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THE EXAMINATION OF PAINTINGS DIGITAL IMAGE ANALYSIS

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THE EXAMINATION OF PAINTINGS BY DIGITAL IMAGE ANALYSIS

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Abstrac

As part of the EC-supported VASARI project (ESPRIT II project 2649), a system has been developed which allows the whole surface of a painting up to 1.5m by 1.5m to be digitally imaged at very high resolution (more than 10 pixels per mm) using visible radiation.

A series of seven broad-band optical filters were used to produce colorimetric images of paintings. It is expected that the degree of colour accuracy so obtained will be sufficient to allow the system to detect small changes in surface colour with time.

Using an even higher resolution on small areas, it is possible to examine the surface texture of paintings and to extract and compare craquelure patterns. This is of great interest with respect to the detection of transportation damages.

Both the measurement of colour change and the detection of surface texture changes are applications of great relevance for long-term preservation of paintings, for problems that cannot be solved with conventional techniques (e.g, photography or video techniques). The image processing techniques developed, particularly those for creating mosaic images, have been applied to additional infrared and X-ray applications.

This paper presents the technical solution and a critical evaluation of our involvement in recent advances in technology, as well as a series of applications.

1 INTRODUCTION

The VASARI project (July 1989 - February 1992) was funded by the European Commission under ESPRIT II and aimed to show that high resolution colorimetric imaging directly from art objects, in our case paintings, is feasible. A VASARI image processing package, which allows digital images to be grabed and handled, was designed according to the needs of museums and universities involved. Much effort was expended in the set-up of the repositioning system. Basic and advanced image processing software was written with a user-interface which enables the inexperienced user from the art world to work with the VASARI system without any deeper knowledge of the mechanics and electronics of the VASARI system or the computing part of image processing in general.

The project took place within the following framework:

(i) Encouraged by the ESPRIT II concept, the museums and universities formulated requirements according to their needs. This user-driven approach was a new and challenging experience for those users mentioned who usually have to live with technical equipment provided by the market.

(ii) The development of the VASARI system followed a prototyping approach. Two VASARI prototypes were set up, one at the National Gallery, London with a special focus on lighting and filtering problems and a second one with a more advanced repositioning system at the Doerner-Institut, Munchen.

(iii) The London prototype is mainly designed for colour applications. Previous work suggested that the quality of colour representation could be considerably improved by digital imaging with the final aim to measure colour (changes) on paintings.

(iv) The Munchen prototype is designed to image the surface texture of paintings. By comparison of digital images before and after an art transport, changes in craquelure and losses indicate transportation damages.

(v) The VASARI system - the acronym VASARI stands for Visual Art System for Archiving and Retrieval of Images - aimed to create more accurate and more permanent records for research in conservation (science) or history of art, for teaching (computer aided learning) and printing. The quality and permanance of those digital images is expected to be superior to photographs or video images. If stored in a suitable data base the reduction of handling and the speed of access will be improved. A multi-user access to both image and text related to the object will preserve the original from degradation through prolonged use.

(vi) Both systems are designed to allow non-destructive testing of paintings or '2 1/2' dimensional objects in general, i.e. directly to generate digital high resolution colorimetric images for any purpose or to image secondary sources such as X-ray or beta-radiographies for further image processing.

The huge effort - which went far beyond the capabilities of the conservation science departments involved - requested conceptual and technical input from many partners all over Europe such as the authors' institutions mentioned above, Brameur Ltd Aldershot (UK) (which acted as prime), Télécom Paris (F), TÜV Bayern Munchen (D) and as subcontractors Laboratoires de Recherche des Musées de France LRMF Paris (F), SIDAC Rome (I) and SYSECA Rennes (F). Although the coordination and administration of such a big group with partners of a very different background from museums as well as from industries is difficult, the synergic approach allowed the development of a very advanced European solution to the wide range of problems mentioned above.

2 THE VASARI SYSTEM - USER REQUIREMENTS AND TECHNICAL SOLUTIONS

The description of the VASARI system /1/ follows the requirements as formulated by users. They are based on previous practical experience; for example during transport condition assessments and scientific results concerning light damage. All the single components described form a fully integrated and computer controlled system.

2.1 The area to be imaged

The size of the paintings to be imaged defined the size of the VASARI imaging system. A statistical evaluation on 256 paintings which went on loan from Munchen to exhibitions showed that the unframed paintings had a mean height of 82 ± 44cm and a mean width of 84 ± 47cm. If the area to be scanned is chosen as 150x150cm, 90% of the paintings could be investigated with the VASARI system. This gave the size of the easel on which the painting is mounted as well as the distances which the camera has to cover.

2.2 Resolution

The resolution chosen immediately influences the quality of the image, the size of the detail which can be imaged with one single exposure and the amount of information to be stored. To draw a common comparison, if a detail of 30 cm height is imaged with a resolution of 10 pixel elements per mm (p/mm) the image quality is equivalent to that of a 35 mm transparency with estimated 3000 lines 121. Thus, the definition of the resolution required for digital imaging turned out to be crucial for the selection of most of the hardware components of the VASARI system, such as the camera (see 2.3) and the mechanics of the positioning system (see 2.4).

As originally defined by the user, 'sufficient' resolution is that required to see small details on paintings, such as cracks or brush strokes. This rather vague definition led to an investigation of crack widths which may be be seen as the smallest detail to be resolved. Major cracks showed a typical width of about 0.13 mm, minor ones about 0.019 mm. This led to the decision to define 13 p/mm as a minimum resolution.

If a painting of 150x150cm is to be imaged with 13 p/mm, the final digital image will have 19.500x19.500 pixels, which is far more than most other images usually known or handled in image processing. However, there was no suitable camera on the market which yields more than 3000 pixels. Consequently, larger paintings clearly require more than one exposure and thus, a procedure to move the camera in front of the painting ('the positioning system'). The single exposures are joined to form one large digital image, which made a 'mosaicing procedurć necessary. The benefit of this approach is that the acquisition is independent of the size of the painting and of the technology of the camera and the positioning system.

2.3 The camera

A high resolution CCD camera (Kontron ProgRes 3000), designed at the Technical University Munchen, was chosen for the VASARI prototypes /3/. The camera produces about 3000 by 2300 pixel images which was far more than all other cameras on the market at that time. The high resolution is reached by moving a 500 by 290 pixel CCD sensor minute amounts by piezo-ceramic actuators, so that multiple exposures can be interleaved to cover the whole image area. A black-and-white as well as a 3-band colour sensor are provided, which can be easily exchanged. The camera is controlled via an ATboard (Kontron PRI-AT) plugged into a 386 PC.

2.4 The positioning system

As mentioned, several exposures are needed to cover the full painting. Therefore, the camera has to be moved accurately over the plane of the painting (with x vertical and y horizontal). Additionally, the camera can be moved towards the painting (z direction) to allow focussing without changing the focus of the optics. On the positioning system in München (Fig. 1), the z direction is fully motorized with a length of 180 cm. Having chosen a resolution, the camera will automatically go to the correct z position. The x, y and z movements are made by linear robotics using stepper motors with a step width of 2.5 micrometer in x and 4 micrometer in y and z. Special attention was paid to the modularity of the system to allow later adaptations for new applications. Following our prototyping approch the London positioning system was built by Time & Precision (GB); the more advanced Munchen prototype by ALKO Engineering (D).

2.5 The repositioning problem

After imaging the painting a first time, both the London and the München applications require the possibility to reposition the painting accurately after a distinct event (such as a long-term exhibition in the gallery or an art transport). A second image acquisition should then allow a comparison between digital images recorded before and after this event. The result of the comparison could be a detection of colour changes or of transport damages. This is only possible, however, if the digital images show exactly the same detail before and after the event. Therefore, much effort has been expended to keep any movement of the positioning system as reproducible as possible and to make the system statically as rigid as possible. For the Munchen prototype, the absolute reproducibility is 10 micrometer for each axis.

2.6 Controlling the image acquisition

A UNIX workstation is being used (Sun Sparcstation 2 with the UNIX operating system SunOS 4.1.1) to control the image acquisition system and to process the VASARI images. The workstation is equipped with 32 MB RAM as well as with a 24 bit true colour graphic board. Whereas the camera is controlled via the PC mentioned and the ethernet, the positioning system is controlled via a microcontroller directly connected to the workstation. Both the PC and the microcontroller, are 'invisible to the user' for whom a unified 'user interfacé on the workstation is provided. To handle the sometimes very large VASARI images more than 1.7 GB of hard disk are available (which turned out to be not sufficient at all).

2.7 The lighting and filtering

The London acquisition system uses the monochrome sensor and has a coloured light projector mounted on the positioning equipment behind the camera. Since the light projector moves over the painting with the camera, the same correction for non-uniformity in illumination can be used for every sub-image. Two 24V, 250W DC tungsten halogen lamps are contained in separate enclosures. The light from these two sources is fed through a 'y' shaped fibre-optic guide into a filter box, where it passes through one of seven broadband interference filters mounted in an aluminium wheel. A fan passes a steady stream of air through an elaborate set of channels cut in the filter wheel, cooling whichever filter is currently in the light path. The filter wheel can be turned under computer control. From the filter, the light passes into a second fibre-optic guide which divides into six 'tails', each terminated by a frosted lens unit. These frosted lenses provide even illumination over the region to be imaged.

In München, successful experiments have been conducted by using high quality slide projectors (G67P Götschmann München) to lighten the area to be imaged and using the slide changing mechanism to introduce cut-off or interference filters into the optical path.

2.8 The image display and output

The X-windows system is used for displaying images in windows with up to 24 bits per pixel. Because the resolution of computer monitors is still limited (1.150x900 pixels on our 19" monitors) the VASARI system offers the possibilty to zoom on the images and to scroll the high resolution images. So, in practice, only a very small part of these images is visible on the monitor.

One limiting problem concerns the representation of colorimetric images on monitors that have varying characteristics and limitations in the colours they can display. Therefore, experiments have been conducted with a Barco Calibrator monitor where the screen can be calibrated /1/.

To visualize the results on other than a monitor digital proofs can be produced on laser printers (e.g. Mitsubishi S340) either on paper or on photographic emulsions.

2.9 The image processing software

An integrated package of image processing routines has been developed called VIPS (VASARI Image Processing System) 141. VIPS is tailored for art imaging. No easily extensible commercial system could be found capable of processing images of the necessary size. VIPS provides the usual range of operations found in image processing packages, including an unusually full range of arithmetric operations, morphological operators, colour change operators and filtering operations.

Much work has gone into the development of the sections of VIPS concerned with the assembly of image mosaics. Two images are displayed and the user selects a pair of points. From these the computer calculates the region of overlap which is then divided into three parts. Sixty points with good contrast are selected automatically, 20 in each of the three regions. The optimum correlation between points in the adjacent images is computed by searching an area in the second image using the information provided by the user's initial estimation. The final displacement between images is calculated from the 60 individual calculations. In the region of overlap the computer merges data from the two images to give a smooth transition. The merged image is then stored and the process repeated to build strips of the mosaic. Once theses strips have been produced, they are joined in the same manner to yield the finished mosaic.

2.10 The human computer interface

To handle the VASARI images as well as the image processing routines a comfortable X-Windows based human computer interface has been developed /5/. It is designed for those who are not experts neither in programming nor in image processing.

The human computer interface offers a 'depository' where the digital images can be found, as well as a 'tool-box' with image processing functions included. The images and the tools are symbolized by icons (Fig. 2). The 'imagé icons are clicked with the mouse to get the quicklook of an image displayed. Drawing an area on that quicklook or moving that area makes the corresponding part of the high-resolution image be displayed in another window. When required a 'tool' icon is simply dropped with the mouse on an image. The result image is then automatically displayed.

The interface is able to adapt itself to a wide range of image processing functions for which it provides separate windows to enter relevant parameters. The functions are included by means of a configuration file. The image processing routines present in the tool-box can be easily 'chained' whereby the user is able to define its own specific image processing 'macrò-function to be used within its special application. The macro can be kept in the tool-box and handled as any other tool. Several image processing routines can be run at the same time, on the same machine or on several workstations connected by a local network.

2.11 The image storage

The storage of the large VASARI images (one high resolution black and white frame uses about 7 MB) turned out to be a key issue. In any case, the image files are losslessly compressed (factor 2 to 3:1).

Then, a 150 MB tape drive, a 2 GB exabyte tape drive or a 1 GB magneto-optical disk drive (Maxtor Tahiti) make it possible permanently to store the images. In practice, the read and write procedure on each of the storage devices turned out to be very time-consuming.

3 THE VASARI APPLICATIONS

To demonstrate the performance of the VASARI prototypes three main applications have been conducted. Actually, the number of applications of the system is steadily growing covering all areas of nondestructive investigation of '21/2' dimensional objects of art.

3.1 Colour calibration and colorimetric acquisition

Each point in the image must be assigned accurate colour coordinates. It was decided that data should be converted to and stored in a recognized colour notation. The colour system chosen is the Commission Internationale de l'Eclairage (CIE) XYZ standard colour space 161. Since other CIE colour co-ordinates, for instance L*a*b*, may be derived from the values of XYZ, the latter is a sensible choice.

For a given pixel, the tristimulus values (X, Y and Z) can be derived from the camera response through seven filters X_1, X_2, ...X_7 by matrix multiplication. Thus:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} f_{X1} & f_{X2} & f_{X3} & f_{X4} & f_{X5} & f_{X6} & f_{X7} \\ f_{Y1} & f_{Y2} & f_{Y3} & f_{Y4} & f_{Y5} & f_{Y6} & f_{Y7} \\ f_{Z1} & f_{Z2} & f_{Z3} & f_{Z4} & f_{Z5} & f_{Z6} & f_{Z7} \end{pmatrix} \cdot \begin{pmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \\ X_7 \end{pmatrix}$$

The colour calibration routine calculates the values Of f_{X1} to f_{Z7} in the conversion matrix above. This is achieved by imaging a series of seven colour standards from a Macbeth ColorChecker Chart (with known XYZ values) through each of the filters. The response to each colour through each filter (X_{11}, X_{12}, X_{77}) is combined with known XYZ values for the seven colours (X_1, Y_1, Z_1, ..., X_7, Y_7, Z_7) to generate the transpose of the conversion matrix. Thus:

$$\begin{pmatrix} f_{X1} & f_{Y1} & f_{Z1} \\ f_{X2} & f_{Y2} & f_{Z2} \\ f_{X3} & f_{Y3} & f_{Z3} \\ f_{X4} & f_{Y4} & f_{Z4} \\ f_{X5} & f_{Y5} & f_{Z5} \\ f_{X6} & f_{Y6} & f_{Z6} \\ f_{X7} & f_{Y7} & f_{Z7} \end{pmatrix} = \begin{pmatrix} X_{11} & X_{12} & X_{13} & X_{14} & X_{15} & X_{16} & X_{17} \\ X_{21} & X_{22} & X_{23} & X_{24} & X_{25} & X_{26} & X_{27} \\ X_{31} & X_{32} & X_{33} & X_{34} & X_{35} & X_{36} & X_{37} \\ X_{41} & X_{42} & X_{43} & X_{44} & X_{45} & X_{46} & X_{47} \\ X_{51} & X_{52} & X_{53} & X_{54} & X_{55} & X_{56} & X_{57} \\ X_{61} & X_{62} & X_{63} & X_{64} & X_{65} & X_{66} & X_{67} \\ X_{71} & X_{72} & X_{73} & X_{74} & X_{75} & X_{76} & X_{77} \end{pmatrix}^{-1} \cdot \begin{pmatrix} X_1 & Y_1 & Z_1 \\ X_2 & Y_2 & Z_2 \\ X_3 & Y_3 & Z_3 \\ X_4 & Y_4 & Z_4 \\ X_5 & Y_5 & Z_5 \\ X_6 & Y_6 & Z_6 \\ X_7 & Y_7 & Z_7 \end{pmatrix}$$

A colorimetric image of a painting is built in two distinct phases, acquisition and calibration. During acquisition, images are made of the painting and a set of calibration charts through each of the seven filters. The calibration charts, which are mounted with the painting on the easel, are a white reference, a resolution target, a grey scale and the Macbeth colour standard. In the calibration procedure, thé workstation first corrects all of the images for non-uniformities in the distribution of light, then analyses the images of the gray scale to generate correction tables to remove non-linearities in the response of the CCD. The seven corrected images of the Macbeth chart are used to calculate the colour correction matrix described above. This matrix is then used to convert every sub-image of the painting to XYZ colour space. The corrected sub-images are joined using the mosaic assembly routine described previously. Finally, an image of the whole painting which can be displayed on the workstation's screen is calculated from XYZ image.

A comparison of colorimetric images recorded at different times allows an assessment of colour change to be made.

3.2 Detection of transportation damages

A second application is the detection of transportation damages. While actually most of the effort is spent to optimize the transportation procedure or to understand the physical and mechanical behaviour of paintings during transportation /7/ only very little attention is paid to the actual condition of the painting before and after transportation. The condition reports usually are based on written or drawn observations which are in some cases enriched by polaroids or photographs. These photographs are often taken under insuitable, irreproducible conditions /8/. To improve this, recently the use of a laser scanner has been proposed to record the paintings condition before and after a transportation and then to compare the digital images /9/.

Within VASARI, the same idea is translated into a different technical solution. Following daily experience images of very high resolution (22 pixel/mm) are used to locate damages. However, the computer is supporting our visual perception which is not good in comparing very similar images.

The full painting is digitally imaged before and after transportation. To allow any comparison a careful and precise repositioning of the painting is crucial. This is mainly done by the mechanical repositioning system described above.

In most of the cases a geometrical correction (i.e. resampling) of the two images is required. Satisfying results were achieved by resampling in two steps using classical correlation techniques: The first step is a rough approximation by using shrunken images, the second uses several zones of the high resolution image to be resampled.

A change in cracks and losses is used to locate any damages. This requires that the computer is able to identify the surface texture of the painting. Cracks usually show detectable contrast to the surrounding area of rather homogeneous brightness. This can be used to separate the texture from the depiction itself. To detect surface texture several software tools have been developed which mostly are derived from mathematical morphology /10/. Originally designed for binary images, advanced procedures are used to process the VASARI greylevel images. The most suitable algorithm acts like a 'hat' which is moved along the greylevel function of the image. Parameters allow the control of the size of the details to be detected and their contrast (i.e. the dimension of the 'hat') /11/. A second useful algorithm implemented is that proposed by Vanderbrug where 14 specially designed masks are used to detect texture /12/.

Finally, the texture extracted from the two images is compared and overlayed to the original image (Fig. 2). The damages then appear in colour. So far, the evaluation procedure described is still time-consuming and in an experimental state. However, within several case studies close to 'real transportation situation' damages such as microcracking, crack prolongations, flacking, scratches and losses could be evidentially proven /13/.

3.3 Computer-aided learning

A third application is the use of VASARI images within the field of computer-aided learning in the history of art. So far, most computeraided learning programs are electronic versions modeled on the concept of the book and the interactivity of television, however significant development can be expected from electronic digital imaging technologies.

The aim of this application was to acquire and process the VASARI 24 bit images on a UNIX workstation as described, but to provide these images to the common user on a 386 PC (33 MHz in 24 bit under Windows 3.0). The images are handled with the Superbase 4 data base system. Commercially available software programs (PhotoStyler and Photoshop for the Macintosh) allow an easy 'improvement' of the images (such as sharpening, smoothing and more powerful functions). Other applications are quick reconstructions such as placing a painting into a different frame or recreating an altarpiece from its constituent panels. Patches of local colour can be selected, cut and juxtaposed with other selected areas for comparative purposes. The multiband VASARI images permit accurate calculations and display as to what an painting would look like under different illuminants.

3.4 Other applications

The limited space of this contribution does not allow to go deeper into other applications. So far, the VASARI system has been used to improve the readability of β-radiographies, or to assemble x-radiographies for publication purposes. The Munchen prototype showed its modular capability, when recently being equipped with a Hamamatsu vidicon to generate mosaics of infrared-reflectograms /14/.

4 CONCLUSION

On the one hand, the VASARI project led to a considerable input from the very advanced field of information technology in the 'archaic' conservation and museum world. Unexpectedly, on the other hand the user-driven approach provided challenging tasks and unusual new views for the computer science and high-tech industries involved. Thirdly, the European commission saw that the interdisciplinary approach of VASARI opens possible future markets for the European information industry as well as new perspectives for the European consumer interest in culture in general.

Technically, the VASARI prototypes fulfil most of the user requirements. This is especially true for the image acquisition system, the image processing software and the user interface. For technical and financial reasons, there is still a weakness in image storage, output and data base. It is to be expected that these problems will be overcome during the follow-up project MARC (Methodology for Art Reproduction in Colour, ESPRIT III) which is ready to be signed.

From a conservation point of view, the VASARI project opened so-far unexplored continents. We are still at the beginning of these expeditions, but recent results proved that colour changes in paintings induced by optical light as well as transportation damages can be detected by the VASARI system.

The VASARI project has clearly underlined the future significance of the use of digital imaging in the field of conservation, the visual arts and computer-aided learning. The new electronic digital imaging technologies provide conservators, conservation scientists and art historians with new sets of tools which may radically change their methodologies and approaches to the conservation, study and teaching of art.

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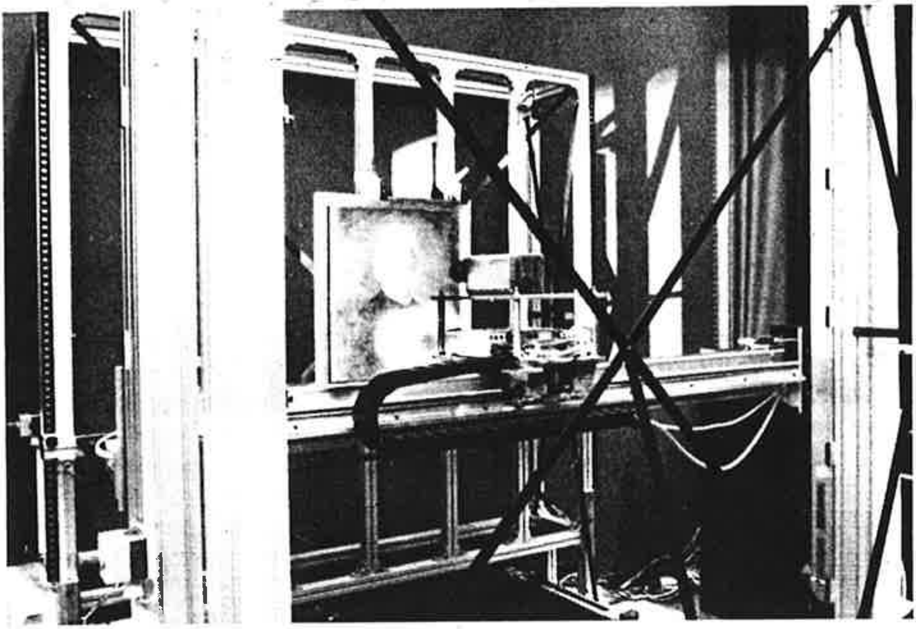

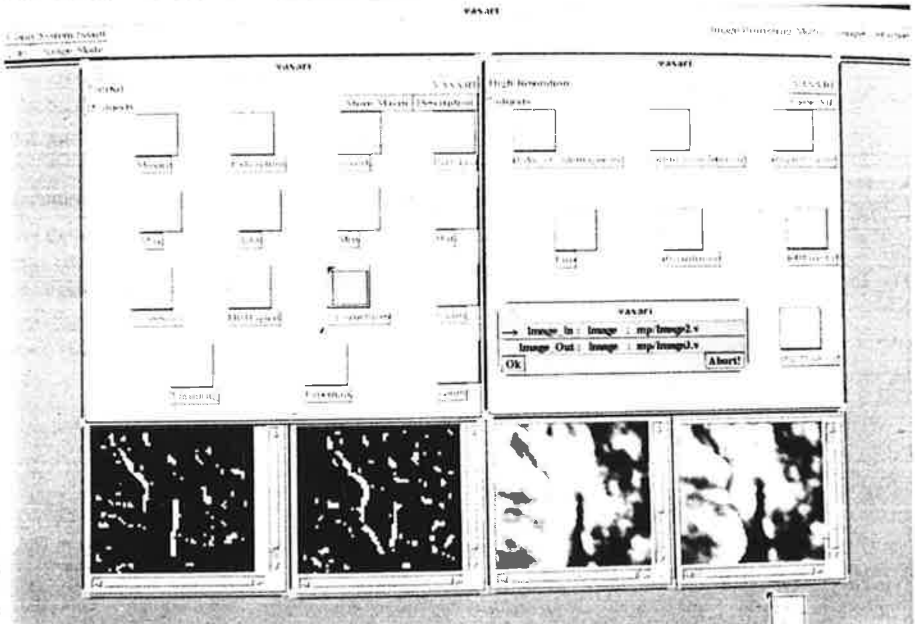

Fig. 1 - The Munchen VASARI acquisition system with a painting on the easel, and the Kontron ProgRes 3000 high resolution camera below the Hamamatsu Infrared camera on the positioning unit wherefrom the x and y axes are visible.

Fig. 2 - The VASARI user interface with image 'depository' and 'toolbox' with implemented VIPS and crack detection tools. The four VASARI images show the texture and the original detail (7 x 7mm with 22 p/mm) before and after transportation.