Engineering Considerations in Commercial Watermarking

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ABSTRACT

This article explores some of the engineering and design considerations for a commercial implementation of watermarking technology. Watermarking technology has many performance characteristics that rival one another in the system design space. After a brief discussion of these characteristics, we will examine the engineering trade-offs required for a particular commercial instantiation of watermarking technology, the *Digimarc MediaBridge* system. We will begin with an overview of the system and its requirements, and then discuss the engineering considerations that led to its successful implementation.

INTRODUCTION

Over the past few years, watermarking technology has seen intense interest in the research and scientific community. This special issue of *IEEE Communication Magazine* is occasioned by the explosive growth and popularization of this new discipline. Driven by extensive, fundamental work at a large number of first-rate research centers, the open literature in this field is full of important and exciting concepts. Other articles in this issue illuminate the broad, fundamental scientific considerations for watermarking technology. As shown in those articles, the technology has exciting potential applications across a wide range of products. The potential applications include such diverse possibilities as notification of copyright in digital images, broadcast monitoring, and the annotation of analog data with extensive digital files. This article explores the design considerations for one such application, that of connecting watermarked printed materials with information stored on the Internet.

Realizing the full potential of this technology calls for innovation. Innovation requires two fundamental components: novel ideas and implementation. Novelty comes from new perspectives and concepts, along with the requisite research into their implications. Implementation converts these new perspectives, concepts, and research into applied technology, where engineering creates successful applications of a new technology. Novelty without implementation carries no economic benefits or rewards. And implementation without new ideas is simply incremental improvement, with no capacity to radically change or challenge existing technology paradigms.

WATERMARKING AS A COMMERCIAL ACTIVITY

As an exceptionally powerful technology, watermarking has many potential commercial applications, in many fields. And as digital content, such as images, music, and video, becomes more pervasive, the ability to imperceptibly embed digital information into the digital work will find growing numbers of imaginative commercial applications. For instance, the capability of some forms of digital watermarks to survive transition to the analog domain, and a subsequent redigitization, creates additional attractive system capabilities.

DIGIMARC'S VISION OF WATERMARKING

In the future, all digitally created works will carry a digital communications side channel, intimately and imperceptibly embedded in the content of the work. This additional digital content will travel with the work throughout the digital domain, surviving manipulation and file format changes. The digital content can then travel with the work into the analog domain and can be recovered in the digital domain. Thus, all forms of media, in any domain, will be regarded, effectively, as digital objects. The communications side channel will be used in a variety of ways ultimately, through linkages to other information, creating extended or enhanced capabilities for all media works.

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Possible Commercial Watermarking Applications

Additional digital capabilities, added to any form of multimedia, bring value to the user in a variety of imaginative ways [1, 2]. This extra information was originally developed to inform users of copyright information in digital images. It may also be used to enhance the security of documents through authentication of images included in the document. The ability of the watermark to survive passage into the analog domain allows printed images to be seamlessly linked with data stored in a local or online database. This is the basis for the *Digimarc MediaBridge* system.

Watermarking provides a separate communications channel that is an intrinsic and imperceptible part of the content of the watermarked work. The information in this channel can be used to protect the work, to prevent misappropriation of the work, or to enable the user of the work in a way that enhances his experience of the work. The function of preventing misuse or of informing of ownership rights is a familiar function from the world of copyright protection. The function of empowering the user and enhancing his experience is new and unique to the world of digital watermarking. It will be exciting to watch the development of new applications that embody this empowering capability.

We can see from the above discussion that every commercial watermarking system will, by design, not deliver the same experience to the user. The functionality and performance required of the watermarks used in each design will be unique to the intended use of the system. This will radically affect the required properties of each watermarking system.

Attention to Customer Needs and Requirements

The route to the design of a winning application of digital watermarking has a principal underlying theme: identify the customers and pay close attention to what you are trying to do for them. It is easy to lose sight of this idea. There is often an unspoken set of assumptions about what the customer requirements might be. These frequently reflect the interests of the inventor or engineer, generalized to a mythical, universal customer. If allowed to stand unexamined, these inexplicit assumptions may over constrain the particular watermarking technology employed and result in a system that does not meet the customers' requirements.

System Design

The most frequent cause of failure in the delivery of an engineering system is the failure to properly define customers and their needs. A common mistake is to focus on features with high technological content and to ignore those features that satisfy customer requirements, with less interest to the designer. The resulting system, while perhaps delightful to its creator, will leave the customer confused, unsatisfied, or worse, irritated. This is not the path to commercial success!

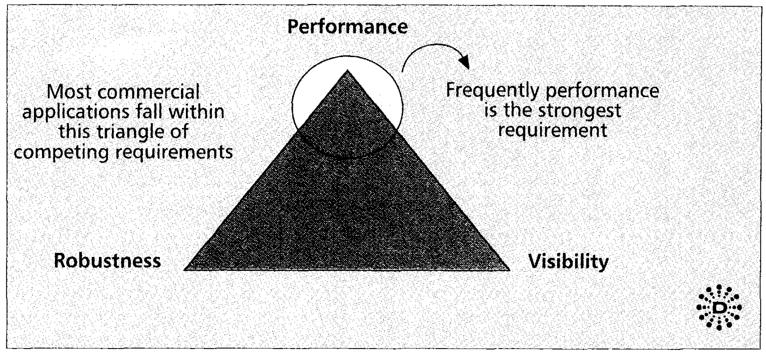


Figure 1. *Competing requirements triangle.*

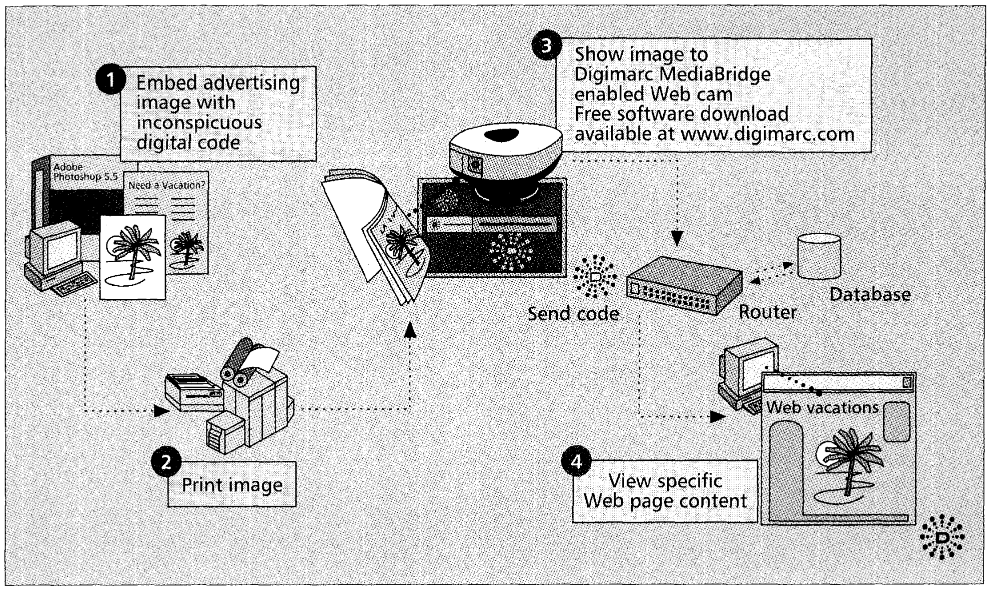
In any real-world system implementation, in any engineering discipline, there will be a number of contradictory constraints that must be traded against one another to best satisfy the customers' requirements. Optimization of one requirement at the expense of system performance will result in a system that does not deliver to its intended design goals. Although in the discussion that follows, the system requirements are divided between watermarking technology requirements and other considerations, this is an artificial distinction, used to facilitate the discussion. All customer requirements must be fulfilled to deliver a completely successful system. The design task is complete when the system meets the full requirements.

Watermarking Requirements

Inside the watermarking sub-system of any commercial instantiation of watermarking, there will be a number of competing performance capabilities that must be selected with system performance in mind. Different systems will require different mixtures of these capabilities. For example, a system that expects all images presented to it to be watermarked with a variety of embedded messages will have different needs than one that expects most images to be unwatermarked with only an important, but numerically insignificant, number of marked images. The tension between various combinations of performance characteristics must be successfully resolved to create a viable system. If there is no remaining design space after the system requirements have been defined, the system cannot be implemented. There are several common trade-offs that may have to be considered by a watermarking system designer. Robustness, the ability of the system to detect the watermark, especially after manipulations of the media content, is frequently in tension with the amount of information the watermark can carry (i.e., payload capacity). Figure 1 illustrates another common dilemma. The system will have specified maximum levels of visibility or perceptibility that oppose the specified level of system robustness. This design space is further limited by the required performance of the system.

Performance, an important characteristic that is not frequently discussed in the literature, is the speed with which the watermark will be embedded or detected. These two characteristics are called embedding performance and detection performance. An additional measure of performance, in an application where few watermarked

With the watermark code serving as a pointer to an online database, the application connects the user's Web browser to a Web site designated by the publisher of the image. This is a fundamentally new way to access the Web.



■ **Figure 2.** *Digimarc MediaBridge process.*

images are encountered, is the speed at which the absence of a watermark is determined, freeing the processor for other tasks.

Performance requirements do vary from system to system, but their importance does not. At Digimarc, customers demand that the use of the watermarking technology must be transparent to the user's experience with the overall workflow. This creates an inevitable tension between performance, robustness, and perceptibility. Figure 1 illustrates this trade-off. In this triangle, the designer may fix any two of the vertices, and the third will be determined. For example, if visibility and performance are fixed, robustness will suffer. Our customers' firmest requirements have generally clustered around the high-performance vertex of the triangle.

OTHER SYSTEM REQUIREMENTS

There are a number of system requirements that are essential to a successful system that have little to do with the capabilities of the watermarking system. Such requirements may include: what image formats need be considered, what are the memory requirements imposed by the algorithms, what network connectivity will be required, and what will be the cost of implementation.

OVERVIEW OF DIGIMARC MEDIABRIDGE SYSTEM

The *Digimarc MediaBridge* system enables the connection of printed images to other content, whether in electronic form or conventional media (Fig. 2). The images, also referred to as "Smart Images," [3, 4] bear a robust digital watermark that survives commercial printing processes and can be recovered through redigitization of the image. The images can be redigitized with a tethered PC camera, a consumer scanner, or a digital camera. The watermark is extracted from the image by the *Digimarc MediaBridge* application resident on the user's computer. With the watermark code serving as a pointer to an online database, the application connects the user's Web browser to a Web site designated by the publisher of the image. This is a fundamentally new way to access the Web, offering significant benefits to users, requiring careful implementation to meet their needs.

SYSTEM REQUIREMENTS

A number of performance requirements must be met, as outlined below:

- The digital watermark must survive printing on a wide variety of commercial presses.
- The imperceptibility of the mark must satisfy three groups: the owner or designer of the image, its publisher, and the consumer.
- The watermark embedder must fit the workflow of the prepress houses and must be compatible with commercial prepress software.
- The end user must be able to use the system in a typical home or office environment, under a wide variety of lighting conditions and orientations to the camera.
- The system must work with a variety of consumer PC cameras.
- The time to enable a "read" of the image should be short and convenient.
- The watermark detection time should be comparable to the frame rate of PC cameras.
- The central database servers have requirements of speed, constant availability, and ease of database update to ensure dynamic linking.
- The application should work well in a controlled, but unattended, retail kiosk, as well as a home or office scenario.

SYSTEM OPERATION

In this application, Digimarc's watermarking technology is used to embed digital watermarks in printed images, such as magazine articles and advertisements, event tickets, CD covers, book covers, direct mailers, debit and credit cards, greeting cards, coupons, catalogs, business cards, coffee cup holders, and goods packaging (Fig. 2).

As shown in Fig. 3a, creating a *Digimarc MediaBridge* image is very simple. The process starts with a digital image, into which the watermark is embedded. This produces a *Digimarc MediaBridge* image in digital form. Then, the digital *Digimarc MediaBridge* image is printed and published using normal commercial printing processes.

When a person uses a PC camera, digital camera, or flatbed scanner to produce a digital image version of a printed *Digimarc MediaBridge* image, the *Digimarc MediaBridge* reader application detects and reads the embedded watermark (Fig. 3b). The embedded watermark represents an n-bit index to a database of URLs stored at locations on the Internet, e.g., the Digimarc servers. This index is used to fetch a corresponding URL from the database. Specifically, the watermark reader connects to the Digimarc server to get the URL and then instructs the browser to navigate to that URL. The browser does not directly interact with the Digimarc server. This displays the related Web page or starts a Web-based application specified by the creator of the image. Thus, *Digimarc MediaBridge* creates a bridge between the printed material and the Internet, permitting users to link directly to relevant Web destinations without any typing, mouse clicks, or time consuming searching. This provides physical media with digital capabilities, allowing new forms of interaction with the digital world, thereby enhancing information access, advertising, and electronic commerce.

To experience an example of the *Digimarc MediaBridge* system operation, the images in this article have been created as "Smart Images," with embedded watermarks. Should you wish to try the system, download the client software from the Digimarc Web site (http://www.digimarc.com/).

Digimarc MediaBridge Design Challenges

As initially conceived and specified, the *Digimarc MediaBridge* system seemed to present insurmountable design challenges. The redigitization of an image printed on a commercial four-color press using a PC Web camera as the redigitizing engine of choice presented the need for improvements in existing watermarking technology.

Camera Designs and Quality

The quality of images from a scanner data source is fairly well controlled. Even the least expensive consumer scanner presents a high-resolution, low-noise, distortion-free image. The world of the PC camera is not nearly so uniform. In many cases, once an acceptable image quality level is reached (which may be very low), the design is driven by cost considerations. The camera design is optimized for a particular use, i.e., video conferencing over the Web. Our usage places significantly different requirements on the camera's performance. A closer look at the design of a typical PC camera will help highlight the areas where the camera design impacts its performance in the *Digimarc MediaBridge* application (Fig. 4).

First, the lens may have focal lengths and accompanying depths of field that vary from model to model. The focal length is fixed and the focus position is set manually. The lens will be characterized by varying degrees of distortions, which will damage the watermark, regardless of the domain in which the watermark is imbedded.

Additionally, the camera sensor may be a relatively low noise and high quality CCD or a less expensive CMOS sensor. The sensor will deliver a resolution that can range from 160 × 120 pixels to 640 × 480 pixels. The exposure and white balance may be controlled by an automatic scheme, again unique to each vendor. In some cases, the camera's automatic gain control is well designed and helps the application capture good images. In other cases, the application must control the camera more tightly. Once the image has been captured, the effects of the color filtration in the CCD are undone using interpolation schemes that are proprietary to each vendor. This also introduces noise into the captured image that can interfere with the watermark. Depending on

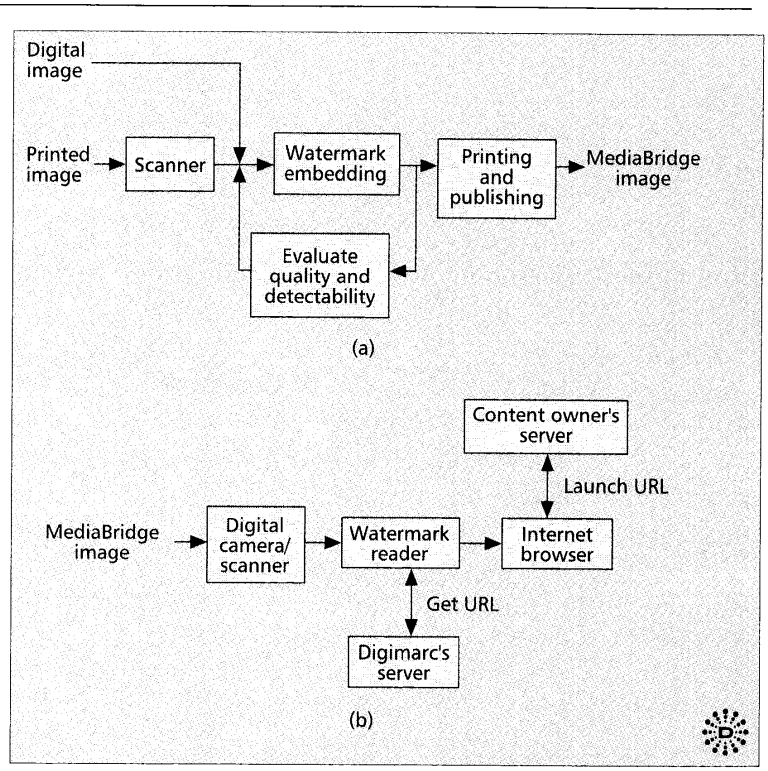


Figure 3. *Digimarc MediaBridge: a) embedding information; b) decoding information.*

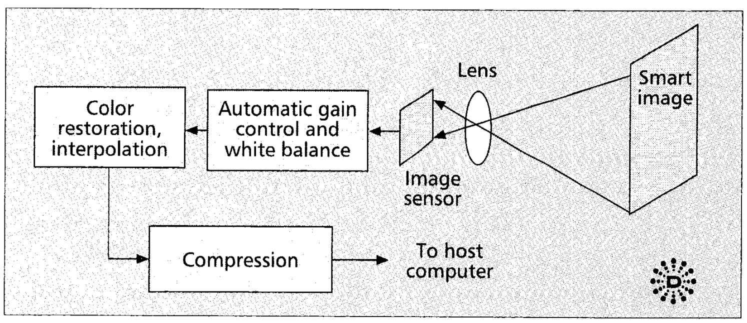


Figure 4. *Web camera operation.*

System users may be set up in an office, brightly illuminated by fluorescent lights, or may be set up in the stygian blackness of a home study, with minimal tungsten-based lighting. In response, the application must monitor the video stream for the overall lighting level.

the bandwidth of the link from the camera to the computer, at some frame rate the camera will automatically begin to compress the images, again impacting the watermark signal. Finally, the host computer's speed and memory capacity may restrict the amount of processing that can be performed on the captured image.

To overcome the difficulties presented by the various camera designs, the development of the *Digimarc MediaBridge* system has required detailed understanding of camera designs, and how to control and optimize the behavior across a broad range of cameras.

No Control Over Usage Conditions

Additional challenges to the system design are presented by the wide variety of potential usage conditions, as described below.

Ambient lighting conditions will vary tremendously. System users may be set up in an office, brightly illuminated by fluorescent lights, or may be set up in the stygian blackness of a home study, with minimal tungsten-based lighting. In response, the application must monitor the video stream for the overall lighting level.

The *Digimarc MediaBridge* system is intended to allow the user to manually present a commercially printed image to the camera. This implies that any part of the image may be anywhere in the field of view of the camera. The application will not always recover the watermark from the same portion of the image. The image may be presented at any angle to the camera, at any distance, and may or may not be in focus or perpendicular to the optic axis of the camera. The image may not be planar, and the page may be distorted or warped.

These conditions imply several system requirements. The watermark must be invariant to cropping (any part of the image must permit detection), rotation (the image may be presented at any angle), and scale (varying the distance of the camera to the image changes the amount of watermarking information recovered by each pixel). In addition, the system must be optimized to tolerate the widest range of focus conditions and the highest degree of perspective distortion possible.

Digimarc's technology uses an orienting signal to provide a watermark that is robust to scale, cropping, and rotation. The efficiency of the detector allows the watermark to be recovered throughout the effective depth of focus of PC cameras.

Detection Speed

The image capture devices used with the system presented a wide variety of image sizes and quality. On the high end, the use of a consumer scanner produces a file of potentially high resolution (600 pixels/inch) and large size (up to 32 million pixels), presented once. On the low end, a minimally capable 320×240 pixel PC camera produces a file as small as 76 thousand pixels, variants of which would be presented repeatedly in a video stream. The watermark might be embedded in the entire image or a portion of the image. So, in the case of the scanner image, the application must be able to quickly winnow through a very large amount of data to find, read, and deliver the embedded information for processing by the Digimarc database server. In the case of the PC camera, the application must quickly decide whether a given frame is a good candidate to spend time trying to read the watermark, or whether to go back for the next frame. In both cases, the time involved must be significantly shorter than navigating down through a complex Web site or using a search engine to find the information related to the image. In the case of the image manually presented to the PC camera, we have found that only a few seconds are available before the impatience-induced motion of the user degrades the quality of the image captured. In either case, the performance or speed of the detector is vital.

The typical PC camera will provide from five to eight frames per second of uncompressed image data at a 320×240 pixel image quality. If the camera is allowed to compress the data, the image quality will degrade, but the frame rate will rise. Higher image quality improves the chances of detecting the image; lower quality reduces the detector robustness. Counter balancing this, the higher frame rates provide more opportunities to read the watermark from freshly captured data. The optimal detector will detect the watermark at approximately the same rate as the video stream presents images. The detector must be structured in a hierarchical manner so that decisions about the probability of detection are made at various points in the process and a new frame acquired, if needed. It is not profitable to waste time on a frame with a low probability of yielding successful watermark detection.

Optimizing the detector presented a number of interesting trade-offs, as outlined above. These were finally resolved by bearing in mind the needs of the customer. The customer wants the fastest possible first read. The system only has to read the data once. Assuming a new frame is always available, the time to first read is proportional to the product of the probability of failure to detect and to the time to perform a detection.

Embedding Tool Requirements

The image capture and watermark detection process is only half the system. The watermark information must make its way into the image to be printed and survive the transition to the domain of analog, printed images.

A matching product had to be developed to permit the embedding of the watermark into images destined for commercial presses. The customer for this product is not the same as the customer for the detector (a.k.a., reader) product. This watermark embedder had to be able to be used by printing professionals during the pre-press process. The embedder had to produce a strong watermark signal with minimum impact on the aesthetics of the image to be printed. Thus, the embedder is required to consider the content of the images and to automatically adjust the strength of embedding, according to local visibility constraints. Furthermore, the artist creating the image needed to be able to dictate the level of embedding in various regions to accommodate artistic intent. To be useful to the customer, the embedder had to fit smoothly into the pre-press workflow. The tool also needed to predict the readability of the image in the final printed state.

The printing process imposes additional distortion on the image and on the embedded watermark. The image is converted into CMYK color planes, half-tone screened, and rasterized for output to plates. The printing process may be thought of as a communications channel, subject to poorly characterized noise and distortion.

The development of the successful embedding tool required a great deal of empirical characterization of the printing process and trial runs on representative commercial presses. Laboratory printers and sheet fed commercial printers were used in the development process, but before product release, watermarked images were printed in high volume circulation publications as blind tests.

Central Server Design

The most important design consideration for the central server was to maximize the number of transactions per second. It had to be able to receive, look up, and respond with the URL within thousandths of a second, under heavy load, to keep the consumer from noticing any additional delays. This required the employment of load balancers and multiple servers (and locations). In addition, the central server always had to be on, even under the worst load, physical, and network conditions. Thus, the system had to be redundant and fault-tolerant.

Another server design requirement was its ability to immediately change an associated URL. This enabled the "dynamic" nature of the watermark linkages.

Role of Quality Assurance

On the development team, in addition to the critical roles played by the watermarking algorithm and software engineers, quality assurance engineers played a crucial role. The *Digimarc MediaBridge* system required the development of a variety of automated testing methods and tools, long before the application was complete. In fact, the initial development of the algorithms depended, sensitively, on the reproducibility of relevant testing techniques.

Early in the project, the need for precise and reproducible control of lighting and camera-to-image placement led to the design and development of a camera control robot. This test stand had control over six degrees of freedom in the relative camera/image positioning. Being microprocessor controlled produces highly accurate, reproducible motion tracks for the camera under test, under a variety of conditions. This was useful in characterizing embedded materials and embedder algorithm changes. Test scripts were written for the robot, which provided a means of not only reproducing tests but of reducing the amount of error through human interaction.

The ability to create and maintain reusable test scripts provided the ability for the engineering team to baseline the embedder technology and to perform both quantitative (i.e., detector/reader based) and qualitative baselining.

To stress test the *Digimarc MediaBridge* system and provide reproducible inputs to the detector meant creating a growing library of reference videos, saved as standard AVI files. These sets of AVIs, used as test inputs or test cases, allowed us to establish baseline metrics for read/detection rates, performance, false/positive identifications, etc.

Testing cameras on the robotic test stand, while extremely valuable during early development stages, did not effectively reproduce the user experience with the system. For camera screening and qualification purposes, a protocol for reproducible hand testing was developed. To predict camera performance in typical user situations, time-to-first read was used as a performance metric on a fixed suite of hand held images, under a variety of conditions. All design considerations are moot if the system does not perform well in the hands of the users. Fortunately, feedback from customers and from formal usability testing indicates a high degree of satisfaction with the overall system performance.

Once the technology development activities were frozen for a particular phase of product development and engineering was halted, the quality assurance team transitioned to testing the technology through the user interface of the target application. This enabled additional assessment, or another level of testing and quality benchmarking.

The most important design consideration for the central server was to maximize the number of transactions per second. It had to be able to receive, lookup and respond with the URL within thousandths of a second, under heavy load, to keep the consumer from noticing any additional delays.

Summary

Using the *Digimarc MediaBridge* system as an example of a commercial watermarking system shows some of the complex issues that must be resolved in order for successful instantiations of watermarking technology to be developed. Perceptibility, robustness, performance, and many other watermarking-related issues must be carefully balanced. However, there is more to a successful watermarking system than exciting watermarking algorithms. The engineering of a successful system requires a plethora of engineering disciplines. If the system is to be successful commercially, it must all work together to deliver value to the user. Thus, the paramount value of carefully considered customer requirements is to guide the inevitable trade-offs in performance.

Digimarc MediaBridge is one realization of a watermarking system, offering new capabilities to the users of various media types. In the future, we expect the ability of images, audio, and video to carry embedded digital data intrinsically, as part of the content of the work, to open up an array of new possibilities for the use of digital and analog media.

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Biography

Steve Decker (sdecker@digimarc.com) received a B.S. (physics) in 1969 from Auburn University, a M.S. (physics) and a Ph.D. (Applied Physics) from the California Institute of Technology in 1971 and 1975. After a number of years developing electronic imaging systems he joined Digimarc as Director of R & D in 1999. Current research interests include digital watermarking, image and signal processing.