubiquitous Computing, Digital Watermarking, and others. The remainder of this paper explores a vision for Signal Rich Art with emphasis on topics needing further exploration and research.

2.2. The Conundrum of Imperceptibility

One significant challenge facing future applications is that watermarking is currently implemented as a post-production step applied to a work after its creation. For example, photographs are typically watermarked between capture and publication. This approach was preferable when art was created with traditional tools, but digital tools are rapidly becoming dominant in the creation of art and consequently new areas of research are opening up.

Watermarking as a post-production step creates the conundrum of imperceptibility. Making changes to the signal of the original to enable digital devices to reliably identify the object must be done in a narrow interstitial of physics and biology wherein the modification is imperceptible to the art's creator. Compared to the original work, the modified work can have difficulty withstanding the scrutiny of the eyes and ears of the artist, or of the "golden eyes" and "golden ears" employed by industry. Artists are consequently reluctant to allow the embedding of signals in their art. Downstream partners are likewise reluctant to embed signals in works of art for fear of alienating the artist, however much value those signals add.

This problem persists in spite of a rich legacy of research on finding the boundaries of perceptibility of digital watermarks. Perceptibility is an artifact of the post-production nature of watermarking and its presence is a significant obstacle to the broad realization of the benefits of watermarking summarized above as Signal Rich Art.

Suppose, however, that watermarking was not a post-production step but part of the process of creating art. In this scenario, there would be no separate original and marked works. The original and the embedded work are one and the same, and there is no downstream imposition of an external signal on the work. In this vision of Signal Rich Art, the artist retains full control over creation of the final work yet still reaps the benefits of creating art with a valuable network attribute — Signal Rich Art. By making the watermark a design element and empowering the artist to embed the signal during the art creation process, the conundrum of imperceptibility can be circumvented.

3. SIGNAL RICH ART IN PRACTICE

This section explores some scenarios made possible by Signal Rich Art.

3.1. Illustration and Painting

While you're walking downtown with your mobile device observing your environment, you notice a poster announcing a concert by one of your favorite artists. You instruct your device to "look at" the poster. It tells you of an upcoming concert in town and a nearby ticket outlet.

Flipping through a bicycling magazine, you notice an advertisement for a bike you've been thinking about. Your mobile device looks at the ad and gives you the bike's technical specifications (models, sizes, components, colors, etc.), shows you recent customer reviews, and tells you that a local dealer has the bike on sale for the rest of the week.

When you see an interesting photo in the newspaper, your device can bring you up-to-date on the related story, including video footage of recent events. Having registered your previous interest in historical background, your device can also display the Wikipedia page on the country where events are occurring.

A quick scan of the packaging of a new medication reveals in-depth information on the medication's benefits, risks, potential side-effects, etc. With information about your medical background, your device also advises you of potential interactions with other medications you're taking. You can also learn how long this particular item has been on the shelf.

As a student of French Impressionist art, you can usually identify an artist's work quickly, but you're stumped by a print hanging in a hotel lobby. Your mobile device not only identifies the work but also provides you with biographical information, the date of the painting's creation, the location where it was painted, where the original currently is, and other data of interest.

3.2. Photography and Video

You instruct your mobile device to look at or listen to a movie that you're watching and, knowing your history of following certain actors, it brings up bios of the actors, complete with lists of the movies in which they've previously appeared. Depending on your interests, it can also access and display other information related to the movie — sports, geography, space travel, or any area where your interests intersect with the movie.

After returning from vacation, you sit down to watch your favorite TV show. Your tablet computer recognizes the show and pauses the replay while it displays a summary of the episodes you missed while traveling.

At a gallery where the work of a well-known nature photographer is being shown, you linger in front of a mural-sized photograph of the Grand Teton range. Your mobile device identifies the peaks in the photo and offers to show you pictures of the local wildlife or a video of the area. Or it could play audio of the sounds you'd hear if you were standing by the river where the photo was taken.

While you're watching a fascinating TV documentary on the Paranal Observatory in Chile, your device presents you with more in-depth information on discoveries made there and the scientists who made them as well as additional films and resources on observatories you may be interested in. You are also shown pictures of the proposed European Extremely Large Telescope to be built nearby.

3.3. Music and Audio

While you're shopping in the mall, you have put your mobile device in "listen mode" and it picks up a song coming from a nearby music store. Knowing you like the artist, it lets you know that CDs by that artist are on special today. It also shows you the video for the song that's playing.

Sitting in a coffee shop where some oldies music is playing, you and your friends can't agree on who the artist is. Your mobile device quickly settles the debate, plus it refreshes your memory about the song's lyrics and other music by the same artist.

While you're listening to an opera broadcast by your local classical music station, your mobile device recognizes the piece and displays the lyrics in English as they're sung in Italian.

3.4. Sculpture and Other Objects

You've just purchased a new outdoor grill that you're going to assemble yourself. Your mobile device looks at the packaging or at the grill itself and can easily see what model you have and lead you through the assembly process step by step with detailed instructions and an interactive video guide. It can also register your grill with the manufacturer for the warranty, offer discount coupons for accessories, and enter the grill and its value into your list of household items for insurance.

You're in the Rodin Museum in Paris and you realize how little you actually know about Rodin beyond his widely recognized sculpture of The Thinker. Just point your mobile device at the plaque at the base of the sculpture and it can give you a complete audio and video history of Rodin, plus background on every sculpture in the Museum — history, value, historical context, etc. You could also view a video of how a bronze or marble sculpture is created.

4. CREATING SIGNAL RICH ART

This section contains basic examples in the creation of Signal Rich Art.

4.1. Illustration and Painting

Painting and illustration software such as Adobe Photoshop and Corel Draw typically contain a set of tools for applying digital paint to a digital canvas: brushes, pencils, paint buckets, erasers, smudgers, basic geometric shapes, etc. These tools can be extended to apply signal to the canvas.

Consider brushes, for example. Brushes can be configured with different tips, sizes, dispersal rates, opacities, etc., and artists can apply brushes with varying pressures, speeds, colors, etc. Conventional brush tools can be extended to include a signal in the paint that is applied to the canvas. The painted pattern can represent a unique ID. As the artist uses the brush, a watermark can be interwoven with the pattern using Spread Spectrum[8] or Quantization Index Modulation[9] (QIM) techniques. Simple pattern matching or traditional watermarking detection techniques can be used to recover the embedded signal.

Also, the artist can constitute a signal by arranging carefully chosen artistic elements of specific shapes, sizes, colors, or other characteristics, as done in some security documents such as drivers' licenses. An obvious and well known example of this is barcode technology, where the artistic elements are line thickness and spacing. Such artistic elements can be employed as signals in a subtler, more acceptable fashion by using them to fill objects the artist wants to draw. Depending on the nature of the composed signal, either a simple spatial domain pattern matching technique or frequency domain analysis can be used to recover the embedded signal.

More sophisticated techniques can be constructed along these lines to maximize detection and payload capacity while operating within the sphere of artistic creativity. The integrity of the embedded signal must be carefully maintained throughout the use of many different types of software tools. Techniques must be general enough to apply to all kinds of art used in posters, illustration, and painting, or techniques could be optimized by genre and delivered in ways that would support intended uses by audiences. Some art work will naturally be more amenable to embedding using one technique rather than another. Artists must learn the capabilities and limitations of each technique and use them as they deem fit.

Another opportunity for investigation lies in the pervasive use of textures in painting large surfaces. Textures such as orange peel and popcorn are often applied to interior walls and other large areas as an aesthetic addition, providing visual variety to the eye. Such textures are random in nature, but it may be possible to manage the creation of such textures to contain a signal and so provide more data to a context-aware device.

4.2. Photography

Photographers could embed a desired watermark while capturing an image by employing techniques from computational photography.[10] For example, computational illumination technique allows the photographer to control the illumination in a structured fashion, and then process the captured images to create new images of desired illumination. Also coded aperture and coded exposure techniques allow the photographer to boost the image quality by capturing optically coded images that can be processed by computational decoding to produce new images of desired characteristics. Integrating watermark embedding with computational photography would provide a tool for the photographer to select and embed a desired payload as he points his camera to take a favorite picture.

4.3. Music and Audio

Music could be watermarked during its composition or creation. IBM Japan introduced a way of embedding a spread spectrum watermark in live performance by playing the watermark in the background during performance.[11] The watermark is recorded along with the performance. Yamamoto proposed a real-time method of watermarking the music synthesized by digital instruments.[12] He embedded the watermark in wavetables that are included in the digital instruments. These early efforts presage possible approaches to be further examined by the research community. The ultimate synthesis might be better achieved by changing the attributes of the music during its composition at the instrument or channel levels. Many interesting signal processing issues would be involved in such an approach.

Music offers numerous characteristics that can be modified — tone, rhythm, volume, tempo, instrumentation, etc. Any of these characteristics could be modified during composition to embed a watermark. However, it is a challenge to determine what is entailed by embedding signals in this way. Could types of signals be defined that would not constrain the composer? Would a composer employ a tool or method that required, for example, the presence of certain tones in certain sequences to convey a message? How would the artistic “costs” of such new processes measure up against the benefits of Signal Rich Art?

4.4. Video

Video has historically been watermarked in post-production by slightly modifying the video frames or the audio using spread spectrum or QIM techniques. However, there are other possibilities for embedding a signal in video. For example, the type, length, and other attributes of the transition effects between scenes can be carefully modified during production to carry a signal. The embedded signal can be recovered using techniques developed for the detection and categorization of transition effects in video. A pilot signal is needed to distinguish signal-carrying transition effects from effects devoid of signal.

Another approach to watermarking video is to compose background music specifically to carry a signal, as described in the previous section. This music is mixed with the video during production.

4.5. Sculpture and Other Objects

Objects with flat surfaces can obviously be watermarked in the same way that digital photography and art is watermarked, using either the historic approach or the newer ideas introduced above. Medical packaging, for example, is beginning to be watermarked during printing as a way of providing additional important resources to purchasers.

Objects, however, literally offer additional dimensions to consider in watermarking. One additional dimension is that of texture. Signal can be embedded in an object by adding textured patterns or by modifying an object's natural texture. This form of watermarking is currently employed to track sensitive or high-value machine parts and to identify containers carrying toxic or hazardous materials.

Three-dimensional objects also raise the possibility of encoding signal by arranging artistic elements in space. This possibility raises the same kinds of issues as those brought up by embedding signals in music or painting by careful arrangement of artistic elements. While practical applications do not yet exist, research has been done in watermarking 3D models through modulation of triangle vertices.[13] It can be extrapolated that such modulations would persist through the manufacturing process.

5. CHALLENGES AND RESEARCH OPPORTUNITIES

Obviating the conundrum of imperceptibility through Signal Rich Art raises a host of issues and opportunities. The challenges of this new approach to digital watermarking present researchers from industry and academia with research opportunities to enhance art, promote commerce, simplify search, and facilitate intuitive and Ubiquitous Computing. Solutions will require relentless effort and genuine creativity. They also entail an unprecedented cooperation among artists, scientists, marketing professionals, software developers, hardware manufacturers, and network providers. Some of these challenges and research opportunities are discussed below.

5.1. Generalizing the Concept of Signal

Several simple signaling mechanisms have been suggested in the preceding paragraphs to obviate the conundrum of imperceptibility: patterns painted by a brush, transition effects in video, arrangement of elements in illustration, tonality in music, etc. These are modifications to the structure of the work itself, not to the digital representation of the work.

Virtually any of the characteristics or elements of a work can be modified to embed a signal. The challenge is to expand the underlying idea of the signaling mechanisms suggested above to create sophisticated signaling schemes that accommodate a large ID space as well as ensure robustness and ease of detection. The implications of this approach to embedding signals must be carefully assessed. For example, if an artist defined such a pattern to encode a signal, how could that pattern be communicated downstream to sensing devices? How would one artist's pattern be distinguished from another's?

How would a work that contained no signal be distinguished from a work that did? How would false positives be avoided in an environment of essentially infinite combinations of artistic elements? How could such signals be made robust in the face of manipulations of art works, whether routine or malicious? How would all these patterns interfere with each other?

There are obviously numerous interesting questions raised by the idea of generalizing the concept of signal. Clearly this approach will require thorough investigation to ensure its practicality and superiority to traditional embedding methods.

5.2. Tools

Creating Signal Rich Art using the generalized concept of signal requires the development and integration into production environments of a set of embedding tools that are transparent, easy to use, and supportive of creativity. These tools should seamlessly integrate with those already commonly used for art creation. For example, tools for embedding signal in posters, illustrations, and paintings should be integrated with art creation packages such as Adobe Photoshop and Corel Draw. Similarly, tools for embedding video should be integrated with video editing tools such as Corel Video Studio, Adobe Premiere, and Sony Vegas Movie Studio.

New embedding tools should include all the elements required to create Signal Rich Art. They should use a designated signaling scheme or support creation of new schemes. They must enable embedding specific payloads and support the registration of signal schemes and payloads in standardized databases for association of network attributes with artwork. The tools should minimize interference between signals. They should foster creation of signals that will encourage creativity and enhance art.

Fast and reliable detectors are needed to bring to life the signals latent in Signal Rich Art. These detectors should have maximum detection rates and minimum false positive rates. They should enable detection on low power mobile devices or split the work optimally between servers and clients running on mobile devices.

Server-based tools will be required to manage the registration of different signaling schemes, support association of network attributes with each payload, and initiate the proper actions when a user's context-aware device encounters a work of Signal Rich Art.

5.3. Infrastructure

As mentioned previously, digital watermarking has a significant legacy of applications in digital media. The infrastructure required to support these applications is not insignificant. Successful applications require development of both hardware and software encoders and decoders, followed by deployment of encoders and decoders to art originators and consumers. Deployment raises issues of interoperability and standardization among a wide range of constituents. Widely available network connectivity is necessary to manage the actions triggered by watermark detections.

The environment of Signal Rich Art described here greatly expands the infrastructure requirements. For example, if signals are encoded in patterns defined by the originators of art themselves, a repository for patterns will be needed to prevent duplication or conflict among different patterns. Where would such a repository reside and how would it be accessed? How would additions to it be mediated? Could the repository be searched in real time? How scalable would it need to be?

5.4. Software and Hardware

Mobile devices are increasingly sensate. With a mobile device, you can take pictures, record music, learn where you are, and find out where you're going. But each of these actions is initiated by you and otherwise your device is inactive.

To take full advantage of the signal-rich environment, mobile devices must become more like human perception — constantly receiving input. But also like humans, devices could be overwhelmed without some ability to filter the input. The first question is how to determine which inputs are signals. Next, how would a device determine which signals are important? What knowledge would the device require to make good decisions about where to focus and what actions to take?

Context-aware devices capable of reliable object identification would benefit from capabilities like memory of previous interactions in similar contexts by a range of users and knowledge of the particular user's history and preferences. Object recognition and context awareness raise the question of inference — determining the optimal response to known circumstances. Such cognitive capabilities begin to approximate intelligent behavior. Enhancing machines along these lines will require significant advances in both hardware and software.

6. CONCLUSION

We are on the cusp of major changes in the ways that people interact with media of all kinds. People are increasingly equipped with mobile devices that are becoming ever more perceptive of their environment and context. And through these same devices, people have constant access to the internet and all that it offers.

But while the devices are advancing rapidly, the environment in which they function has remained relatively static. Media and objects in the environment remain passive participants in the world.

This situation can be changed with the advent of Signal Rich Art — art that identifies itself and connects the audience to its network attributes for a richer experience of their environment. Digital watermarking offers significant potential for realizing the vision of Signal Rich Art, but many questions remain and much research and work must be done to realize the vision of new artistic experiences and the richer, more pervasive, and more intuitive computing model that it would enable.

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