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Image Analysis and Object Surfaces

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Abstract

Advanced information technology deals with the computer technology appropriate to the capture, encoding, storage, communication, manipulation, and use of information in digital form. A special topic in this field is information capture; in particular, the capture of visual information. The acquisition of surface data for three-dimensional objects is a major problem in this field, approached by utilizing computer vision techniques. Surface data acquisition and related 3D object analysis is of importance in medicine and biology, in CAD modeling of industrial sites, for topographic models of the earth surface, for documenting museum objects, in architecture, in the movie industry, and in many other applications. This paper illustrates a few recently achieved practical results in computer vision (some obtained at CITR Tamaki) and briefly discusses directions in research.

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ABSTRACT

Advanced information technology deals with the computer technology appropriate to the capture, encoding, storage, communication, manipulation, and use of information in digital form. A special topic in this field is information capture; in particular, the capture of visual information. The acquisition of surface data for three-dimensional objects is a major problem in this field, approached by utilizing computer vision techniques. Surface data acquisition and related 3D object analysis is of importance in medicine and biology, in CAD modeling of industrial sites, for topographic models of the earth surface, for documenting museum objects, in architecture, in the movie industry, and in many other applications. This paper illustrates a few recently achieved practical results in computer vision (some obtained at CITR Tamaki) and briefly discusses directions in research.

Keywords: image analysis, computer vision, object surfaces, shape reconstruction, stereo analysis

1 INFORMATION TECHNOLOGY AND COMPUTER VISION

The subject of advanced information technology is information in digital form, i.e. in a specific encoded form finally based on binary representations which can be "understood" by computers and related storage devices or communication channels. But the more interesting question is to define the term *information* from the beginning, and this is a question of explanation type, i.e. there is no general methodology to answer it [7].

1.1 Information, Matter, and Energy

In (classical) Latin the term *informatio* means "to shape, to create, or to form something", as for example a picture, a vase or a statue. In the European middle ages the term *information* still had this original materialistic meaning. In the time of the European Renaissance the interpretation changed to *instruction by lessons*, and in German speaking states a teacher was called *Informator* until about the beginning of the 19th century. However the pedagogic encyclopedias in the 19th century do not mention this word anymore. The common meaning "*explanation*, *message*, or *notice*" of *information* remained current. A new definition of the term *information* was introduced into the scientific literature by *Claude Shannon* in 1948, and was adopted in nearly all disciplines of science within a few years. This led to a broad web of relationships of this fundamental word with different objects and terms.

Norbert Wiener specified three different object classes - matter, energy, and information ("Information is information not matter or energy."). By his definition, information is the set of relationships where material or energetic aspects are not essential. However information is transferred by a material-energetic carrier. This can be a specific acoustical, optical, linguistical, or musical symbol like a vibration of sound, a printed letter, a picture, a phoneme, or a pitch as note *A*, for example. The carrier of information can also be of electrical or electronic form, for example a signal, a bit or a byte. Information is a certain combination of a *carrier* and its *contents*. A printed letter *R* carries a certain content which can also be carried by the acoustical sign *r*. The 5th symphony of L. von Beethoven can be carried by a CD or by a magnetic tape, and CD and symphony, or tape and symphony may be characterized to be information. The 5th symphony is the carried contents.

Sometimes the carrier already contains the contents to some extent, as in the case of traffic signs or of pictograms. This simplifies the process of obtaining the complete information. Normally structures in a *sender* or a *receiver* are needed to ensure that the complete information can be interpreted. A CD player may act as sender, and a human as receiver. The reception of music requires intellectual work to ensure adequate art experience. A received sequence of bits requires a certain decoder for understanding the contents of this bit stream. The decoder ensures the adequate interpretation of the bit sequence.

1.2 Information Technology

The problem of establishing information technology came with the advent of computers. Now it was possible to build up complex models from the real world, to analyze complex information, and to communicate about the findings. Advanced information technology deals with subjects in computer technology appropriate to information in digital form. The specification of the digital form of the studied information does not include the selection of a specific carrier. However it means that this information is in machine-readable form, and carriers may be bits or bytes in computer memory, on a digital CD or on a digital tape, radio signals, or laser impulses. The contents of information in digital form are *data*.

The *capture of information* in digital form is a special mapping of the real world information into machine-readable information. Real material or energetic objects such as the Earth's surface, a plant, a human face, or a plaster statue normally carry a contents of a non-digital nature. A wide field in science and technology is the design of receiver structures for the interpretation of the information content carried by real objects.

The *encoding of information* in digital form is directed towards efficient structures for senders and receivers. Encodings of digital audio, digital still images, digital video etc. define a certain representation of the data which may be carried by digital storage devices or communication channels.

The *storage of information* in digital form has to ensure efficient access to the data (see Fig.1). Stored information is *potential* information because it is waiting for a reproduction process. The reproduction process (decoder, graphical visualization tool etc.) will allow the evaluation of the stored information according to its quality.

The *communication of information* in digital form requires appropriate channels to transmit data. Starting with local communications in computing centers this has now reached a global, world-wide dimension.

The *manipulation of information* in digital form is the wide field of computer applications for dedicated purposes. Processing and analysis of data is directed towards collecting, transforming, modifying, or selecting information.

Finally the *use of information* in digital form may be within complex digital information manipulation systems, or by a human user. Human-machine interfaces are an important topic to ensure proper or efficient use of information given in digital form.

Information technology requires the interaction of several disciplines in science, technology, engineering, and fields of application. It is multidisciplinary by purpose. The world-

Figure 1 (CITR web site): The number of web pages on the Internet increases. How to access the desired information? This is even now a serious problem, and we are just at the beginning of the "information age".

wide creation of *multidisciplinary centers for information technology* at different locations is the logical consequence. The design of *prototype information infrastructures*, for example within a university or within a local area, will help in the understanding of the potential of information technology for creating humane, efficient, and dynamic interactions within society, and between the environment and society.

Examples of application fields of information technology are: digital libraries (books and still image or video presentations of real objects or real scenes), electronic education (which might change our understanding of educational institutions in the near future), electronic commerce which is, for example, developing very fast on in the Internet, digital patient records (there are large IT projects in medicine about communication between different medical centers), and multimedia presentations in architecture, arts, engineering, ethnic studies, and science.

Principles underlying information technology are the subject of research, such as information capture, information storage, data communication, multimedia technology, integration technology, and human-computer interaction.

1.3 Image Data Capturing, Processing and Analysis

The perception of the real world by human beings is based to a large extent on the visual system, i.e. on information in the form of images. Digital images are of essential importance in information technology applications.

Very advanced solutions have been developed for *capturing image data*, utilizing high-quality optical systems and analog/digital converters, multi-chip, high resolution CCD cameras, or long-range telescopes, or based on techniques like electron microscopy, magnetic resonance images, radar interferometry, or computer tomography.

Image data processing deals with transformations of images for the purposes of enhancement, restoration, feature detection, and encoding. Image data encoding techniques like JPEG (for still images) and MPEG (for digital video) are based on image transforms such as Fourier transform, discrete cosine transform, wavelet transform, or on low-level image data processes such as motion or feature detection.

Image data analysis and computer vision offer specific approaches for transforming real-world information into digital form. Acquired (e.g. CCD cameras) or calculated (e.g. computer tomography) images are used as input data to separate the carried contents from the real-world carrier, to transform it into machine-readable form, i.e. to transform it into image data.

Because image data is relevant to all subjects in information technology (capture, encoding, storage, communication, manipulation, use of digital information), there are worldwide a large variety of research and development projects under way [1] which may be cited in the context of IT programs, as for example

- calibration of image acquisition (e.g. camera calibration, robot location and orientation, and light source calibration),
- capturing of real-world objects and scenes (e.g. image preprocessing, image segmentation, image region analysis, scattered data analysis, fusion of information, depth or range computation, surface reconstruction, and scene reconstruction),
- processing of captured surface or scene data (e.g. mapping sparse data into surface models, processing unorganized surface points, and discrete integration of surface gradients),
- encoding of images, of real-world objects, and of scenes (e.g. still image and video compression, surface data compression, compression of surface data in motion, and encoding of scene descriptions),
- visualization of real-world objects and scenes (e.g. pictorial maps, panoramic movies, view morphing, augmented reality),
- incorporation of image data into multi-media presentations (e.g. access structures to related image data),
- image data bases (e.g. retrieval of still images and digital video by contents, by typical coloring, or by object silhouettes),
- evaluation of images, real-world objects and scenes (e.g. reference views of 3D objects, characteristics of materials using different sensors, as sound of impact using acoustics),
- modeling of real-world objects and scenes (e.g. texture and shape modeling, motion modeling, environment models, and multi-view modeling),
- understanding of real-world objects and scenes (e.g. texture classification, analysis of planar shapes, reverse engineering, analysis of structural relations, model-based vision, recognizing and learning free-form objects, image understanding, motion analysis, landmark recognition in video sequences etc.),
- interactions between vision and environment (e.g. active or purposive vision, visual guidance of a mobile robot, motion tracking)
- evaluation and validation of algorithms (e.g. quantifying the reliability of image analysis results, multigrid convergence analysis, comparison of stereo correspondence techniques, accuracy of 3D measurements).

A recent trend in image analysis and computer vision is the increased interaction with developments in computer graphics, multi-media presentations, and IT in general.

2 SURFACE CAPTURE TECHNIQUES

One of the main contributions of image analysis and computer vision towards information capturing is in the field of calculating depth or range data, or of approximating complete surface descriptions of real objects. A surface of a real object may be characterized by geometry, texture, shading or surface reflection properties, possible shadow or silhouette shapes under selected

Figure 2 (ModelMaker web site): Measurement of surface features by hand is history.

viewing and illumination directions, and further features. Measurement by hand (Fig. 2) is not adequate in recent computer applications. Besides image analysis and computer vision [4], other disciplines contribute to solutions for capturing 3D data about the real world. Different applications are oriented towards objects of specific complexity. Man-made objects have in general a lower shape complexity than real-world objects. However a man-made sponge is probably of even higher complexity than a yucca tree. But probably in both cases nobody will be ever interested in obtaining an accurate three-dimensional shape reconstruction.

2.1. Photogrammetry, Physics, and Engineering

Photogrammetry allows the calculation of high-accuracy digital elevation maps (DEM's) based on stereo image pairs and on manual correspondence analysis. The equipment for image acquisition and interactive stereo image analysis is quite expensive. However there is a long tradition (starting about in the 1950's) of applying photogrammetry techniques in 3D measurements in fields such as architecture, remote sensing, aerial photography, and electron microscopy where stereo pairs of pictures are available. Nowadays photogrammetry is, for example, successful in reverse engineering where CAD models of complete industrial sites are generated for documenting existing industrial environments. Note that such an industrial environment is probably (at a certain "level of resolution") of higher shape complexity than a yucca tree or a sponge. Certain approximate reconstructions (Fig. 3) may be obtained by manual stereo image analysis.

Several techniques developed in physics and engineering can also be used to generate depth or range data. The construction of detailed computer models by tracing object surface features (contact probe) is very time-consuming. However this might be still an appropriate solution in specific model generation situations. Spaceborne radar interferometry has been a hot topic in radar research labs over the past few years. Using data from two passes of a satellite, acquired in nearly identical orbits, scientists have generated high accuracy surface topographic

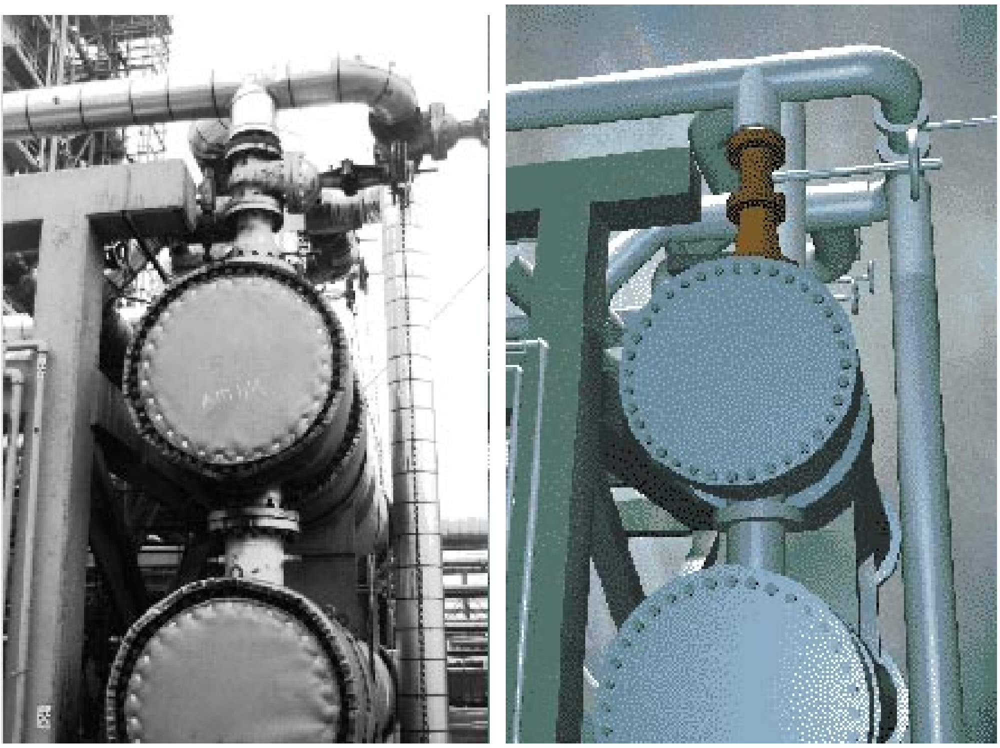

Figure 3 (Sightmodels web site): A CAD model of an industrial site generated by manual stereo image analysis (photogrammetry).

models. Laser range finders may be mentioned as a third example. Based on measurements of the time of flight of reflected laser light impulses it is possible to estimate single range values or even arrays of range data (range maps). Laser range finders have gone down in price recently, but their accuracy is not sufficient to generate 3D surface models.

In general it might be expected that different solutions for different measurement situations will evolve from recent research and development programs for capturing 3D surface data. The different solutions possess specific parameters and flexibility. The deepened understanding of the behavior of measurement approaches, with respect to practical situations and with respect to theoretical understanding and refinement, is also an aim of recent research programs. It may also be expected that the integration of different techniques will arise. Subprocesses in photogrammetry may be automated by image analysis techniques leaving final interactive decisions to the human operator. Range maps are already heavily used in computer vision, for example as a first estimate of surface range data which may be refined by subsequent image analysis techniques.

2.2. The Visual System and Automated Image Analysis

The human visual system (and visual systems of animals) provides an existence proof that an image based approach can be successful for the proper understanding of several categories of information about the real-world. For example, human understanding of spatial relationships in real-world environments, of different textures, of distances between visible objects, and of three-dimensional surface structures is based on complex interactions of knowledge structures about clues such as:

Figure 4 (Magic Eye web site): Height map and autostereogram generated from this height map.

- object geometry,
- surface texture,
- surface shading with respect to illumination,
- object silhouettes,
- motion patterns (e.g. the moving light displays of *Johannson* in the 1960's),
- context knowledge about visible objects, and
- stereopsis (depth impression is originated by minor differences between images for the left and for the right eye, discovered by *Charles Wheatstone*, a British physicist, in 1830/32).

Autostereograms are a nice demonstration of the ability to see three-dimensional scenes based on stereopsis. Visualization techniques in computer graphics prove that simple geometric patterns (such as two-dimensional contours in floating horizon algorithms) are sufficient for obtaining the three-dimensional surface geometry of visualized objects. There are strong recommendations in the field of image analysis and computer vision for emulating the human visual system [3] for success in capturing the real world based on images.

2.3 Surface Capturing Techniques in Computer Vision

There are methodologically several very different approaches in image analysis and computer vision for capturing data about the three-dimensional world [4]. The classical approach in computer vision is *binocular stereo*. The great success of this technique in photogrammetry contributes to the ongoing interest in automated (!) solutions. Assuming that both cameras (Fig. 5) are in known positions with respect to each other, and their image acquisition parameters are known by calibration, then two corresponding points in both images (showing the same object surface point) can be used to calculate the position of the projected object surface point in the three-dimensional world. The mathematics behind this is reasonably simple (triangulation, and occasionally some coordinate transforms). However, the automated determination of which points correspond is a problem. Refined approaches for finding correspondence relations in both images, based on models of the given image data and on derived comparisons of local image data distributions, are still under research for better binocular stereo systems in image analysis and computer vision [2]. There is no "general purpose" correspondence analysis.

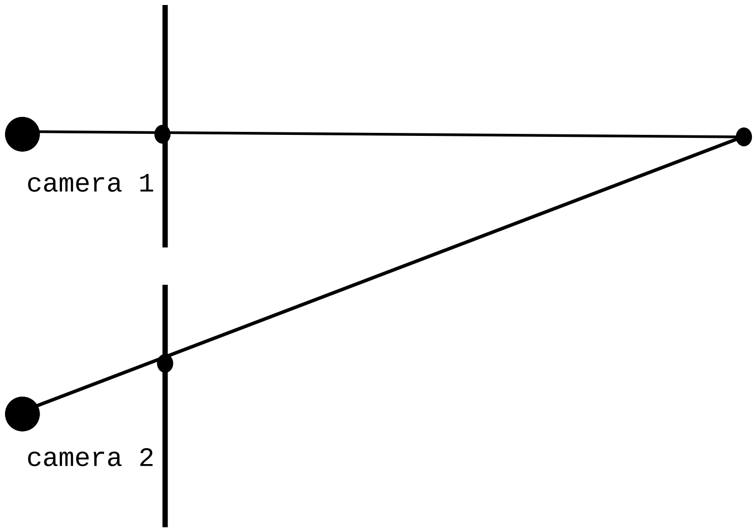

Figure 5: An object surface point is projected into a pair of corresponding points if both cameras can "see" this object surface point.

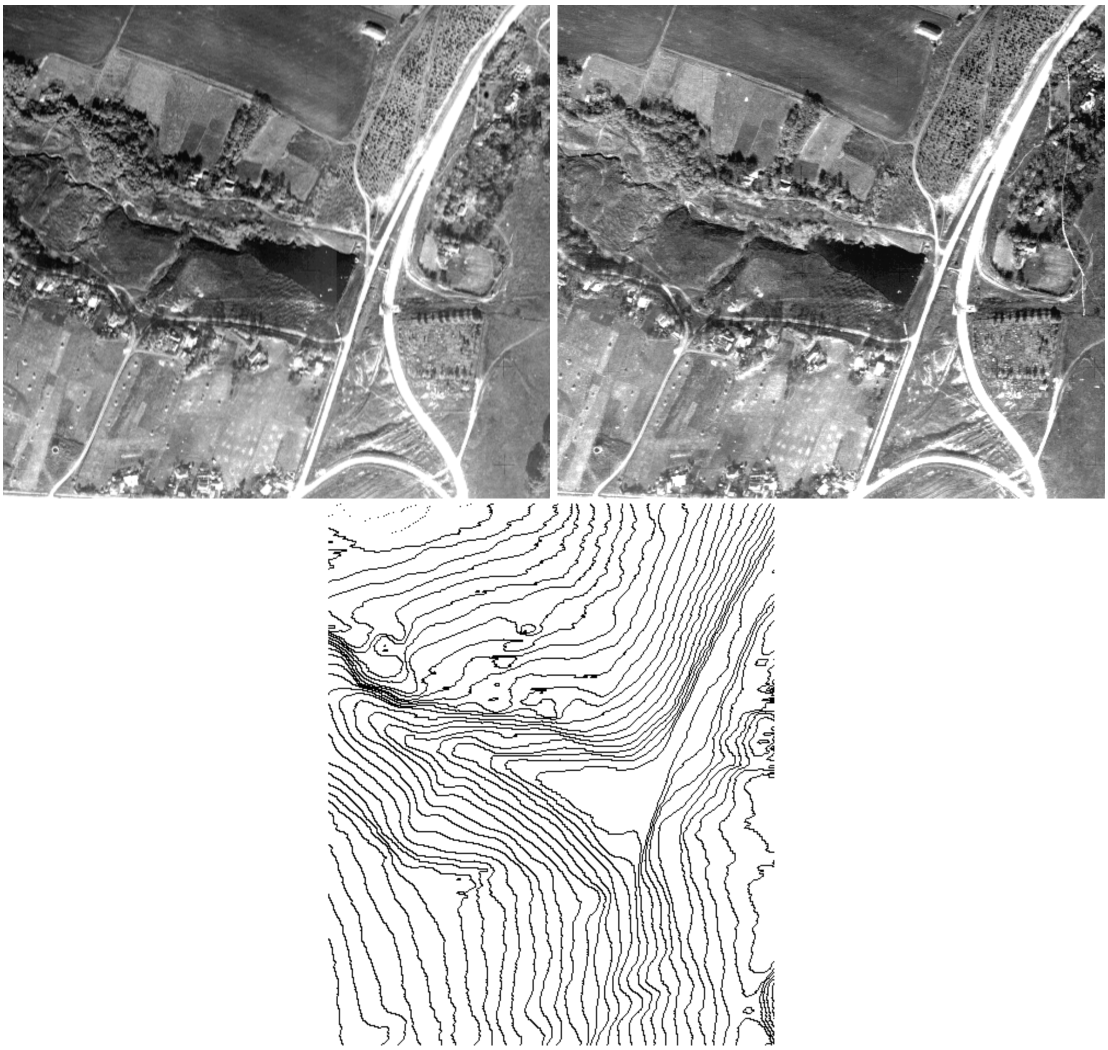

Figure 6 (Georgy Gimel'farb, CITR): A pair of 400x500 stereo input images (scene in Moldavia) and the automatically calculated isolines (45 sec computing time on a PC).

Multiple-source shading based approaches as *photometric stereo analysis* allow the calculation of surface normals based on several images, taken with the same camera, showing the same (static) object under different illumination conditions. This approach is based on careful surface reflectance measurements and the calibration of light sources. A detailed analysis of shadows, interreflections, highlights or specularities, angles between light sources etc. helps in achieving quite accurate calculations of surface normals. The evaluation of the obtained gradient fields is one of the research topics in this field. The calculated normals or gradients are mapped into a height map (see Fig. 4 for an example of a height map), for example by some local or global integration techniques. The improvement of these discrete integration techniques is still under research. The height maps obtained can be used to visualize the captured surface under different viewing directions on a screen, see Fig. 7 for an example. The technique may be used for generating height maps of a human face, a human hand, etc. Using colored illumination this 3D reconstruction may be even achieved for dynamic scenes (recently about 9 height maps of 128x128 resolution per second on an O2 graphics workstation in the CITR lab).

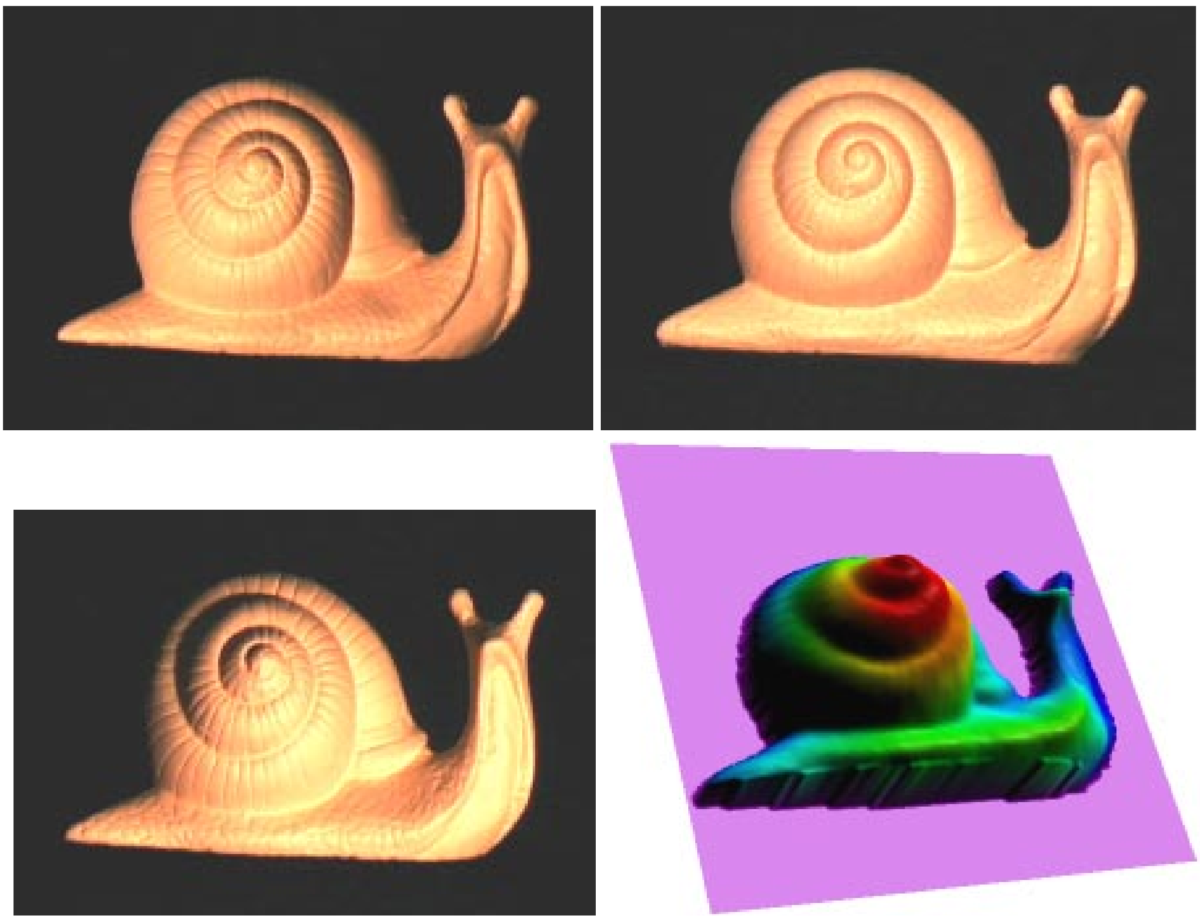

Figure 7 (Karsten Schlüns, CITR): Three input images of a snail for photometric stereo. The generated gradient field can be transformed into a height map which allows the generation of views of the given object from different directions. A special surface coloring is used to demonstrate the dynamics of the calculated height values.

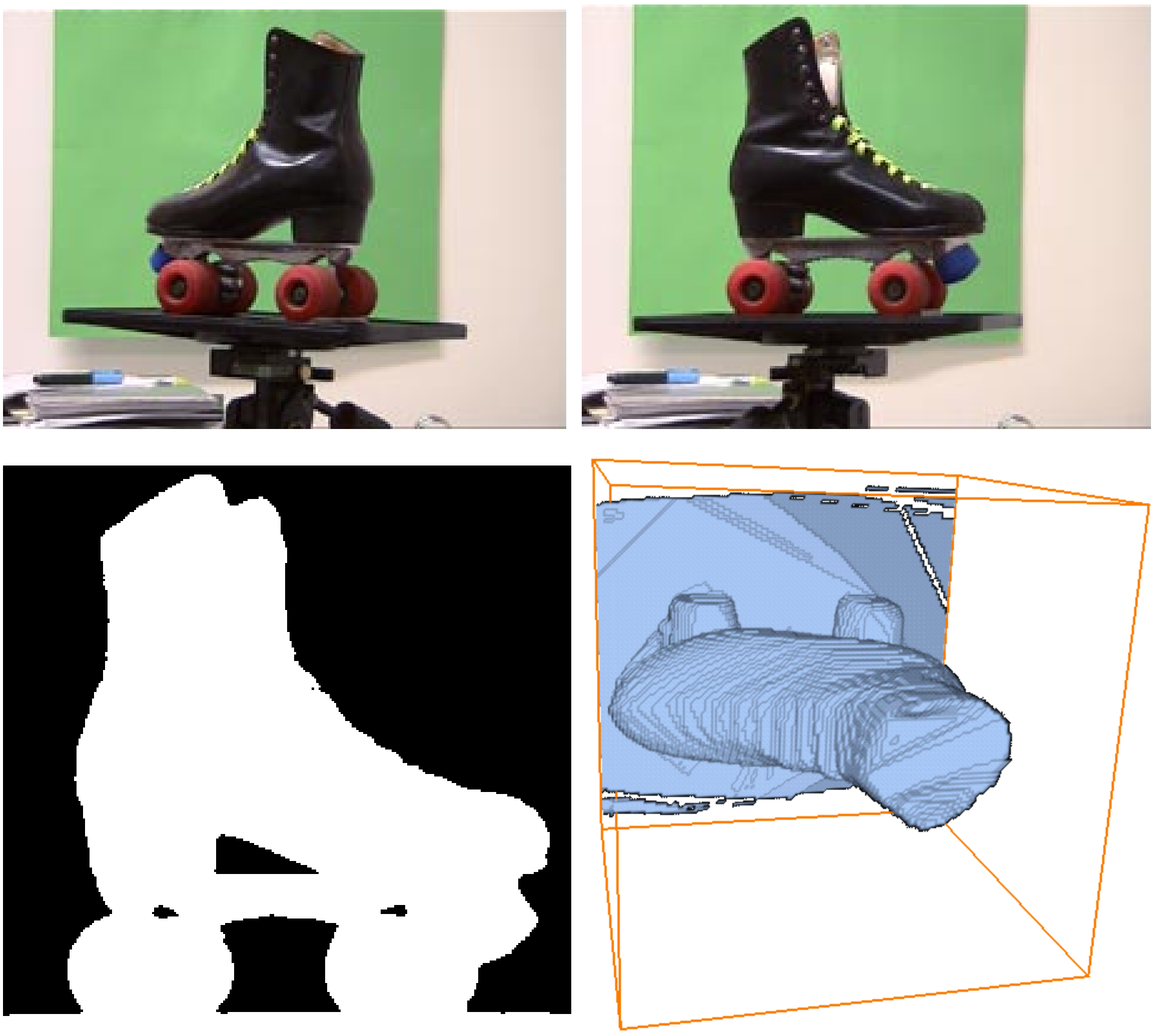

Figure 8 (Karsten Schlüns, CITR): Shape may be calculated from occluding boundaries using a volume based approach. An object on a turntable generates a sequence of occluding boundaries ("silhouettes", see below on the left) which may be transformed into a complete 3D description of the rotating object. Below on the right the given object is shown in reconstructed form (viewing direction from above) where the visualized reconstruction resolution is about 1/64 of the possible accuracy.

The use of inexpensive equipment (three light sources and a video camera), and a fast speed are two advantages of photometric stereo. Furthermore, the image values of (one of) the acquired images may be used for texture mapping without any additional need to solve correspondence problems, because the generated height values are located at the same pixel position as the acquired image values.

A further inexpensive solution for shape reconstruction is possible by *analyzing occluding boundaries* of a rotating object. Sometimes this does not allow the reconstruction of surface concavities with respect to the projection direction. However the reconstructed surface may be used, for example, for further refinement based on multiple-source shading based approaches. Such a combination specifies an integration technique defined by different surface reconstruction techniques.

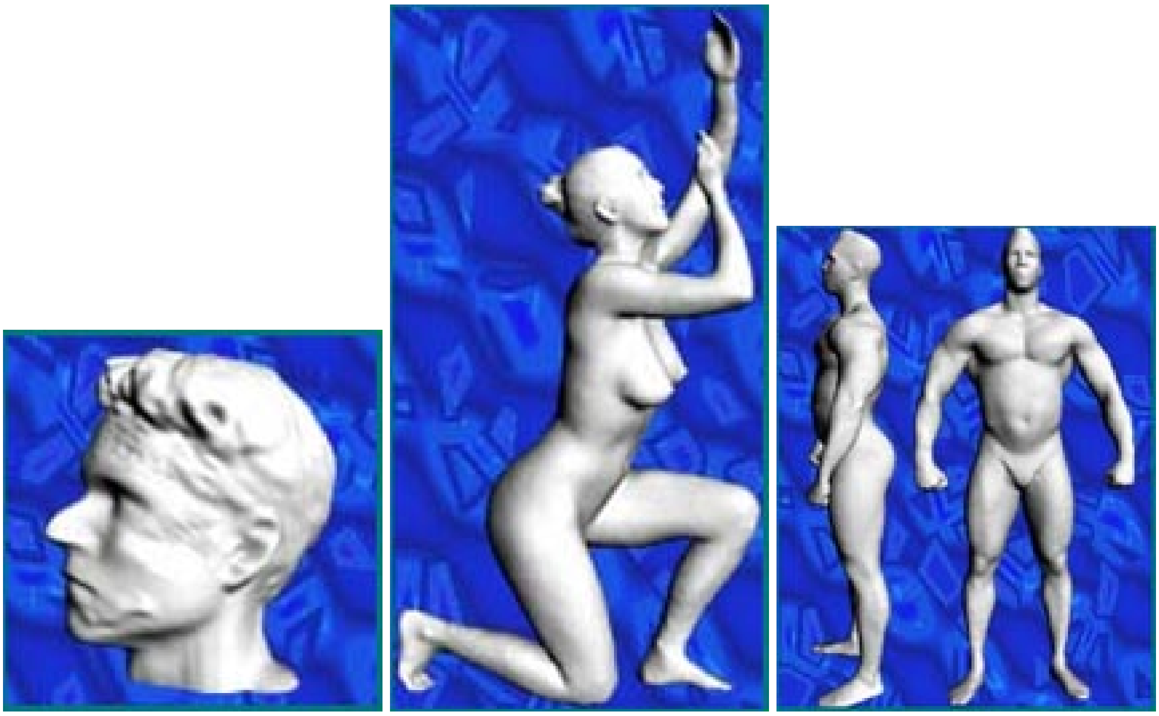

Figure 9 (Cyberware web site): Cyberware (Monterey, CA) announced the first whole body scanner in 1995 for a price of US$410,000.

Structured illumination characterizes a further approach in image analysis and computer vision for obtaining surface data. A light pattern is projected onto the object surface, and its position is then detected in the image taken. Assuming a calibrated image acquisition setup the pixel position of the illuminated surface point allows the reconstruction of this point in three-dimensional space by simply intersecting a plane (light) and a line (projection ray). A technique based on a *projected light point* is similar to a physical probe in that it uses a single point of reference, repeated many times. This is the slowest approach as it involves lots of physical movement by the source of the light point. A technique based on a *projected light stripe* is reasonably fast as it uses a band of many points to pass over the object at once. It is accurate too. So it matches the twin demands for speed and precision. This light stripe technique is used in different commercial products for 3D surface capture. To capture an object in three dimensions, several light stripes are projected from different positions. All the derived surface points together form a pattern of unorganized points (often several million data points) on the object surface. These surface points can be used to calculate different visualizations of the captured object surface (Fig. 9). The mapping of the given object surface textures onto the generated geometrical (!) reconstructions is a further challenge.

The main drawback of these structured illumination systems is still their high price. A reconstruction of a whole human body in about 12 seconds may also be sufficient in some areas, and to slow in others. The first applications of whole body scans were in the movie industry for animations. Objects at different sizes are now scanned for a broad variety of purposes as reverse engineering, CAD modeling, arts, architecture, and advertisements. Scanning of sculptures, e.g. wooden statues in a Marae (see also Fig. 10), might be one application in art or eth-

Figure 10: Statues by Maori artists (each about 1.8 m in height) in the Waitakere visitor center, Auckland. Structured illumination techniques should be appropriate to reconstruct these statues with high accuracy.

nic studies. The control and documentation of the shape of the human body (e.g. of mothers during pregnancy or the feeding of babies) is another application. The textile industry is interested in statistical studies about populations in different areas to supply clothes in fitting sizes. For some of these applications it may be suggested that multiple-source shading based approaches and/or analysis of occluding boundaries offer cheaper and faster solutions.

2.4 Surface Analysis based on Volumetric Image Data

A further approach for reconstructing 3D object surfaces may be based on *volumetric image data* which are composed by sets of images visualizing different slices through a given object structure. Image acquisition techniques as confocal microscopy, magnetic resonance imaging, computer tomography, microscopy of physically sliced objects (see Fig. 11) etc. provide such volumetric image data sets. Visualization techniques allow to display such volumetric data sets. The (final) aim consists in analyzing the given 3D data with respect to specific goals.

For analyzing the object structures within these data cubes a complex sequence of problems has to be solved. An analysis solution starts with specifying adequate image segmentation techniques to separate the object within the given data cube of voxels. Then these object voxels have to be clustered into object components for which a certain topological and geometrical

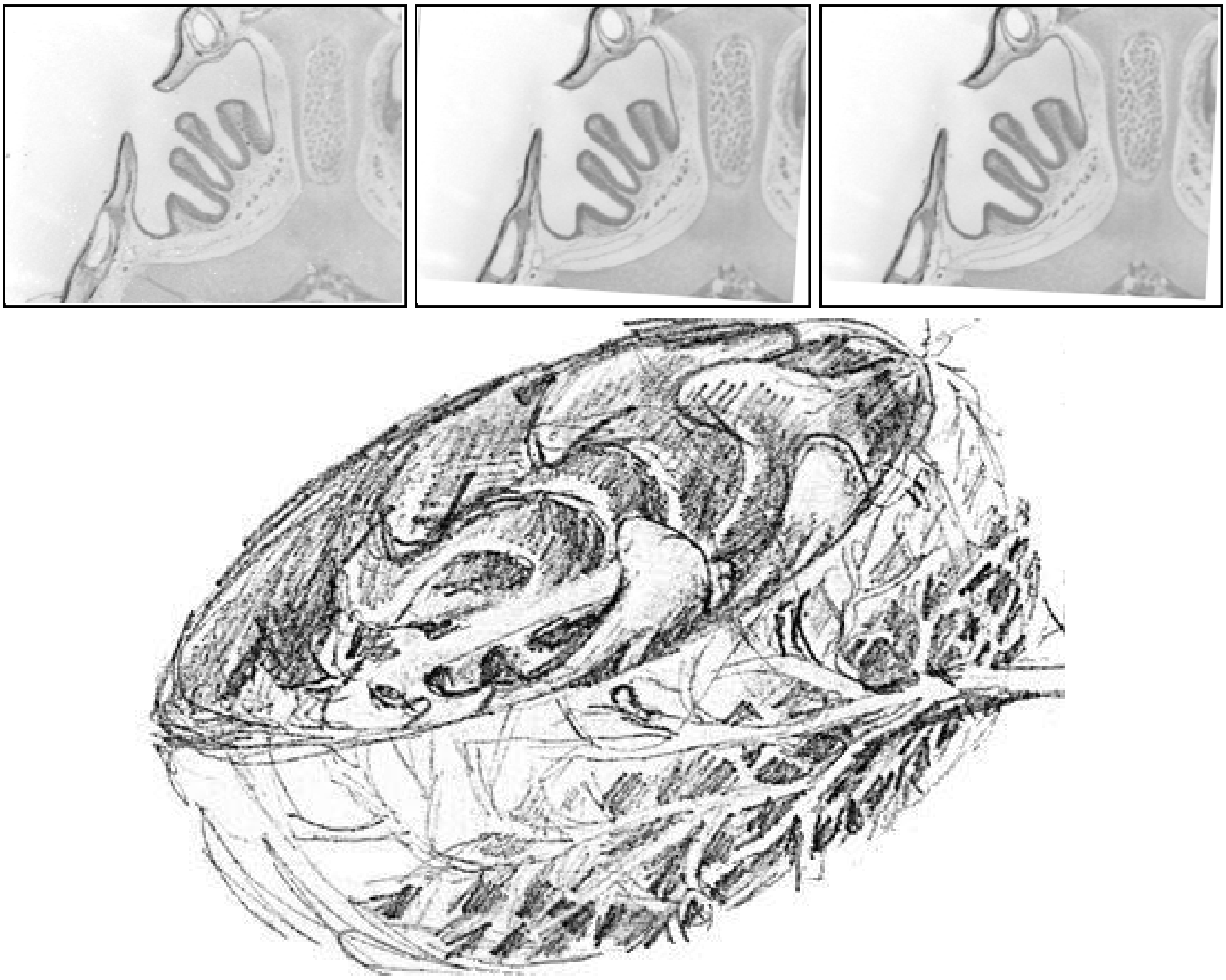

Figure 11 (Carol Diebel 1996, Biology Department, The University of Auckland): Three (manually adjusted) images of a sequence of more than 100 images visualizing slices through the nose of a baby trout, and a drawing of the nose cavity. Interactive support for generating such 3D models based on the given volumetric image data set is available for many applications, however not yet for this special, here illustrated situation.

model has to be applied, to understand these discrete data sets as 3D bodies. *Digital geometry*, founded by *Azriel Rosenfeld* in the 1960's, provides the proper theoretical background for studying geometry and topology in digital spaces [6]. Finally analysis techniques have to be designed for measuring features of these 3D bodies, and for characterizing or classifying these 3D bodies based on the calculated features. A proper model for these 3D bodies is given by *Jordan surfaces* which were introduced into mathematics in the 19th century. Gridding techniques, studied in mathematics since the beginning of the 20th century, allow the analysis of relationships between models of Jordan surfaces in Euclidean real space, and discrete data sets in spaces of digital image voxels. The convergence of volume measurements (assuming finer and finer grids) based on gridding techniques is well known since the beginning of the 20th century. However, the study and design of convergent methods for surface area measurement is still a research topic.

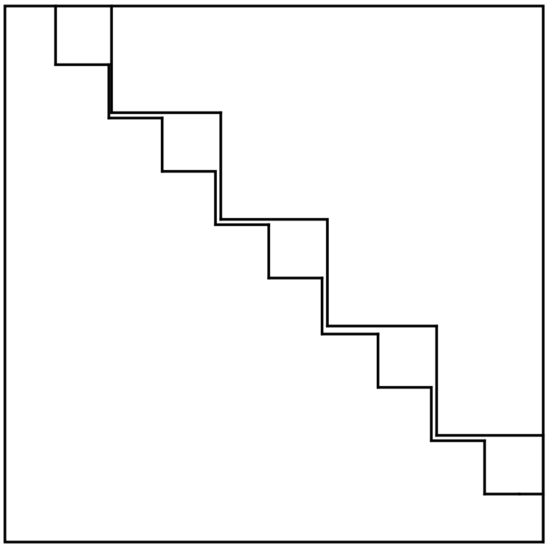

Figure 12: An approximation of a diagonal of a square by staircases of different resolution. The total length of these staircases remains constant.

We illustrate the situation by one popular example. The length of a diagonal of a square with side length a cannot be measured by the length of a piecewise constant function because the total length of the piecewise constant function is always $2a$ independently of the number or the size of the steps, and does not converge towards $a\sqrt{2}$ if the step-size goes to zero (Fig 12). This is a popular example of the following problem: assume that a real-world object is given and we have only some sampled or digitized data about this object. What is the appropriate method to calculate a specific feature of this object, or to represent it?

The measurement of areas in 2D, or of volumes in 3D is normally much more robust or straightforward than measurement of perimeters in 2D, or of surface areas in 3D. For the "diagonal of a square" example above the size of the area below the "diagonal" piecewise constant function will converge to the size of the triangle defined by two sides of the square and the diagonal if the step size goes to zero.

Digital geometry approaches, computational geometry algorithms and further calculations (numerical, statistical etc.) may be used to represent and analyze the given discrete data. The approach should be *sound with respect to the general measurement or representation problem*. Two soundness properties are studied in [5]:

CONVERGENCE: Image acquisition at higher image resolutions should lead to convergence for the values of measured features, such as the geometric shape of reconstructed planes, straight lines, surfaces etc.

PROPER VALUE: Convergence should be towards the "true" value, the "true" data etc.

The first soundness property requires a convergence proof. The diagonal in the example above converges towards $2a$. The second soundness property requires a fundamental problem analysis: what is the "true data", the so-called *ground truth*? Certainly the "true" data is unknown in applications of image analysis. Synthetic input data may be a solution. However these are always just case studies for a specific type of hypothetical input data. The complete solution is the mathematical modeling of the measurement or representation problem where the ground truth is defined in general mathematical terms. It is easy to model a plane, a polygonal face or a straight line. The diagonal in the example above has length $a\sqrt{2}$. A general surface model needs more explanation and is discussed in [5]. This model, the minimum Jordan surface, was introduced and studied by *Fridrich Sloboda* during his research stay at CITR Tamaki in early 1997.

3 CONCLUSIONS

The automated capture of surface data based on image analysis or computer vision techniques has had an eventful history since the 1960's. Different techniques have been developed and have proved to be of practical relevance in a broad variety of application domains. There is no "general purpose" technique, and new application areas result in new problems. Examples of research topics in image data based surface capture and surface analysis are:

- improved capture of surface data (e.g. correspondence techniques for binocular stereo, multiple-source shading based approaches, structured illumination, and integration of techniques),
- capture of 3D environments or scenes (e.g. augmented reality, i.e. virtual reality based on acquired images, control of mobile agents in 3D scenes),
- evaluation of different techniques in different application contexts (theoretical analysis of sound measurement of 3D surface features, comparison of the computational complexities of algorithms, practical evaluation of capturing techniques using test objects as suggested in Fig.13),
- incremental transmission of captured surface or scene data, or progressive visualization of reconstructed surfaces or scenes (e.g. finite element techniques, reconstruction based on unorganized points, incremental algorithms for surface visualization).

A multidisciplinary approach (information technology, physics, engineering, computer science and others) supports successful progress in this field.

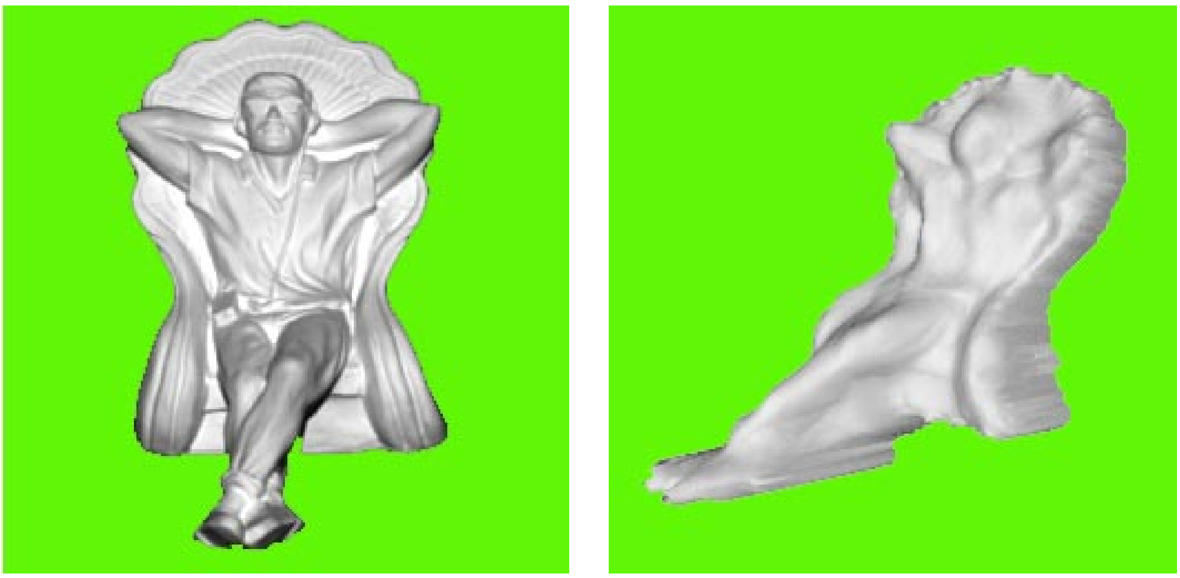

Figure 13: Reconstruction of a plaster statue using binocular stereo and structured illumination (see [4]). Such an object may be used for detailed evaluation studies for comparing different reconstruction techniques with respect to accuracy, speed etc.

4 ACKNOWLEDGMENT

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