First steps toward an electronic field guide for plants

Gaurav Agarwal[1], Peter Belhumeur[2], Steven Feiner[2], David Jacobs[1], W. John Kress[3], Ravi Ramamoorthi[2], Norman A. Bourg[3], Nandan Dixit[2], Haibin Ling[1], Dhruv Mahajan[2], Rusty Russell[3], Sameer Shirdhonkar[1], Kalyan Sunkavalli[2] & Sean White[2]

[1] *University of Maryland Institute for Advanced Computer Studies, A.V. Williams Building, University of Maryland, College Park, Maryland 20742, U.S.A. djacobs@umiacs.umd.edu (author for correspondence)*
[2] *Department of Computer Science, Columbia University, 450 Computer Science Building, 1214 Amsterdam Avenue, New York 10027, U.S.A.*
[3] *Department of Botany, MRC-166, United States National Herbarium, National Museum of Natural History, Smithsonian Institution, P. O. Box 37012, Washington, DC 20013-7012, U.S.A.*

We describe an ongoing project to digitize information about plant specimens and make it available to botanists in the field. This first requires digital images and models, and then effective retrieval and mobile computing mechanisms for accessing this information. We have almost completed a digital archive of the collection of type specimens at the Smithsonian Institution Department of Botany. Using these and additional images, we have also constructed prototype electronic field guides for the flora of Plummers Island. Our guides use a novel computer vision algorithm to compute leaf similarity. This algorithm is integrated into image browsers that assist a user in navigating a large collection of images to identify the species of a new specimen. For example, our systems allow a user to photograph a leaf and use this image to retrieve a set of leaves with similar shapes. We measured the effectiveness of one of these systems with recognition experiments on a large dataset of images, and with user studies of the complete retrieval system. In addition, we describe future directions for acquiring models of more complex, 3D specimens, and for using new methods in wearable computing to interact with data in the 3D environment in which it is acquired.

KEYWORDS: Augmented reality, computer vision, content-based image retrieval, electronic field guide, inner-distance, mobile computing, shape matching, species identification, type specimens, recognition, wearable computing.

INTRODUCTION

In the past century, we have made outstanding progress in many areas of biology, such as discovering the structure of DNA, elucidating the processes of micro- and macroevolution, and making the simple but critical calculation of the magnitude of species diversity on the planet. In this century, we expect to witness an explosion of discoveries revolutionizing the biological sciences and, in particular, the relation of human society to the environment. However, most scientists agree that global environments face a tremendous threat as human populations expand and natural resources are consumed. As natural habitats rapidly disappear, the present century may be our last opportunity to understand fully the extent of our planet's biological complexity.

This urgency demands a marriage of biology and advanced scientific tools; new technologies are essential to our progress in understanding global biocomplexity. As field taxonomists conduct their expeditions to the remaining natural habitats on the Earth, they must have access to and methods for searching through the vast store of biodiversity information contained in our libraries, museums, and botanical gardens (Bisby, 2000; Edwards & al., 2000). New techniques being developed in areas of computer science such as vision, graphics, modeling, image processing, and user interface design can help make this possible.

One can envision that 21st century naturalists will be equipped with palm-top and wearable computers, global positioning system (GPS) receivers, and web-based satellite communication (Wilson, 2000; Kress, 2002; Kress & Krupnick, 2005). These plant explorers will comb the remaining unexplored habitats of the earth, identifying and recording the characters and habitats of species not yet known to science. Through remote wireless communication, the field botanist will be able to immediately compare his/her newly collected plants with type specimens and reference collections archived and digitized in museums thousands of miles away. The information on these species gathered by botanists will be sent with the speed of the Internet to their colleagues around the world. This vision of discovering and describing the natural world is already becoming a reality through the partnership of natural history biologists, computer scientists, nanotechnologists, and bioinformaticists (Wilson, 2003; Kress, 2004).

Accelerating the collection and cataloguing of new specimens in the field must be a priority. Augmenting this task is critical for the future documentation of biodiversity, particularly as the race narrows between species discovery and species lost due to habitat destruction. New technologies are now being developed to greatly facilitate the coupling of field work in remote locations with ready access to and utilization of data about plants that already exist as databases in biodiversity institutions. Specifically, a taxonomist who is on a field expedition should be able to easily access via wireless communication through a laptop computer or high-end PDA critical comparative information on plant species that would allow him/her to (1) quickly identify the plant in question through electronic keys and/or character recognition routines, (2) determine if the plant is new to science, (3) ascertain what information, if any, currently exists about this taxon (e.g., descriptions, distributions, photographs, herbarium and spirit-fixed specimens, living material, DNA tissue samples and sequences, etc.), (4) determine what additional data should be recorded (e.g., colors, textures, measurements, etc.), and (5) instantaneously query and provide information to international taxonomic specialists about the plant. Providing these data directly and effectively to field taxonomists and collectors would greatly accelerate the inventory of plants throughout the world and greatly facilitate their protection and conservation (Kress, 2004).

This technological vision for the future of taxonomy should not trivialize the magnitude of the task before us. It is estimated that as many as 10 million species of plants, animals and microorganisms currently inhabit the planet Earth, but we have so far identified and described less than 1.8 million of them (Wilson, 2000). Scientists have labored for nearly three centuries on systematic efforts to find, identify, name and make voucher specimens of new species. This process of identification and naming requires extremely specialized knowledge. At present, over three billion preserved specimens are housed in natural history museums, herbaria, and botanic gardens with a tremendous amount of information contained within each specimen. Currently, taxonomists on exploratory expeditions make new collections of unknown plants and animals that they then bring back to their home institutions to study and describe. Usually, many years of tedious work go by, during which time scientists make comparisons to previous literature records and type specimens, before the taxonomic status of each new taxon is determined.

In the plant world, estimates of the number of species currently present on Earth range from 220,000 to over 420,000 (Govaerts, 2001; Scotland & Wortley, 2003). By extrapolation from what we have already described and what we estimate to be present, it is possible that at least 10 percent of all vascular plants are still to be discovered and described (J. Kress & E. Farr, unpubl.). The majority of what is known about plant diversity exists primarily as written descriptions that refer back to physical specimens housed in herbaria. Access to these specimens is often inefficient and requires that an inquiring scientist knows what he/she is looking for beforehand. Currently, if a botanist in the field collects a specimen and wants to determine if it is a new species, the botanist must examine physical samples from the type specimen collections at a significant number of herbaria. Although this was the standard mode of operation for decades, such arrangement is problematic for a number of reasons. First, type specimens are scattered in hundreds of herbaria around the world. Second, the process of requesting, approving, shipping, receiving, and returning type specimens is extremely time-consuming, both for the inquiring scientists and for the host herbarium. It can often take many months to complete a loan, during which time other botanists will not have access to the loaned specimens. Third, type specimens are often incomplete, and even a thorough examination of the relevant types may not be sufficient to determine the status of a new specimen gathered in the field. New, more efficient methods for accessing these specimens and better systems for plant identification are needed.

Electronic keys and field guides, two modern solutions for identifying plants, have been available since computers began processing data on morphological characteristics (Pankhurst, 1991; Edwards & Morse, 1995; Stevenson & al., 2003). In the simplest case of electronic field guides, standard word-based field keys using descriptive couplets have been enhanced with color images and turned into electronic files to make identification of known taxa easier and faster. More sophisticated versions include electronic keys created through character databases (e.g., Delta: delta-intkey.com, Lucid: www.lucidcentral.org). Some of these electronic field guides are now available on-line or for downloading onto PDAs (e.g., Heidorn, 2001; OpenKey: http://www3.isrl.uiuc.edu/~pheidorn/cgi-bin/schoolfieldguide.cgi), while others are being developed as active websites that can continually be revised and updated (e.g., *Flora of the Hawaiian Islands*: http://ravenel.si.edu/botany/pacificislandbiodiversity/hawaiianflora/index.htm).

Somewhat further afield, previous work has also addressed the use of GPS-equipped PDAs to record in-field observations of animal tracks and behavior (e.g., Pascoe, 1998; CyberTracker Conservation, 2005), but without camera input or recognition (except insofar as the skilled user is able to recognize on her own an animal and its behavior). PDAs with cameras have also been used by several research groups to recognize and translate Chinese signs into English, with the software either running entirely on the PDA (Zhang & al., 2002) or on a remote mainframe (Haritaoglu, 2001). These sign-translation projects have also explored how user interaction can assist in the segmentation problem by selecting the areas in the image in which there are signs.

We envision a new type of electronic field guide that will be much more than a device for wireless access to taxonomic literature. It should allow for visual and textual search through a digital collection of the world's type specimens. Using this device, a taxonomist in the field will be able to digitally photograph a plant and determine immediately if the plant is new to science. For plants that are known, the device should provide a means to ascertain what data currently exist about this taxon, and to query and provide information to taxonomic specialists around the world.

Our project aims to construct prototype electronic field guides for the plant species represented in the Smithsonian's collection in the United States National Herbarium (US). We consider three key components in creating these field guides. First, we are constructing a digital library that is recording image and textual information about each specimen. We initially concentrated our efforts on type specimens (approximately 85,000 specimens of vascular plants at US) because they are critical collections and represent unambiguous species identification. We envision that this digital collection at the Smithsonian can then be integrated and linked with the digitized type specimen collections at other major world herbaria, such as the New York Botanical Garden, the Missouri Botanical Garden, and the Harvard University Herbaria. However, we soon realized that in many cases the type specimens are not the best representatives of variation in a species, so we have broadened our use of non-type collections as well in developing the image library. Second, we are developing plant recognition algorithms for comparing and ranking visual similarity in the recorded images of plant species. These recognition algorithms are central to searching the image portion of the digital collection of plant species and will be joined with conventional search strategies in the textual portion of the digital collection. Third, we are developing a set of prototype devices with mobile user interfaces to be tested and used in the field. In this paper, we will describe our progress towards building a digital collection of the Smithsonian's type specimens, developing recognition algorithms that can match an image of a leaf to the species of plant from which it comes, and designing user interfaces for electronic field guides.

To start, we are developing prototype electronic field guides for the flora of Plummers Island, a small, well-studied island in the Potomac River. Our prototype systems contain multiple images for each of about 130 species of plants on the island, and should soon grow to cover all 200+ species currently recorded (Shetler & al., in press). Images of full specimens are available, as well as images of isolated leaves of each species. Zoomable user interfaces allow a user to browse these images, zooming in on ones of interest. Visual recognition algorithms assist a botanist in locating the specimens that are most relevant to identify the species of a plant. Our system currently runs on small hand-held computers and Tablet PCs. We will describe the components of these prototypes, and also explain some of the future challenges we anticipate if we are to provide botanists in the field with access to all the resources that are now currently available in the world's museums and herbaria.

TYPE SPECIMEN DIGITAL COLLECTION

The first challenge in producing our electronic field guides is to create a digital collection covering all of the Smithsonian's 85,000 vascular plant type specimens. For each type specimen, the database should eventually include systematically acquired high-resolution digital images of the specimen, textual descriptions, links to decision trees, images of live plants, and 3D models.

So far, we have taken high resolution photographs of approximately 78,000 of the Smithsonian's type specimens, as illustrated in Fig. 1. At the beginning of our project, specimens were photographed using a Phase One LightPhase digital camera back on a Hasselblad 502 with an 80 mm lens. This created an 18 MB color image with 2000×3000 pixels. More recently we have used a Phase One H20 camera back, producing a 3600×5000 pixel image. The image is carried to the processing computer by IEEE 1394/FireWire and is available to be processed initially in the proprietary Capture One software that accompanies the H20. The filename for each high-resolution TIF image is the unique value of the bar code that is attached to the specimen. The semi-processed images are accumulated in job batches in the software. When the job is done, the images are finally batch processed in Adobe Photoshop, and from these derivatives can be generated for efficient access and transmission. Low resolution images of the type specimens are currently available on the Smithsonian's Botany web site at http://ravenel.si.edu/botany/types. Full resolution images may be obtained through ftp by contacting the Collections Manager of the United States National Herbarium.

In addition to images of type specimens, it is extremely useful to obtain images of isolated leaves of each species of plant. Images of isolated leaves are used in our

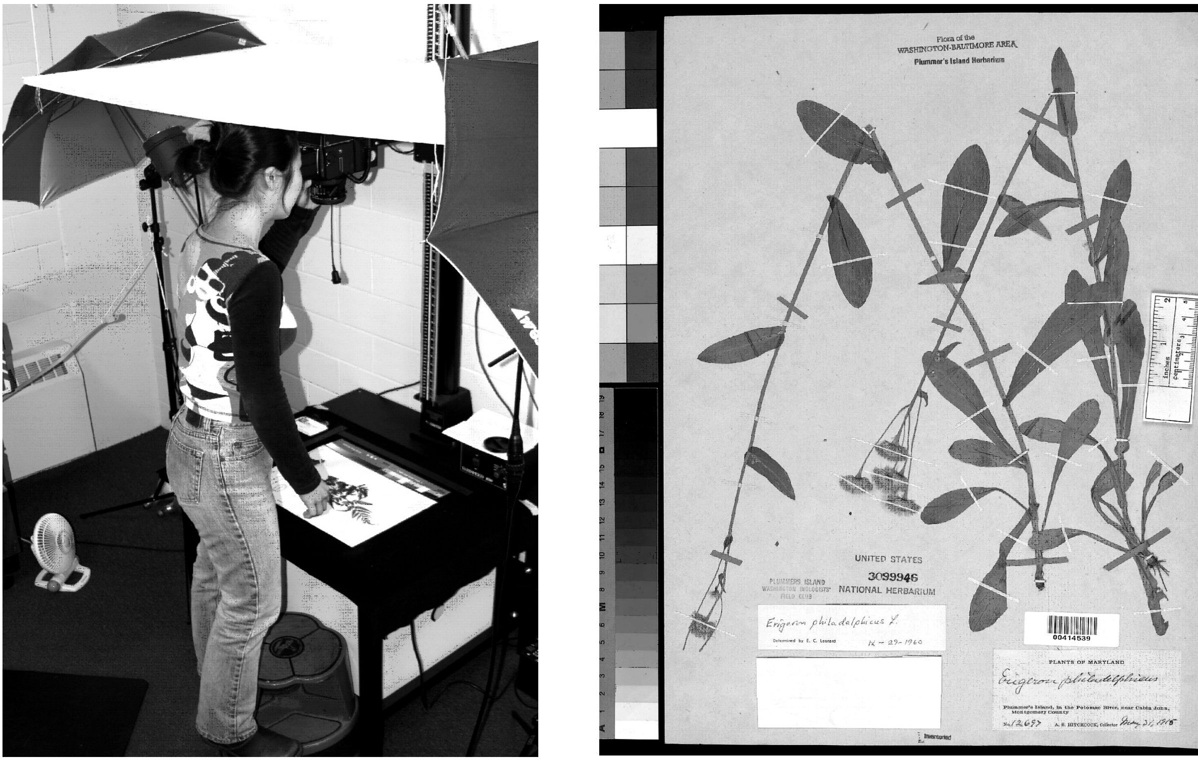

Fig. 1. On the left, our set-up at the Smithsonian for digitally photographing type specimens. On the right, an example image of a type specimen.

prototype systems in two ways. First of all, it is much easier to develop algorithms that judge the similarity of plants represented by isolated leaves than it is to deal with full specimens that may contain multiple, overlapping leaves, as well as branches. While the appearance of branches or the arrangement of leaves on a branch may provide useful information about the identity of a plant, this information is difficult to extract automatically. The problem of automatically segmenting an image of a complex plant specimen to determine the shape of individual leaves and their arrangement is difficult, and still unsolved. We are currently addressing these problems, but for our prototype field guides we have simply been collecting and photographing isolated leaves from all species of plants present on Plummers Island. Secondly, not only are isolated leaves useful for automatic recognition, but they also make useful thumbnails—small images that a user can quickly scan when attempting to find relevant information. We will discuss this further in a following section.

As our project progresses, we plan to link other features to this core database, such as other sample specimens (not types), of which there are 4.7 million in the Smithsonian collection, live plant photographs, and computer graphics models, such as image-based or geometric descriptions. We also aim to enable new kinds of data collection, in which botanists in the field can record large numbers of digital photos of plants, along with information (accurate to the centimeter) about the location at which each photo and sample were taken.

The full collection of 4.7 million plant specimens that the Smithsonian manages provides a vast representation of ecological diversity, including as yet unidentified species, some of which may be endangered or extinct. Furthermore, it includes information on variation in structure within a species that can be key for visual identification or computer-assisted recognition. A potential future application of our recognition algorithms is for automatic classification of these specimens, linking them to the corresponding type specimens, and identifying candidates that are hard to classify, requiring further attention from botanists. In this way, the visual and textual search algorithms discussed in the next section could be used to help automatically discover new species among the specimens preserved in the Smithsonian—something that would be extremely laborious without computer assistance.

The most direct approach to acquisition and representation is to use images of the collected specimens. However, it will also be of interest to explore how advances in computer graphics and modeling could build richer representations for retrieval and display that capture information about the 3-D structure of specimens. A first step towards this might concentrate on creating *image-based* representations of the specimens, building on previous work in computer graphics on *image-based rendering* methods (Chen & Williams, 1993; McMillan & Bishop, 1995; Gortler & al., 1996; Levoy & Hanrahan, 1996; Wood & al., 2000). The challenge for this approach will be to use a small number of images, to keep the task manageable, while capturing a full model of the specimen, making it possible to create synthetic images from any viewpoint. One advantage is that specimens such as leaves are relatively flat and therefore have a relatively simple geometry. One could therefore start with leaf specimens, combining view-dependent texture-mapping approaches (Debevec & al., 1996) with recent work by us and others on estimating material properties from sparse sets of images by inverse techniques (Sato & al., 1997; Yu & Malik, 1998; Yu & al., 1999; Boivin & Gagalowicz, 2001; Ramamoorthi & Hanrahan, 2001).

Finally, it would be very exciting if one could measure geometric and photometric properties to create complete computer graphics models. Geometric 3D information will allow for new recognition and matching algorithms that better compensate for variations in viewpoint, as well as provide more information for visual inspection. For example, making a positive classification may depend on the precise relief structure of the leaf or its veins. Also, rotating the database models to a new viewpoint, or manipulating the illumination to bring out features of the structure, could provide new tools for classification. Furthermore, this problem is of interest not just to botanists, but also to those seeking to create realistic computer graphics images of outdoor scenes. While recent work in computer graphics (Prusinkiewicz & al., 1994; Deussen & al., 1998) has produced stunning, very complex outdoor images, the focus has not been on botanical accuracy.

To achieve this, one can make use of recent advances in shape acquisition technology, such as using laser range scanning and volumetric reconstruction techniques (Curless & Levoy, 1996) to obtain geometric models. One can attempt to acquire accurate reflectance information or material properties for leaves—something that has not been done previously. To make this possible, we hope to build on and extend recent advances in measurement technology, such as image-based reflectance measurement techniques (Lu & al., 1998; Marschner & al., 2000). Even accurate models of a few leaves, acquired in the lab, might be useful for future approaches to recognition that use photometric information. Reflectance models may also be of interest to botanists; certainly research on geometric and reflectance measurements would be of immense importance in computer graphics for synthesizing realistic images of botanically accurate plants.

VISUAL MATCHING OF ISOLATED LEAVES

Our project has already produced a large collection of digital images, and we expect that, in general, the number of images and models of plants will grow to huge proportions. This represents a tremendous potential resource. It also represents a tremendous challenge, because we must find ways to allow a botanist in the field to navigate this data effectively, finding images of specimens that are similar to and relevant to the identification of a new specimen. Current technology only allows for fully automatic judgments of specimen similarity that are somewhat noisy, so we are building systems in which automatic visual recognition algorithms interact with botanists, taking advantage of the strengths of machine systems and human expertise.

Many thorny problems of recognition, such as segmentation, and filtering our dataset to a reasonable size, can be solved for us by user input. We can rely on a botanist to take images of isolated leaves for matching, and to provide information, such as the location and family of a specimen, that can significantly reduce the number of species that might match it. With that starting point, our system supplements text provided by the user by determining the visual similarity between a new sample and known specimens. Our problem is simplified by the fact that we do not need to produce *the* right answer, just a number of useful suggestions.

PRIOR WORK ON VISUAL SIMILARITY OF ORGANISMS

There has been a large volume of work in the fields of computer vision and pattern recognition on judging the visual similarity of biological organisms. Probably the most studied instance of this problem is in the automatic recognition of individuals from images of their faces (see Zhao & al., 2003 for a recent review). Early approaches to face recognition used representations based on face-specific features, such as the eyes, nose, and mouth (Kanade, 1973). While intuitive, these approaches had limited success for two reasons. First, these features are difficult to reliably compute automatically. Second, they lead to sparse representations that ignore important but more subtle information. Current approaches to face recognition have achieved significant success using much more general representations. These are informed by the general character of the object recognition problem, but are not based on specific properties of the human face (e.g., Turk & Pentland, 1991; Lades & al., 1993). Some successful methods do make use of prior knowledge about the 3D shape of faces (e.g., Blanz & Vetter, 2003). However, successful approaches do not necessarily rely on representations of faces that might seem to correspond to human descriptions of faces (e.g., a big nose, or widely spaced eyes). Such systems achieve the best current performance, allowing effective retrieval of faces from databases of over a thousand images, provided that these are taken under controlled conditions (Phillips & al., 2002). This encourages us to explore the use of general purpose shape matching algorithms in plant identification, before attempting to compute descriptions of plants that correspond to more traditional keys.

There has also been work on automatic identification of individuals within a (nonhuman) species. For example, biologists may track the movements of individual animals to gather information about population sizes, demographic rates, habitat utilization, and movement rates and distances. This is done using visual recognition in cases in which mark-recapture methods are not practical because of the stress they place on animals, for example, or the small size of some animals (e.g., salamanders). Some researchers have exploited distinctive visual traits recorded from direct observations and photographs, such as scars on cetaceans (Hammond, 1990) or more general shape characteristics of marine invertebrates (Hillman, 2003), pelage patterns in large cats (Kelley, 2001), and markings on salamanders (Ravela & Gamble, 2004).

A number of studies have also used intensity patterns to identifying the species of animals, and of some plants such as pollen or phytoplankton. Gaston & O'Neill (2004) review a variety of these methods. They primarily apply fairly general pattern recognition techniques to the intensity patterns found on these organisms.

There have also been several works that focus specifically on identifying plants using leaves, and these have generally concentrated on matching the shape of leaves. For example, Abbasi & al. (1997) and Mokhtarian & Abbasi (2004) have worked on the problem of classifying images of chrysanthemum leaves. Their motivation is to help automate the process of evaluating applicants to be registered as new chrysanthemum varieties. The National Institute of Agricultural Botany in Britain has registered 3000 varieties of chrysanthemums, and must test 300 applicants per year for distinctness. They compare silhouettes of leaves using features based on the curvature of the silhouette, extracted at multiple scales, also using other features that capture global aspects of shape. They experiment using a dataset containing ten images each of twelve different varieties of chrysanthemums. They achieve correct classification of a leaf up to 85% of the time, and the correct variety is among the top three choices of their algorithm over 98% of the time. While the number of varieties in their dataset is rather small, their problem is difficult because of the close similarity between different varieties of chrysanthemums.

In other work, Im & al. (1998) derive a description of leaf shapes as a straight line approximation connecting curvature extrema, although they do not report recognition results, only showing a few sample comparisons. Saitoh & Kaneko (2000) use both shape and color features in a system that recognizes wild flowers, using a neural net, which is a general approach developed for pattern recognition and machine learning. In a dataset representing sixteen species of wildflowers, they correctly identify a species over 95% of the time, although performance drops drastically when only the shape of leaves are used. Wang & al. (2003) develop a novel shape description, the centroid-contour distance, which they combine with more standard, global descriptions of shape. They use this for recognition on a dataset containing 1400 leaves from 140 species of Chinese medicinal plants. This approach correctly recognizes a new leaf only about 30% of the time, and a correct match is from the same species as one of the top 50 leaves retrieved only about 50% of the time. However, this dataset appears to be challenging, and their system does outperform methods based on curvature scale-space (Abbasi & al., 1997), and another method based on Fourier descriptors. It is somewhat difficult to evaluate the success of these previous systems, because they use diverse datasets that are not publicly available. However, it appears that good success can be achieved with datasets that contain few species of plants, but that good performance is much more difficult when a large number of species are used.

In addition to these methods, Söderkvist (2001) provides a publicly available dataset (http://www.isy.liu.se/cvl/Projects/Sweleaf/samplepage.html) containing 75 leaves each from 15 different species of plants, along with initial recognition results using simple geometric features, in which a recognition rate of 82% is reported.

MEASURING SHAPE SIMILARITY

The core requirement of providing automatic assistance to species identification is a method for judging the similarity of two plant specimens. While there are many ways one can compare the visual similarity of plant specimens, we have begun by focusing on the problem of determining the similarity of the shape of two leaves that have been well segmented from their background. It will be interesting in the future to combine this with other visual information (e.g., of fruit or flowers) and metadata (e.g., describing the position of a leaf). We will now

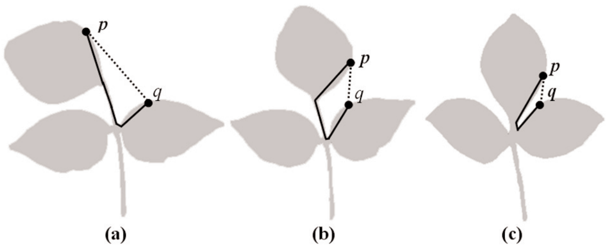

Fig. 2. This figure shows three compound leaves, where (a) and (b) are from the same species which is different from that of (c). The lengths of the dotted line segments denote the Euclidean distances between two points, p and q. The solid lines show the shortest paths between p and q. The inner-distances are defined as the length of these shortest paths. The Euclidean distance between p and q in (b) is more similar to that in (c) than in (a). In contrast, the inner-distance between p and q in (b) is more similar to that in (a) than in (c).

discuss a novel approach that performs this task well. When we discuss our prototype user interfaces, we will explain how we achieve segmentation in practice, and how we use this measure of leaf similarity to aid in species identification.

Our approach is motivated by the fact that leaves possess complex shapes with many concavities. Many approaches to visual recognition attempt to deal with complex shapes by dividing an object into parts (e.g., Siddiqi & al., 1999; Sebastian & al., 2004). However leaves often lack an obvious part structure that fully captures their shape. Therefore, we have instead introduced a new shape representation that reflects the part structure and concavities of a shape without explicitly dividing a shape into parts.

Our representation is based on the *inner-distance* between two points on the boundary of a shape. This is defined as the length of the shortest path that connects the two points and that lies entirely inside the leaf. Figure 2 illustrates the inner-distance by showing a pair of points (p, q) on the boundary of three idealized leaf silhouettes. The Euclidean distance between the two points in (b) is more similar to the Euclidean distance between the pair of points in (c) than those in (a). Shape descriptions based on this ordinary notion of distance will treat (b) as more similar to (c). In contrast, the inner-distance between the pair of points in (b) is more similar to those in (a) than in (c). As a consequence, the inner-distance-based shape descriptors can distinguish the three shapes more effectively.

Using the inner-distance, we build a description of the relationship between a boundary point and a set of other points sampled along the leaf boundary. This consists of a histogram of the distances to all other boundary points, as well as the initial direction of the shortest inner path to each point. This descriptor is closely related to the *shape context* (Belongie & al., 2002), using the inner-distance instead of the Euclidean distance. We therefore call our method the *Inner-Distance Shape Context* (IDSC).

Once a descriptor is computed for each point on the boundary of the leaf, we compare two leaves by finding a correspondence between points on the two leaves, and measuring the overall similarity of all corresponding points. Using a standard computer science algorithm called *dynamic programming*, we can efficiently find the best possible matching between points on the two leaf boundaries that still preserves the order of points along the boundary. More details of this algorithm can be found in Ling & Jacobs (2005).

We have tested this algorithm on a set of isolated leaves used in one of our prototype systems. This test set contains images of 343 leaves from 93 different species of plants found on Plummers Island, and is available at http://www.cs.umd.edu/~hbling/Research/data/SI-93.zip. In the experiment, 187 images are used as training examples that the system uses as its prior information about the shape of that species. The remaining 156 images are used as test images. For each test image, we measure how often a leaf from the correct species is among the most similar leaves in the training set. Information about the effectiveness of a retrieval mechanism can be summarized in the Receiver Operating Characteristics (ROC) curve (Fig. 3). This measures how the probability of retrieving the correct match increases with the number of candidate matches produced by the system. The horizontal axis shows the number of species retrieved, and the vertical axis shows the percentage of times that the correct species is among these.

The figure compares our method to ordinary shape contexts (SC) and to Fourier Descriptors computed using the discrete Fourier transform (DFT). Fourier Descriptors are a standard approach to shape description, in which a contour is described as a complex function, and the low-frequency components of its Fourier transform are used to capture its shape (see e.g., Lestrel, 1997). The figure shows that our new method (IDSC) performs best, although IDSC and SC perform similarly once twenty or more species of plants are retrieved. These results show that if we use IDSC to present a user with several potential matching species to a new leaf specimen, the correct species will be among these choices well over 95% of the time. Note that our results are either much more accurate than, or use a much larger dataset than, the prior work that we have described. However, it is difficult to compare results obtained on different datasets, since they can vary widely in difficulty, depending on the similarity of plants used. We have not yet been able to compare IDSC to all prior methods for species identification on a common dataset. However, Ling & Jacobs (2005) compare IDSC to ten other shape comparison methods on a variety of commonly used test sets of non-leaf shapes. IDSC performs better than the competing methods in every case.

In addition to these experiments we have also tested our algorithm on Söderkvist's dataset. The top species matched to a leaf by our algorithm is correct 94% of the time, compared to Söderkvist's reported results of 82%. Our own implementations of Fourier Descriptors and a method using Shape Contexts achieve 90% and 88% recognition performance, respectively.

While these experimental results are encouraging, they should be viewed with some caution. First of all, in our current test set, all leaves from a single species were collected at the same time, from the same plant. Therefore, data does not reflect the possible variations that can occur as leaves mature, or between different plants growing in different regions. We are in the process of collecting additional specimens now, which will help us to test our algorithm in the face of some of this variation. Second, for many environments, it will be necessary to perform retrieval when many more species of plants are possible candidates for matching. We anticipate that in many cases it will be necessary to supplement shape matching with information about the intensity patterns within leaves, especially of the venation. While important, these features are more difficult to extract automatically, and will pose a significant challenge in future work.

We also plan, in future work, to evaluate our algorithm for use in matching an isolated leaf to a full plant specimen. This would be helpful, since it may not be feasible for us to collect new specimens for every species of plant in the type specimen collection of the United States National Herbarium. One possible solution is to extract isolated leaves from the type specimens, and use these for matching. This might be done manually with a good deal of work and the aid of some automatic tools. We are also exploring methods for automatically segmenting leaves in images of type specimens, although this is a very challenging problem due to the extreme clutter in many of these images.

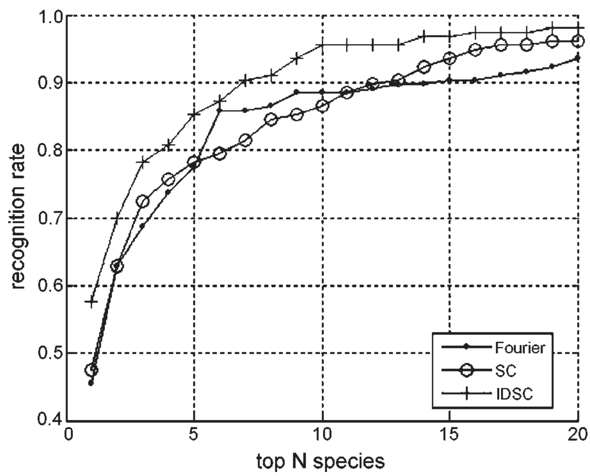

Fig. 3. ROC curves describing the performance of our new method (IDSC) in contrast with two other methods (SC, DFT = discrete Fourier transform).

PROTOTYPE ELECTRONIC FIELD GUIDES

We have integrated our approach to visual similarity with existing tools for image browsing into several prototype Electronic Field Guides (EFGs). Our EFGs currently contain information about 130 species of plants found on Plummers Island.

While we envision that a field guide will ultimately reside on devices no larger than current PDAs, we wanted to avoid the short-term constraints of implementing for existing PDAs, with their low-resolution displays, small memories, underpowered CPUs, and limited operating systems. For this reason, our initial handheld prototype was implemented on a slightly larger, but far more powerful, ultraportable hand-held computer, sometimes referred to as a "handtop". Our entire initial system runs on a Sony VAIO U750, running Windows XP Professional. This device measures 6.57"×4.25"×1.03", weighs 1.2 lbs, and includes a 1.1 GHz Mobile Pentium M processor, 512 MB Ram, a 5" 800×600 resolution, color, sunlight-readable display, a touch-sensitive display overlay, and 20 GB hard drive.

Our initial prototype was based on PhotoMesa (Bederson, 2001), which is a zoomable user interface. It shows the thumbnails of images arranged in 2D array. As a user mouses on an image, the image is shown at a somewhat larger size. The user can zoom in/out using the mouse (left/right) clicks. If the user wants to see more images of a particular species, s/he can double click with the left mouse button. Thus s/he can control the information s/he wants to see at any instant. These mouse-based controls make browsing and navigation easier.

We added some new features to the browsing capabilities offered by PhotoMesa:

Similarity based clustering and display of data. — Species are clustered based on the similarity between images of isolated leaves from these species. To do this we use a variation on the *k-means* clustering algorithm (see, e.g., Forsyth & Ponce, 2003) in which individual leaves are used as cluster centers. The images are displayed so that similar images are displayed as groups. This should help the user to better isolate the group to which the query image belongs. Once the correct group

Fig. 4. Screenshots from our initial EFG prototype, with random placement (top) and placement based on clustering (bottom).

is determined, s/he can zoom into that group to get more information.

Visual search. — The user can provide a query image, which is matched with the images in the database using the IDSC method introduced above. In a complete system, a user will be able to photograph a leaf collected in the field and use this as input to the system. In this initial prototype, images we have taken of isolated leaves are provided as input. Example leaves from the 20 best matching species are then displayed to the user.

Text search. — The user can see the images for a particular genus or species by typing the names. Partial names are accepted.

The prototype database consists of large specimens, including Type Specimens, and isolated leaf images (Fig. 5). At present, the database has over 1500 isolated leaves from 130 species, and approximately 400 larger specimen images for 70 species.

The shape matching algorithm requires the contour of leaves as input. Since leaves are photographed on a plain background, extracting their contour reliably is not too difficult, although this process is simplified if care is taken to avoid shadows in the image. We obtain the contour also by using k-means clustering to divide the image into two regions, based on color. We use the central and the border portions of the image as initial estimates of the leaf and background colors. We then use some simple morphological operations to fill in small holes (see e.g., Haralick & Shapiro, 1992). The input and output of this step are shown in Fig. 6.

We have performed user studies to evaluate the effectiveness of the different features of this prototype system, using 21 volunteers from the Department of Botany at the Smithsonian Institution. In these studies, users were presented with a query image showing an isolated leaf from Plummers Island, and asked to identify the species of the leaf using three versions of our system. In some queries, the users were given the basic features of PhotoMesa described above, with leaves placed randomly. A second version placed leaves using clustering. A third version displayed the results of visual search to the user.

A complete description of our results is presented by Agarwal (2005). Here, we briefly summarize these results. With random placement, users identified 71% of the query leaves correctly, in an average time of 30 seconds. With clustering, users found the correct species 84% of the time, in an average time of 29 seconds. With visual search, users were correct 85% of the time, with an average time of 22 seconds. The superior performance of subjects using visual search was statistically significant, both in terms of time and accuracy. Subjects also performed better with clustering than with random placement, but this difference was not statistically significant. In addition, users reported higher satisfaction with the system using visual search, next highest with clustering, and the least satisfaction with random placement. All these differences in satisfaction were statistically significant.

Our results suggest that visual search can produce a significantly better retrieval system, and that clustering may also produce a system that is easier to use, compared to one in which images are placed randomly. However, visual search will require substantially more overhead than the other methods, since a user must photograph a leaf in order to use visual search to help identify its species. The other features of the EFG can be used without photographic input. We believe that these results are promising, but that to measure the true impact of these methods, it is essential to experiment with larger datasets and with live field tests, in which a botanist uses the system to identify plants in the field. A difference of a few seconds to identify a plant is probably not important in practice, but the differences we observe for this relative-

Fig. 5. A sample photograph of an isolated leaf.

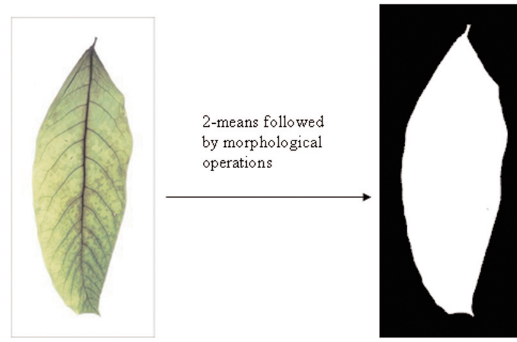

Fig. 6. Isolated leaf before and after preprocessing.

ly small dataset may be magnified in systems containing information about hundreds of species of plants. We plan to expand our experiments in these directions.

More recently, we have developed a second prototype, based on a Tablet PC tablet-based system, which incorporates lessons learned from our user studies and initial prototype to provide a user interface that can be effectively deployed in the field (Fig. 7). The system hardware incorporates an IBM Thinkpad X41 Tablet PC, (shown in the figure, but recently replaced with a Motion Computing LE 1600 Tablet PC with daylight-readable display), a Delorme Earthmate Bluetooth and a Nikon CoolPix P1 camera that transmits images wirelessly to the tablet PC. The user interface comprises five screens accessible through a tabbed interface, much like a tabbed set of file folders: browse, current sample, search results, history, and help.

The browse tab represents the entire visual leaf database in a zoomable user interface developed using Piccolo (Bederson & al., 2004). The species are presented as an ordered collection, based on the clustering algorithm described earlier. Each leaf node in the visual database contains individual leaf images, reference text, and digital images of specimen vouchers for that species. The collection can be browsed by looking at sections of the collection or at individual leaves.

The next tab displays the current sample leaf. Taking a picture of a leaf with the digital camera or selecting an earlier photo from the history list (described later) places the image of the leaf in this tab. Each picture is immediately placed in a database, along with relevant contextual information such as time, collector, and GPS coordinates. The black and white outline of the segmented image, which is used to identify the leaf, is displayed next to the original image as feedback to the botanist regarding the quality of the photo. If the silhouette looks broken or incomplete, a replacement photo can be taken. A button at the bottom of the screen can be used to display the search results.

The third tab presents the results of a visual search using the current sample, as shown in Fig. 7. Leaves are displayed in an ordered collection, with the best matches presented at the top. Each represented species can be inspected in the same way that leaves in the browser can be inspected, including all voucher images for a given species. If the botanist feels they have found a species match, pressing a button with a finger or stylus associates that species with the current sample in the database.

The fourth tab provides a visual history of all the samples that have been collected using the system. The samples in this leaf collection can be enlarged for inspection and the search results from a given sample can be retrieved. The last tab provides a simple help reference for the system.

Our current visual search algorithm returns an ordered set of the top ten possible matches to a leaf. In the future, it will be interesting to explore how the user can help narrow the identification further. This could involve a collaborative dialogue in which the system might suggest that the user provide additional input data, such as one or more new images (perhaps taken from an explicitly suggested vantage point, determined from an analysis of the originally submitted image). In addition, it would be interesting to develop ways for users to specify portions of a 2D image (and, later, of a 3D model) on which they would like the system to focus its attention, and for the system to specify regions on which the user should concentrate. Here, we will rely on our work on automating the design and unambiguous layout of textual and graphical annotations for 2D and 3D imagery

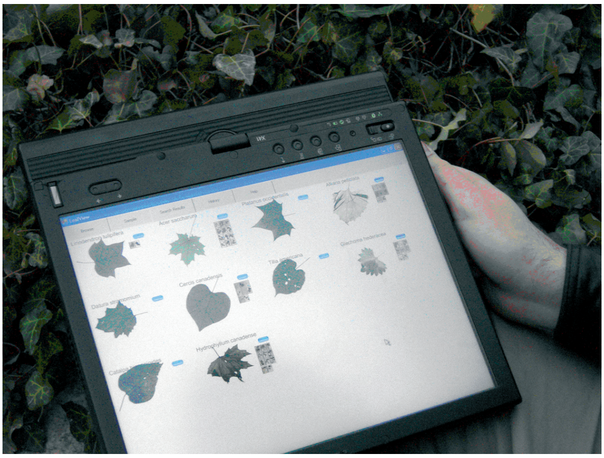

Fig. 7. Search results shown by our second prototype, running on a Tablet PC.

(Bell & Feiner, 2000; Bell & al., 2001), which we have already used with both head-worn and hand-held displays.

WEARABLE COMPUTING

To complement our hand-held prototypes, we are exploring the use of head-tracked, see-through, head-worn displays, which free the user's hands and provide information that is overlaid on and integrated with the user's view of the real world. Here, we are building on our earlier work on wearable, backpack-based, mobile augmented reality systems (e.g., Feiner & al., 1997; Höllerer & al., 1999b). One focus is on addressing the effective display of potentially large amounts of information in geospatial context, including spatialized records of field observations during the current and previous visits to a site, and 3D models. Another focus is facilitating the search and comparison task by presenting results alongside the specimen.

Our earlier backpack systems have used relatively large and bulky displays (e.g., a Sony LDI-D100B stereo color display with the size and appearance of a pair of ski goggles, and a MicroVision Nomad retinal scanning display). In contrast, we are currently experimenting with a Konica Minolta prototype "forgettable" display (Kasai & al., 2000), which is built into a pair of conventional eyeglasses, a commercially available MicroOptical "clip-on" display that attaches to conventional eyeglasses, a Liteye LE-500 monocular see-through display, and several other commercial and prototype head-worn displays. In addition to the touch-sensitive display overlays that are part of our hand-held prototypes, we are also interested in the use of speech input and output, to exploit the hands-free potential of head-worn displays, and smaller manual interaction devices that do not require the user's visual attention (Blaskó & Feiner, 2005).

We have been developing two mobile augmented reality user interfaces that use head-tracked head-worn displays (White & al., 2006). One user interface provides a camera-tracked tangible augmented reality in which the results of the visual search are displayed next to the physical leaf. The results consist of a set of *virtual vouchers* that can be physically manipulated for inspection and comparison. In the second user interface, the results of a visual search query are displayed in a row in front of the user, floating in space and centered in the user's field of view. These results can be manipulated for inspection and comparison by using head-movement alone, tracked by an inertial sensor, leaving the hands free for other tasks.

To support geographic position tracking in our hand-held and head-worn prototypes, we have used the DeLorme Earthmate, a small WAAS-capable GPS receiver. WAAS (Wide Area Augmentation System) is a Federal Aviation Administration and Department of Transportation initiative that generates and broadcasts GPS differential correction signals through a set of geostationary satellites. These error corrections make possible positional accuracy of less than three meters in North America. While regular GPS would be more than adequate to create the collection notes for an individual specimen and assist in narrowing the search to winnow out species that are not known to live in the user's location, we are excited about the possibility of using the increased accuracy of WAAS-capable GPS to more accurately localize individual living specimens relative to each other.

Future prototypes of our electronic field guide could take advantage of even higher accuracy real-time-kinematic GPS (RTK GPS) to support centimeter-level localization, as used in our current outdoor backpack-driven mobile augmented reality systems. Coupled with the inertial head-orientation tracker that we already exploit in our augmented reality systems, this would allow us to overlay on the user's view of the environment relevant current and historical data collected at the site, with each item positioned relative to where it was collected, building on our earlier work on annotating outdoor sites with head-tracked overlaid graphics and sound (Höllerer & al., 1999a; Güven & Feiner, 2003; Benko & al., 2004). Further down the road, we will be experimenting with an Arc Second Constellation 3DI wide-area, outdoor, 6DOF tracker (+/- .004" accuracy) to track a camera and display over a significant area. This could make it possible to assemble sets of images for use in creating 3D models in the field of both individual plants and larger portions of a local ecosystem.

In our current prototypes, all information is resident on the disk of a mobile computer. This may not be possible for future prototypes that make use of more data, or data that might not be readily downloaded. These prototypes and their user interfaces should be built so that the databases can reside entirely on the remote server or be partially cached and processed on the mobile system. We also note that in field trials even low-bandwidth world-wide-web connectivity may not be available. In this case, a local laptop, with greater storage and computation capabilities than the hand-held or wearable computer, could be used to host the repository (or the necessary subset) and run the recognition algorithms, communicating with the hand-held or wearable computer through a local wireless network.

CONCLUSIONS

New technology is making it possible to create vast, digital collections of botanical specimens. This offers important potential advantages to botanists, including greater accessibility and the potential to use automatic strategies to quickly guide users to the most relevant information. We have sketched an admittedly ambitious plan for building and using these collections, and have described our initial results.

The work that we have accomplished thus far helps underscore three key challenges. The first challenge is to build digital documents that capture information available in libraries, herbaria, and museums. This includes the well-understood task of building large collections of high resolution images and the still open problems of how best to capture visual information about 3D specimens. The second challenge is to build effective retrieval methods based on visual and textual similarity. While this is a very difficult research problem, we have improved on existing methods for visual search and provided evidence that these methods may provide useful support to botanists. We have done this by building prototype systems that combine visual similarity measures with image browsing capabilities. This provides a retrieval system that doesn't solve the problem of species identification, but rather aims to help a botanist to solve this problem more efficiently. While our work to date has focused largely on leaf shape, we intend to consider other measures of visual similarity, such as leaf venation, texture, and even multispectral color. Furthermore, we have just begun to investigate how visual search can be combined with textual search, with an aim toward leveraging the existing taxonomic literature. Finally, in addition to the image retrieval methods present in our prototype systems, we have discussed some of the ways that future work in wearable computing may allow us to build systems that make it possible for a botanist to use and collect even more information in the field.

ACKNOWLEDGEMENTS

This work was funded in part by National Science Foundation Grant IIS-03-25867, An Electronic Field Guide: Plant Exploration and Discovery in the 21st Century, and a gift from Microsoft Research

LITERATURE CITED

Abbasi, S., Mokhtarian, F. & Kittler, J. 1997. Reliable classification of chrysanthemum leaves through curvature scale space. Pp. 284–295 in: Romeny, B. M., Florack, L., Koenderink, J. J. & Viergever, M. A. (eds.), *Proceedings of the First international Conference on Scale-Space theory in Computer Vision.* Springer-Verlag, London.

Agarwal, G. 2005. *Presenting Visual Information to the User: Combining Computer Vision and Interface Design.* MScs Thesis, Univ. Maryland, Maryland.

Bederson, B. 2001. PhotoMesa: A zoomable image browser using quantum treemaps and bubblemaps. Pp. 71–80 in: UIST 2001: *Proceedings of the 14th Annual ACM Symposium on User Interface Software and Technology, New York*. ACM Press, New York.

Bederson, B., Grosjean, J. & Meyer, J. 2004. Toolkit design for interactive structured graphics. *IEEE Trans. Software Engineering* 30: 535–546.

Belongie, S., Malik, J. & Puzicha, J. 2002. Shape matching and object recognition using shape context. *IEEE Trans. PAMI* 24: 509–522.

Bell, B. & Feiner, S. 2000. Dynamic space management for user interfaces. Pp. 239–248 in: *Proceedings of the ACM Symposium on User Interface Software and Technology (CHI Letters, vol. 2, no. 2), San Diego*. ACM Press, New York.

Bell, B., Feiner, S. & Höllerer, T. 2001. View management for virtual and augmented reality. Pp. 101–110 in: *Proceedings of the ACM Symposium on User Interface Software and Technology (CHI Letters, vol. 3, no. 3).* ACM Press, New York.

Benko, H., Ishak, E. & Feiner, S. 2004. Collaborative mixed reality visualization of an archaeological excavation. Pp. 132–140 in: (eds.), *Proceedings of IEEE and ACM International Symposium on Mixed and Augmented Reality, Arlington*. IEEE Computer Society Press, Los Alamitos.

Bisby, F. A. 2000. The quiet revolution: biodiversity informatics and the Internet. *Science* 289: 2309–2312.

Blanz, V. & Vetter, T. 2003. Face recognition based on fitting a 3D morphable model. *IEEE Trans. PAMI* 25: 1063–1074.

Blaskó, G. & Feiner, S. 2005. Input devices and interaction techniques to minimize visual feedback requirements in augmented and virtual reality. In: *Proceedings of HCI International, Las Vegas, NV, July 22–27*. Lawrence Erlbaum Associates, Mahwah. [published on CDROM only].

Boivin, S. & Gagalowicz, A. 2001. Image-based rendering of diffuse, specular and glossy surfaces from a single image. *SIGGRAPH* 01: 107–116.

Chen, S. & Williams, L. 1993. View interpolation for image synthesis. *SIGGRAPH* 93: 279–288.

Curless, B. & Levoy, M. 1996. A volumetric method for building complex models from range images. *SIGGRAPH* 96: 303–312.

CyberTracker Conservation. 2005. *Website for CyberTracker Software and CyberTracker Conservation*. http://www.cybertracker.org

Debevec, P., Taylor, C. & Malik, J. 1996. Modeling and rendering architecture from photographs: A hybrid geometry and image-based approach. *SIGGRAPH* 96: 11–20.

Deussen, O., Hanrahan, P., Lintermann, B., Mech, R., Pharr, M. & Prusinkiewicz, P. 1998. Realistic modeling and rendering of plant ecosystems. *SIGGRAPH* 98: 275–286.

Edwards, J. L., Lane, M. A. & Nielsen, E. S. 2000. Interoperability of biodiversity databases: biodiversity information on every desktop. *Science* 289: 2312–2314.

Edwards, M. & Morse, D. R. 1995. The potential for computer-aided identification in biodiversity research. *Trends Ecol. Evol.* 10: 153–158.

Feiner, S., MacIntyre, B., Höllerer, T. & Webster, A. 1997. A touring machine: Prototyping 3D mobile augmented reality systems for exploring the urban environment. *Pers. Technol.* 1: 208–217.

Forsyth, D. & Ponce, J. 2003. *Computer vision: a modern approach.* Prentice Hall, Upper Saddle River.

Gaston, K. & O'Neill, M. 2004. Automated species identification: why not? *Phil. Trans. Royal Soc. B, Biol. Sci.* 359: 655–667.

Gortler, S., Grzeszczuk, R., Szeliski, R. & Cohen, M. 1996. The lumigraph. *SIGGRAPH* 96: 43–54.

Govaerts, R. 2001. How many species of seed plants are there? *Taxon* 50: 1085–1090.

Güven, S. & Feiner, S. 2003. A hypermedia authoring tool for augmented and virtual reality. *New Rev. Hypermed. Multimed.* 9: 89–116.

Hammond, P. S., Mizroch, S. A. & Donavan, G. P. 1990. *Individual Recognition of Cetaceans: Use of Photo-Identification and Other Techniques to Estimation Population Parameters*. International Whaling Commission, Cambridge, Massachusetts [Special issue 12].

Haralick, R. M. & Shapiro, L. G. 1992. *Computer and Robot Vision.* Addison-Wesley, Reading.

Haritaoglu, I. 2001. InfoScope: Link from real world to digital information space. Pp. 247–255 in: Abowd, G. D., Brumitt, B. & Shafer, S. (eds.), *Proceedings of Ubicomp 2001 (Third International Conference on Ubiquitous Computing), Atlanta, GA, September 30–October 2.* Springer, Berlin.

Heidorn, P. B. 2001. A tool for multipurpose use of online flora and fauna: The Biological Information Browsing Environment (BIBE). *First Monday* 6: 2. http://firstmonday.org/issues/issue6_2/heidorn/index.html.

Hillman, G. R., Wursig, B., Gailey, G. A., Kehtarnavaz, N., Dorbyshevsky, A., Araabi, B. N., Tagare, H. D. & Weller, D. W. 2003. Computer-assisted photo-identification of individual marine vertebrates: a multi-species system. *Aquatic Animals* 29: 117–123.

Höllerer, T., Feiner, S. & Pavlik, J. 1999a. Situated documentaries: embedding multimedia presentations in the real world. Pp. 79–86 in: *Proceedings of IEEE International Symposium on Wearable Computers, San Francisco, California, October 18–19*. IEEE Computer Society Press, Los Alamitos.

Höllerer, T., Feiner, S., Terauchi, T., Rashid, G. & Hallaway, D. 1999b. Exploring MARS: developing indoor and outdoor user interfaces to a mobile augmented realty system. *Computers Graphics* 23: 779–785.

Im, C., Nishida, H. & Kunii, T. L. 1998. Recognizing plant species by leaf shapes—a case study of the *Acer* family. *Int. Conf. Pattern Recognition* 2: 1171–1173.

Kanade, T. 1973. *Picture Processing by Computer Complex and Recognition of Human Faces*. Department of Information Science, Kyoto University, Kyoto.

Kasai, I., Tanijiri, Y., Endo, T. & Ueda, H. 2000. A forgettable near eye display. Pp. 115–118 in: *Proceedings of IEEE International Symposium on Wearable Computers, October 16-17, Atlanta*. IEEE Computer Society Press, Los Alamitos.

Kelly, M. J. 2001. Computer-aided photograph matching in studies using individual identification: an example from Serengeti cheetahs. *J. Mammol.* 82: 440–449.

Kress, W. J. 2002. Globalization and botanical inventory. Pp. 6–8 in: Watanabe, T., Takano, A., Bista, M. S. & Saiju, H. K. (eds.), *Proceedings of the Nepal-Japan Joint Symposium on "The Himalayan plants, Can they save us?" Kathmandu, Nepal.* Society for the Conservation and Development of Himalayan Medicinal Resources, Tokyo.

Kress, W. J. 2004. Paper floras: how long will they last? A review of Flowering Plants of the Neotropics. *Amer. J. Bot.* 91: 2124–2127.

Kress, W. J. & Krupnick, G. A. 2005. Documenting and conserving plant diversity: the future. Pp. 313–318 in: Krupnick, G. A. & Kress, W. J. (eds.), *Plant Conservation: a Natural History Approach*. Univ. Chicago Press, Chicago.

Lades, M., Vortbrüggen, J. C., Buhmann, J., Lange, J., von der Malsburg, C., Würtz, R. P. & Konen, W. 1993. Distortion invariant object recognition. *IEEE Trans. Computers* 42: 300–311.

Lestrel, P. 1997. *Fourier Descriptors and their Applications in Biology.* Cambridge Univ. Press, Cambridge.

Levoy, M. & Hanrahan, P. 1996. Light field rendering. *SIGGRAPH* 96: 31–42.

Ling, H. & Jacobs, D. 2005. Using the inner-distance for classification of articulated shapes. Pp. 719–726 in: *IEEE Conf. on Comp. Vis. and Pattern Recognition*, vol. 2. IEEE Computer Society Press, Los Alamitos.

Lu, R., Koenderink, J. & Kappers, A. 1998. Optical properties (bidirectional reflection distribution functions) of velvet. *Appl. Opt.* 37: 5974–5984.

Marschner, S., Westin, S., Lafortune, E. & Torrance, K. 2000. Image-based BRDF measurement. *Appl. Opt.* 39: 2592–2600.

McMillan, L. & Bishop, G. 1995. Plenoptic modeling: an image-based rendering system. *SIGGRAPH* 95: 39–46.

Mokhtarian, F. & Abbasi, S. 2004. Matching shapes with self-intersections: application to leaf classification. *IEEE Transactions on Image Processing* 13: 653–661.

Pankhurst, R. J. 1991. *Practical Taxonomic Computing.* Cambridge Univ. Press, Cambridge.

Pascoe, J. 1998. Adding generic contextual capabilities to wearable computers. Pp. 92–99 in: *Proceedings of IEEE International Symposium on Wearable Computers,* *Pittsburgh, PA, October 19–20*. IEEE Computer Society Press, Los Alamitos.

Phillips, P., Grother, P., Michaels, R., Blackburn, D., Tabassi, E. & Bone, M. 2003. *Face Recognition Vendor Test 2002, NISTIR 6965*. National Institute of Standards Technology, Gaithersburg.

Prusinkiewicz, P., James, M. & Mech, R. 1994. Synthetic topiary. *SIGGRAPH* 94: 351–358.

Ramamoorthi, R. & Hanrahan, P. 2001. A signal-processing framework for inverse rendering. *SIGGRAPH* 01: 117–128.

Ravela, S. & Gamble, L. 2004. On recognizing individual salamanders. Pp. 742–747 in: *Proceedings of Asian Conference on Computer Vision, Ki-Sang Hong and Zhengyou Zhang, Ed. Jeju, Korea*. Asian Federation of Computer Vision Societies, Jeju.

Saitoh, T. & Kaneko, T. 2000. Automatic recognition of wild flowers. *Int. Conf. Pattern Recognition* 2: 2507–2510.

Sato, Y., Wheeler, M. D. & Ikeuchi, K. 1997. Object shape and reflectance modeling from observation. *SIGGRAPH* 97: 379–388.

Scotland, R. W. & Wortley, A. H. 2003. How many species of seed plants are there? *Taxon* 52:101–104.

Sebastian, T., Klein, P. & Kimia, B. 2004. Recognition of shapes by editing their shock graphs. *IEEE Trans. PAMI* 26: 550–571.

Shetler, S. G., Orli, S. S., Beyersdorfer, M. & Wells, E. F. In press. Checklist of the vascular plants of Plummers Island, Maryland. *Bull. Biol. Soc. Wash.*

Siddiqi, K., Shokoufandeh, A., Dickinson, S. & Zucker, S. 1999. Shock graphs and shape matching. *Int. J. Computer Vision* 35:13–32.

Söderkvist, O. 2001. *Computer Vision Classification of Leaves from Swedish Trees*. MSc Thesis, Linköping Univ., Linköping.

Stevenson, R. D., Haber, W. A. & Morriss, R. A. 2003. Electronic field guides and user communities in the eco-informatics revolution. *Cons. Ecol.* 7: 3. http://www.consecol.org/vol7/iss1/art3.

Turk, M. & Pentland, A. 1991. Eigen faces for recognition. *J. Cognitive Neurosci*. 3: 71–86.

Wang, Z., Chi, W. & Feng, D. 2003. Shape based leaf image retrieval. IEE proc. *Vision, Image and Signal Processing* 150: 34–43.

White, S., Feiner, S. & Kopylec, J. 2006. Virtual vouchers: Prototyping a mobile augmented reality user interface for botanical species identification. Pp. 119–126 in: *Proc. 3DUI (IEEE Symp. on 3D User Interfaces), Alexandria, 25–26 Mar. 2006.* IEEE Computer Society Press, Los Alamitos.

Wilson, E. O. 2000. A global biodiversity map. *Science* 289: 2279.

Wilson, E. O. 2003. The encyclopedia of life. *Trends Ecol. Evol.* 18: 77–80.

Wood, D., Azuma, D., Aldinger, K., Curless, B., Duchamp, T., Salesin, D. & Stuetzle, W. 2000. Surface light fields for 3D photography. *SIGGRAPH* 00: 287–296.

Yu, Y., Debevec, P., Malik, J. & Hawkins, T. 1999. Inverse global illumination: Recovering reflectance models of real scenes from photographs. *SIGGRAPH* 99: 215–224.

Yu, Y. & Malik, J. 1998. Recovering photometric properties of architectural scenes from photographs. *SIGGRAPH* 98: 207–218.

Zhang, J., Chen, X., Yang, J. & Waibel, A. 2002. A PDA-based sign translator. Pp. 217–222 in: *Proceedings of International Conference on Multimodal Interfaces, Pittsburgh.* ACM Press, New York.

Zhao, W., Chellappa, R., Phillips, P. J. & Rosenfeld, A. 2003. Face recognition: a literature survey. *ACM Computing Surveys* 35: 399–458.