TEACHING OF MEASUREMENT BASED ON DIGITAL IMAGES

K. Marjanen, M. Mettänen, and H. Ihalainen

Department of Automation Science and Engineering, Tampere University of Technology, Tampere, Finland,
P.O. Box 692, FI-33103 Tampere, Finland

Abstract: This paper gives an example of an education strategy aimed at teaching image based measurement and increasing the awareness of the importance of systems thinking and uncertainty analysis in measurement based on images. The name of the course is Measurements Based on Digital Image.

Keywords: Education, image based measurement, uncertainty, digital camera, image analysis

1. INTRODUCTION

Acquisition, processing and analysis of digital images have become feasible and increasingly popular during the past decade. This is due to the remarkable development of computer and camera technology and due to new demands on different industrial sectors. The problem is to create useful measurement systems for the increasing demands using the technology available today and in the future. This means that the education of measurement technology has to address also the topics related to image acquisition and image analysis.

This paper introduces the undergraduate level course on image based measurement taught at the Department of Automation Science and Engineering at Tampere University of Technology (TUT). Our approach in education is quite broad, but aims to emphasize the systems thinking perspective and the importance of uncertainty and performance analysis in measurement, whether based on images or any other type of data. By systems thinking we refer to the conceptualization of the whole system, including the environment, the subject of measurement, data acquisition, data processing, and decision making based on the measurement information.

The paper is organized as follows. Section 2 describes the background of the work, including the advances and needs of industry. Section 3 relates our image based measurement course to the other image processing courses at TUT, and Section 4 introduces the contents and organization of the course. Section 5 discusses the teaching and learning experiences and draws conclusions.

2. BACKGROUND

The success of any industrial system depends on the user need for the system, feasibility, costs and availability. The demand for image based measurement systems rises from different fields of industry. For example, the process industry needs better understanding, modification and control of their processes and the process parameters. These needs come from increasing productivity requirements, competition and environmental points of view. The image based measurements provide a new insight to processes. The image based measurements can be combined with the current measurements and process knowledge thus providing new tools to meet the industry goals.

Recent hardware development: The image based measurement systems are now more feasible and their hardware costs have decreased while computational and other capabilities have significantly increased. This development is currently driven by the consumer markets. A short review of the recent and very important hardware development follows.

The computational capability of the common central processing units (CPUs) increased significantly during the last decade. According to [11] the computational efficiency is approximately 20 times that provided eight years ago. The current CPUs have several cores allowing running of multiple instructions at the same time. This decreases the overall computational time for programs and helps running several different processes such as image capture and analysis on the same CPU.

The computers have highly parallel graphics processing units (GPUs) to produce images for the user. The driving force has been the computer gaming industry trying to provide more realistic games for the consumers. The GPUs can be used for low level image processing and analysis instead of image synthesis only. They provide great possibilities for low level image processing. The GPU provides peak arithmetic and memory bandwidth compared to CPUs [8]. The computational capabilities of the current GPUs are between $100 - 2500$ GFlops with memory bandwidths $120 - 200$ GB/s. The GPUs are programmable using card producer's own languages such as NVidia Cuda [9] or more general frameworks such as OpenCL [10].

One important aspect of the computational capability development is the change from the 32-bit operational systems to 64-bit. Though the 64-bit systems did exist at the end of sixties, the breakthrough of the 64-bit systems occurred in the past couple of years. One of the advantages is the easy increase of the memory amount. The 32-bit systems have memory limit of 4 GB that might be to small amount when large amounts of image data combined with complex computational methods are needed. The current 64-

bit systems can easily have memory of 16 or 32 or 64 GB. These amounts of memory are still considerably lower than the theoretical maximum of 64-bit systems. Thus the amount of memory will increase in the near future.

The number of digital cameras has increased significantly during the last decade. Cell phone cameras, security cameras, machine vision cameras and compact and digital SLR cameras are widely used. The number of pixels is commonly between 1 – 30 MPix and the images are 8-16 bit color or monochrome images, while the price range is 50 – 20 000 eur.

The huge amounts of acquired image data can be collected to hard discs of size about 500 GB – 3 TB with the theoretical speed of 6 Gb/s. The most limiting resource seems to be the data transfer from cameras to computers by gigabit Ethernet or various USB systems. The machine vision camera producers have their special systems with grabber cards though.

Education: Availability of the image based measurement systems is then affected by the competence of people working in the industry and research organizations. The problem is to create useful systems for the increasing demands with the affordable and efficient tools accessible today. The education and research of the image based measurement answers the problem of availability.

The need for image based systems is widely recognized. University level education on image analysis has been described by e.g., [2,3,4]. They review the image processing methods that are being taught and emphasize the importance of instruction and practical experience in learning. Contributions with a practical aspect have also been seen in recent IMEKO conferences. Education on machine vision equipment has been presented by both universities and companies [5,6], and a simulation software for teaching camera calibration has been introduced by Samper et al. [7]. A topic that seems to have had little attention in these educational efforts, however, is measurement science. Image analysis can provide classifications and results that are taken as measurement results. The sources of uncertainty are often ignored, even though these results are incomplete without statement of uncertainty [1]. Our approach differs from most of the current teaching. The main difference is that we try to give a system approach to image based measurement & control systems accompanied with the concept and significance of measurement uncertainty and overall system performance.

3. RELATION TO OTHER COURSES

The education in image processing in universities is typically organized by departments of computer science, information technology or signal processing. Also at TUT, the Department of Signal Processing is responsible for most of the courses on image and video processing and pattern recognition. The Department of Production Engineering offers one course in machine vision and optical measurements, and the Department of Physics has several courses on optics. As the areas of expertise of our department include process automation, microsystems, systems analysis, measurement technology and

measurement information, it is natural that we provide the course on image based measurement. It complements the selection of courses related to cameras and image processing at TUT and offers the students a practical view of applying the image analysis methods to extract information from images. It is also our responsibility to keep in mind the uncertainties related to data acquisition and measurement information during the course.

The course is directed to undergraduate students who have some knowledge of image processing and of using MATLAB® which is the programming language applied on the course. Basic skills in linear algebra, statistics and measurement technology are also recommended. Often the participants have some measurement technology courses passed, typically as a minor. After completing this course, the students should be able to specify the basic hardware and software components of image based measurement systems and evaluate the whole system performance at some level. The organized systems thinking perspective provides a good framework for further studies in image analysis and also for working life.

4. ORGANIZATION OF THE COURSE

The image based measurement course familiarizes the students with the systems thinking and system performance analysis, the properties of the camera as a sensor, and some selected computational methods providing easily understandable results. Both theoretical understanding and practical experience of measurement systems are actively pursued. This section is divided into three subsections; the first one describes the topics of the course mentioned above, the second subsection describes how the teaching is implemented, and the third subsection briefly introduces two examples which are discussed on the course and which link the teaching to the ongoing research at the department.

Topics of the course: The image based measurement system is considered to have two subsystems. These subsystems are the imaging system and the computational system. The imaging system usually contains the camera and the illumination system. The design of the imaging subsystem is based on the requirements set by measurement task, object properties and environmental properties. The object properties include optical properties (reflectance, transmittance), movement, size, and shape, to name a few. The environmental properties include the optical properties of the medium, vibrations, presence of explosive or burning materials and variation of the external light. The need for imaging system protection rises from the environments having corrosives, moisture, water etc. present.

The computational system is designed to respond to the system requirements set by the measurement task. The common requirements are related to computation time, uncertainty levels, probability of correct decision, size of the computational unit, data transfer rates and types, and energy consumption. The choice of the algorithms depends on the knowledge and tools available to the system designer. The image formation has its effect on the selected algorithms also. Often the choices are evaluated and adjusted iteratively. The computational methods taught in this course are shortly

introduced later in this section. The overall mechanics and the reliability of mechanical, electrical and software components are topics that fall outside the scope of the course.

The teaching about the camera as a sensor contains several aspects of image formation. The following aspects are considered: the detection and properties of light and color, properties of the imaging through medium, geometrical image formation [13] and geometric calibration [15], sensor noise properties [12], cameras as linear systems and the effect of movement on image quality [11].

The selected image processing and analysis methods contain pre-processing, general two-dimensional (2-D) linear systems, 2-D sampling and 2-D transforms. The pre-processing methods contain zero-phase 2-D filtering [17], corner and interest point operators [21], affine and projective geometrical transforms [14], gray scale interpolation [16] and the basics of image registration. The analysis methods contain detection of geometrical shapes, 2-D power spectral analysis, orientation analysis, texture analysis and basics of the thresholding, segmentation, classification and statistical decision making. A very limited tutorial of fitting different models specially to 2-D data is given. Two 3-D measurement methods are briefly visited, namely the photogrammetric stereo [14] and the photometric stereo [18].

The selection of the image processing and analysis methods is based on our prior experience on measurement based on digital images and random signal analysis. The selected analysis methods can provide a set of as simple as possible measures that should describes the measured phenomenon well. These measures include simple statistics of different phenomena such as mean particle size and variance, particle shape distributions, orientation and vector field analysis combined with local circular statistics [20] and mean and median wavelengths and variances as function of wavelength (or spatial frequency) to name a few. A short philosophical point of view about selecting as good as possible measure set is also given.

The main principles of the photogrammetric and photometric stereo are presented to the students. The better understanding of these methods would need more lectures and exercises even some crucial parts are considered in more detail.

Teaching: Teaching is implemented in the form of weekly lectures, and right after the lectures there is a 2-hour exercise session. Some exercises start with using a camera to acquire images, which is instructed by the teacher but performed by the students. The main part of each exercise session consists of image processing and analysis by MATLAB. The exercises have a problem-based approach and they promote interaction between the students and the teacher. The grading of the course is based on the final exam and on the project assignments in which the students follow up a specific image based measurement system and examine the solutions to a specified measurement task.

The number of participants on the course is approximately 15 each semester. The students usually have varying levels of prior experience in MATLAB programming, and they are often found to lack knowledge in

linear systems, linear algebra and statistics. This course is an excellent opportunity to develop these skills, due to the following reasons: (1) There are weekly exercises with MATLAB, supervised by the teacher, (2) the number of students is rather small, and thus everyone can have assistance with the exercises, (3) the topics are very practical. Practicality arises from the fact that most of the theoretical topics presented in the lectures are done in the exercises.

Examples: In the following we present two examples of the applications in which product quality has been successfully characterized through image based measurement. These applications are used as examples of different kind of image based measurement task. The first example contains a full system approach and the second example is more analysis oriented in our teaching.

The first example is the on-line measurement of paper surface topography and surface fibre orientation. It is an ongoing research case that encompasses several important features of an image based measurement system. The task consists of acquiring micrometer-resolution digital images of a paper web moving 25 m/s and estimating the surface topography and surface fibre orientation based on the images. Using 100 ns flashing light pulses to illuminate the target ensures that the paper has not moved more than 2.5 µm during the exposure time, which provides the necessary spatial resolution. The images taken with inclined illumination from at least three different directions are used to estimate the surface gradients. They reveal the small-scale shape, i.e., topography, of the surface, as well as the orientation of the surface fibres. The camera, data transfer, and computation should be of high enough speed to produce at least 25 frames per second. Multi-camera system can provide more samples if higher frame rate is needed. The surface topography and orientation distribution are computed on-line. Part of the data can be stored for further analysis if necessary. Illumination, which is the critical part of numerous image based measurement systems, needs to be efficient to ensure an adequate signal-to-noise ratio. The illumination direction affects the fibre orientation estimates,
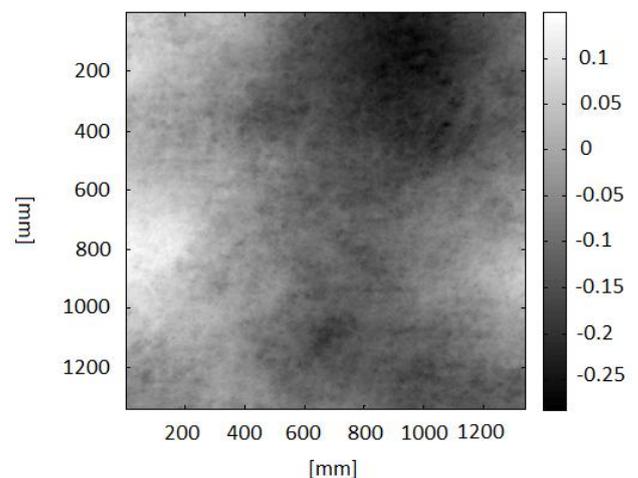

Figure 1. Measured topography of the paper. The horizontal and vertical axes contain the position of the topography measurement as [mm]. The gray scale values correspond to the height of the topography as [mm] and can be interpreted using the colorbar.

which is one of the most prominent challenges of the measurement at the moment.

An example of the measured paper surface topography is shown in Fig. 1 and an example of the paper surface fibre orientation distribution is shown in Fig. 2.

The second example concerns the measurement of paper surface topography. The motivation to measure the surface topography – either on-line in the paper manufacturing or converting process or in the laboratory – is that the topography affects print quality. This has been recently investigated in [19] by the joint statistical analysis of aligned maps that present the paper surface topography before printing and the local print density after printing. These micrometer-scale maps have been acquired by a photometric stereo imaging system that consists of a systems camera and inclined illumination from four directions. The measurements have been done before and after printing, and aligned thereafter. The image based measurements provide a massive number of data points (pixels) through which reliable statistical analysis is possible. Fig. 3 presents an example of the joint histogram of surface height and print reflectance (density is proportional to the negative logarithm of reflectance). The figure also illustrates the parametric Gaussian mixture model (GMM) fitted to the bivariate data. This method has been used to estimate the mutual information (MI) between surface height and print reflectance. Comparing this generic dependence measure against the linear dependence measure (correlation coefficient) within the image data has shown that the linear measure usually gives a good approximation to MI. It has also been shown that the dependence between print quality and the local surface heights is statistically significant. Thus, image based measurements that combine modern imaging equipment with a great deal of computational power have enabled results that would not have been feasible using the traditional point-wise measurements of paper industry.
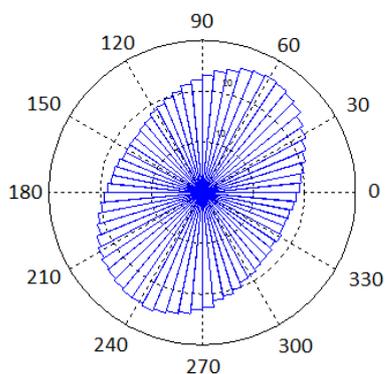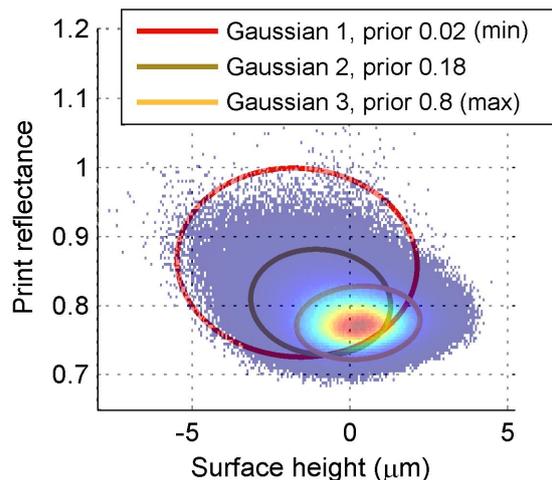
Figure 3. Histogram of the aligned measurements of print reflectance and local surface height of the paper. Negative heights denote pits on paper surface and they are often related to high reflectance, i.e., missing printing ink.

5. DISCUSSION

The teaching of the measurement based on digital image has continued several years and some conclusions can be made. The knowledge about the digital image and camera based measurement systems has been spread to approximately 150 students during the existence of the course. The careers of these students are mainly unknown, but about 10 % work in areas related to image processing, quality, enhancement and measurement thus responding to the needs of industry and research.

We feel that the hands on training on imaging, lighting and programming is a necessity for the good learning outcome. The understanding about the image based measurement systems comes from the strong theoretical background combined with reality roughly met in practical exercises. The treatment of the measurement uncertainty should be more rigorous on this course. The uncertainty treatment is somewhat limited to the recognition of different error sources and their relative significance on the measurement. The main challenges are the computational algorithms that are often composed of linear and non-linear components and their full treatment is practically out of the scope of the course.

The future has to be considered in the university level education. The future of the image based measurement teaching depends on the organizational and funding politics, general economical situation, industrial need for the camera based systems, and the general development of the field of image based measurement, image processing and optics research, to name few. The technical future of image based measurement and control systems might contain massive cheap on-line multicamera systems, massively parallel computational units, low energy and wireless camera and measurement systems, increased demands for complex computational methods, real-time measurements and minimal measurement uncertainty. These factors create challenges for the teaching of measurement based on digital image – challenges that have to be met in the next few years.

Figure 2. An example of the estimated surface orientation distribution. The surface fibres are oriented in the mean direction $\mu_d = 159.03^o$ and the having moderate orientation strength with circular variance $v_d = 0.36$.

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