Remote laboratories for optical metrology: from the lab to the cloud

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Abstract. The idea of remote laboratories is reviewed, and the potential of the approach on selected examples with special focus on the field of optical metrology is illustrated. The concept of remote metrology is extended beyond the simple exchange of data between distant laboratories and the remote access to experimental facilities embedded in modern educational concepts. We describe an architecture that provides the opportunity to communicate with and eventually control the physical setup of a remote metrology system. We show that such a concept can be implemented within cloud-computing environments, and may extend their current performance by the access to experimental facilities. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.OE.52.10.101914]

1 Introduction

The idea of remote optical metrology has been reported as early as 2000 with a conceptual illustration using comparative digital holography, aiming at the remote comparison of two nominally identical but physically different objects.[1,2] However, the concept of remote metrology can be extended far beyond this, as it not only allows for the transmission of static holograms over the Internet, but also provides an opportunity to communicate with and eventually control the physical setup of a remote metrology system. Furthermore, the metrology system can be modeled in the environment of a three-dimensional (3-D) virtual reality using CAD or similar technology providing a more intuitive interface to the physical setup within the virtual world. An engineer or a scientist wishing to access the remote real-world system can log on to the virtual system, moving and manipulating the setup, and take the desired measurements. The sets of data gained in the measurement process are stored and interpreted automatically for appropriate display within the virtual world providing the necessary feedback to the experimenter. Important metadata, including a description of the setup, the objects under investigation and all relevant system parameters, simultaneously generated by the system, can be recorded automatically to support the processing of the data or the future reproduction of the experiment for verification purposes, even by the third parties. Such a system opens up many novel opportunities in industrial inspection such as remote master-sample comparison or the virtual assembly of parts that are fabricated at different locations without the need for transportation and actual physical assembly. Moreover, a multitude of new techniques can be envisaged, and among them advanced ways for the documenting processes, the efficient methods for metadata storage, the possibility for remote reviewing of experimental results, the addition of real experiments to publications by allowing remote access to the metadata and to the experimental setup via the Internet, the presentation of complex experiments in classrooms and lecture halls, the sharing of expensive and complex infrastructure within international collaborations, new ways of remote testing of new devices for their maintenance and service, and many more.

In this article, we describe the architecture for a remote metrology system with a special focus on the support of the whole scientific workflow, from the actual experiment and collection of data, the analysis and interpretation of the data, to the publication of the results including the raw data for dissemination to and reproduction by the third parties. We show ways of implementing such a system within a cloud-computing environment, effectively adding access to experimental facilities to the cloud paradigm. Furthermore, we outline the potential of such an implementation, and describe the advantages based on the example of the master-sample comparison using inverse fringe projection,[3,4] comparative holography,[5] and digital holographic microscopy.

2 Some Reasons to Have Remote Access to Experimental Facilities

Optical metrology has been shown to be a versatile tool for addressing many inspection problems.[6] The main advantages of optical methods are their noncontact, nondestructive, two-dimensional working principle, their fast response, high sensitivity, resolution, and accuracy. However, optical measurement technologies are currently faced with numerous challenges. Special attention is directed to the continuous reduction of feature sizes to be measured, the increased complexity of items to be inspected, the need for in-line inspection systems in partially hostile environments, the increased globally distributed activities of worldwide operating enterprises, and the associated trend of drastic cost increase for appropriate measurement and testing facilities that is in conflict with the requirement for continuous decrease in costs of manufactured items. Consequently, a paradigm shift in using

measurement and in testing equipment has been a matter of discussion for several years. Some of the key issues include: is the pooling of expensive and complicated facilities an appropriate way to relax the cost and availability problem? Which prerequisites (technical or personnel) have to be provided to guarantee a feasible, safe, and reliable environment for remote access? Which challenges arise from the decision to deploy a remote laboratory? What additional benefits might be achieved following this approach?

Today's Internet technology provides a convenient way to develop an integrated network environment for remote laboratories using different robotic technologies. However, to be successful in real-world applications, Internet-controlled robots require a high degree of autonomy and local intelligence to deal with the restrictions of remote access via data networks with limited bandwidth and reliability.[7] The approaches discussed here refer to two aspects that are strongly connected with each other with respect to the required technical boundary conditions: the creation of a laboratory environment that can be shared by distant users having dedicated user rights for the execution of joint and/or single experiments, and the creation of a technology that allows one to connect distant measurement setups for remote metrology technologies. One advantage of such a remote laboratory environment is quite obvious: the pooling of expensive resources is an attractive way to save personnel and monetary resources. Moreover, in times of increasing global cooperation there are numerous other reasons to promote such a trend (see Sec. 7).

Joint international laboratories with so-called "world-machines" (e.g., ISPRA in Italy, CERN in Switzerland, and DESY in Germany) are already the state-of-the-art. But controlled remote access to physical facilities is still a matter of investigation. Especially, astronomers have done pioneering work in this field. The idea of a remote controlled telescope goes back to the early days of the Internet.[8,9] One example is the Bradford Robotic Telescope[10] that was installed between 2002 and 2004 at the Teide Observatory on Tenerife for remote use by schools, amateurs, and professionals worldwide. Most of the implemented systems have local autonomy. Consequently, a minimum transfer of information between the remote system and its controller is achieved, the so-called sheepdog approach. Based on adequate sensor technology, the telescope is not just remotely controlled but decides on the optimal program based on the current weather conditions and objects scheduled for investigation. Similar installations on Tenerife are the Stella I and Stella II robotic telescopes of the Leibniz Institute for Astrophysics, Potsdam, Germany.[11]

Remote instrumentation for grid computing has been investigated in a number of international projects since the turn of the millennium. RINGRID[12] and the follow-up DORII[13,14] project focused on the development of an Infrastructure aimed at the remote control of scientific instruments and the processing of the generated data in a grid. The GRIDCC project[15,16] designed an end-to-end pipeline mapping a user defined workflow for physical measurements and processing of data in remote instrumentation on a grid with particular emphasis on the predefined quality of service constraints, taking into account factors like available resources and their performance data. The VLab Virtual Laboratory project at the Poznan Supercomputing and Networking

Center[17] designed the Dynamic Measurement Scenario Language[18,19] to design a virtual laboratory from existing remotely available components and to define an experimental workflow within the so-defined system.

One example may illustrate the advantages of such a practice for a remote metrology laboratory. Consider a scenario in which we have to compare a sample with a master, and both parts are not available at the same location. In a first step, the relevant data (3-D shape and/or the response to loading) have to be measured at their current location and provided for comparison. One major advantage of the optical technology is the ability of recording the information required for the reconstruction of complex 3-D shapes and their deformations in the relatively simple form of a camera signal, well suited for transfer in data networks. Consequently, this information can be applied in remote comparison.[1] Digital holography, in particular, provides excellent boundary conditions for the remote master-sample comparison for all aspects: shape, deformation, and faultiness. The complete wave front (amplitude and phase) can be digitally recorded and transferred to make it available for comparative metrology.[20]

In the following sections, we present the technical background, early implementations, and some applications of our remote laboratory. Here, we will find a good technical basis in current cloud-computing activities. But we will also discuss some extensions of the available technology with respect to the inclusion of real experimental facilities.

3 Principles of Cloud Computing

The underlying concepts of cloud computing date back to the early 1960s. John McCarthy stated in his speech at the MIT Centennial in 1961, "If computers of the kind I have advocated become the computers of the future, then computing may someday be organized as a public utility just as the telephone system is a public utility." As a definition, we can take the explanation of the U.S. National Institute of Standards and Technology (NIST):[21] "Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction." Cloud computing refers to the following three aspects:[22]

- The illusion of infinite computing resources available on demand.
- The elimination of an up-front commitment by the cloud user.
- The ability of paying for use of computing resources on a short term basis as needed.

The goal is to provide virtual computing resources as a utility over the Internet. Consequently, the cloud is a synonym for the Internet. Three basic levels of service can be distinguished and defined by the types of capabilities that are provided:[23]

- Hardware as a Service: Access to complete computer systems, grids, or data centers. The user can install and run their own system and software as needed (e.g., the Google App Engine[24] or the Amazon Elastic Compute Cloud Amazon EC2[25]).

- Software as a Service: Access to software or applications. The actual hardware and platform remains completely transparent for user (e.g., Google Doc[26]).
- Data as a Service: Access to data for storage and semantic access over the net (e.g., Google's Bigtable[27]).

With the concept of cloud computing, several supposed advantages for the user are announced including global access to (unlimited) resources, decreasing IT costs, decreasing energy consumption, improving service quality, simple adaptation to customer-specific needs, and centralized resources. However, the restrictions of such an implementation are obvious: the access is limited to computer resources (computing power, software, data storage, and service). Embedding external facilities is not intended in that concept. Therefore, our approach extends this paradigm by adding noncomputational hardware, especially physically existent scientific facilities to the cloud (see Fig. 1).

4 Remote Laboratory Concept

Various implementations of remote laboratories are being investigated and have begun to be employed (see, for example, Refs. 28–32). Concepts of e-distance or online learning play a central role in existing implementations. In the field of chemistry and chemical engineering, such weblabs have been widely employed for education in different curricula at many universities including MIT in the US[23] and the University of Cambridge in the UK.[33,34] However, we are convinced that there is additional untapped potential in the remote laboratory concept beyond distance learning and digital education.

With the further development of the Internet beyond 100 Gbit/s transfer rates and software for remote control, the way is open for progress toward the building and connection of efficient remote metrology systems. We have implemented such a system based on digital holography and fringe projection. Our prototype, developed within the framework of the BW-eLabs project,[35,36] does not intend to implement all the functionality stated above in the current project phase. The current system implements a remote experimental setup that can perform deformation measurement on small objects such as MEMS under various loads on a nanometer scale[37] and 3-D holographic microscopic imaging of (e.g., biological) samples on a micro scale[38,39] by providing universal access through the Internet. Digital
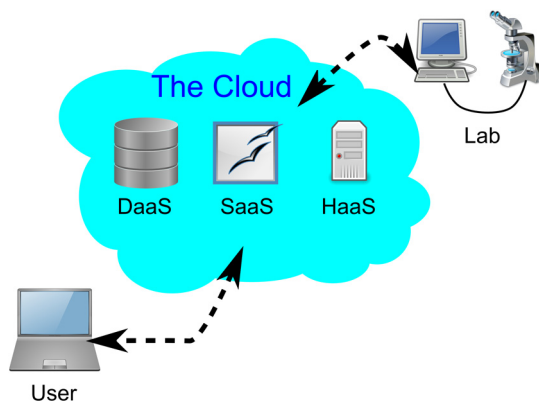
holography offers several fundamental advantages in the field of microscopy, ranging from increased contrast in the phase reconstruction mode for transparent objects to the inherent ability for aberration correction and numerical focusing in arbitrary reconstruction planes. The physical hardware is controlled through LabView,[40] and can be connected to a 3-D virtual reality, based on the open source project Open Wonderland.[41] Data storage and retrieval, including a search engine and metadata generation, are handled through the open source project eSciDoc.[42,43] The system is primarily designed for deployment in the field of scientific research, in particular for international collaboration in joint experiments. Nevertheless, it is equally useful in education.

5 Architecture of the Remote Laboratory

The system architecture for the remote lab is shown schematically in Fig. 2. At the heart of the architecture is the laboratory with the respective remote experiment (e.g., the digital holographic microscopy system) referred to as the "rig." The experiment is hidden behind a proxy server and firewall, and can be accessed directly only by an operator at the institute. The computer running the software necessary for controlling the physical experiment is invisible from the outside. All outside contact is handled by the proxy server, using a secure shell tunnel for encrypted secure data exchange. Users access the experiment through their client, starting the BW-eLabs GUI loaded from the BW-eLabs portal. Authentication to access the BW-eLabs executor and ultimately the rig is performed against the eSciDoc user database using Pluggable Authentication Modules and the Shibboleth single-sign-in system. eSciDoc is also responsible to check the availability of the experiment against the Booking Database before granting access to the user. In addition, the open source research environment eSciDoc also provides storage of and access to experimental data, passing data for automatic configuration of the experiment to the BW-eLabs executor, and access to the publication infrastructure of OPUS.[44] From the user's perspective, the functionality of eSciDoc is mostly transparent and working

Fig. 1 Connecting real-world laboratories to the cloud.
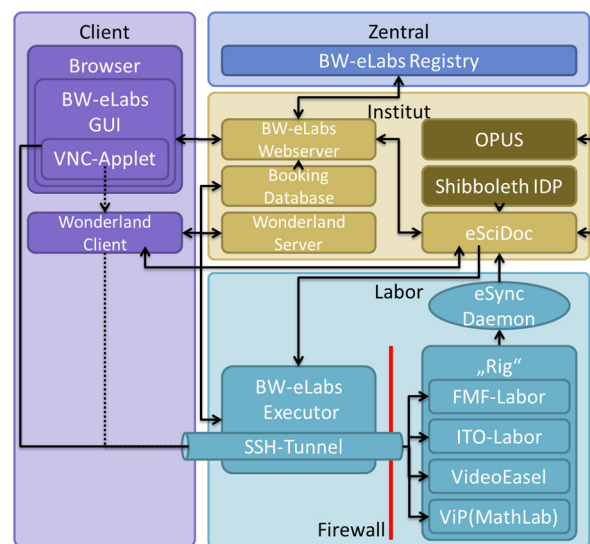

Fig. 2 Schematic system architecture and software components of the remote metrology laboratory.

automatically in the background. The coordinator has to provide a script defining the data, the format, and the metadata to be stored. It is very important to state that the so-called metadata providing additional information about one or more aspects (e.g., means of the creation of the data, purpose of the data, time and date of creation, author, location on a computer, format, used standard, etc.) are recorded automatically by the system and are stored together with the raw data through the eSync Daemon. The actual storage process and the corresponding retrieval process is fully symmetrical allowing not only access to raw data for analysis, but also to restore the complete state of the experimental setup (e.g., in the case of digital holographic microscopy: the object under investigation, its position, the focusing of the microscope, the parameters required in the reconstruction of the hologram, etc.). eSciDoc is accessible by generic users, providing search functionality based on metadata generated during the experiment. The roles and rights of users in eSciDoc are rather complex, and can be set individually for each experimental setup and each set of data (if desired) protecting against undesired third party access, while enabling collaboration between privileged partners. If a user has the rights necessary to access the rig and has the software necessary to analyze the data, he can reproduce both the actual experiment and the results from the stored data sets with their corresponding metadata. Finally, the user generating the data can decide to publish his data (raw data with associated metadata) through the OPUS document server software including the assignment of a persistent digital identifier (PID, in our case, a DOI) for online access.

6 Data Flow

Figure 3 shows the basic data flow within the BW-eLab architecture. The user logs on to the BW-eLabs portal. His login is authenticated against the eSciDoc database. Choosing an experiment and associating it with an investigation (basically a set of experiments which includes additional metadata such as organization, project, etc.) provides access via VNC to the physical experiment through the ITO-Proxy if the booking system allows it (the booking system is not yet implemented). At the same time, eSciDoc provides a first set of metadata to the BW-eLabs executor, including time stamp, user data, and the above-mentioned metadata. VNC provides direct real-time access to the LabView controlled setup. VNC was chosen for the prototype implementation since it provides generic access to the actual hardware and separates the question of hardware control from the generation, storage, analysis, reuse, and publication of experimental data, which this project focuses on. Running the experiment will generate raw data enriched with metadata, both the data generated before and data required to interpret the raw data or to reproduce the experiment. A simple software daemon watching a specified directory returns this data set through the ITO-Data Converter, a script that has to be provided by the operator of the experiment. The ITO-Data Converter produces an eSciDoc Item, a very flexible XML format that organizes the raw data and associated metadata for storage within eSciDoc. This eSciDoc item is consequently submitted to eSciDoc through the eSciDoc Deposit Service and stored. The user can choose to publish the data through the OPUS document server system. A PID is assigned, allowing direct access from a publication back to the data stored in eSciDoc.

7 Use Case Study

The system is defined by three main factors: user, coordinator, and generic user. The coordinator is a research scientist at the institute, maintaining and iteratively improving the experimental system. The user is a person who can access the remote system and perform a scheduled experiment, a role that can also be assumed by the operator. The generic user can be either the user, the coordinator, or a third person. The generic user will not be given access to the experimental setup, but is interested in the data stored in the repository or
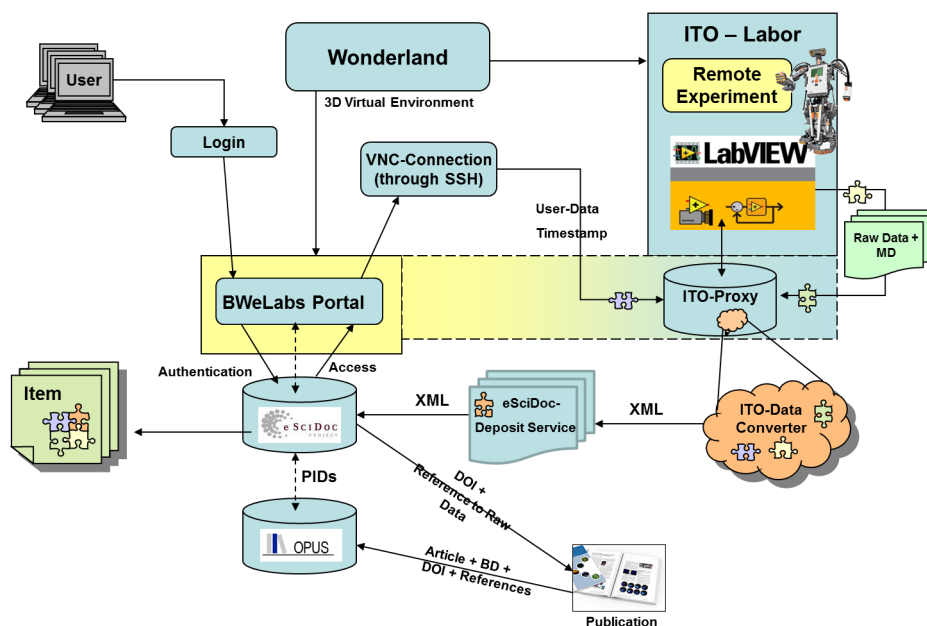

Fig. 3 Data flow in the BW-eLabs system.

database. For the user, the most important functionality of the system is the remote access to the physical experimental setup (Use Case: Perform Experiment) and the ability to store the data collected in the measurement process.

The generic user requires access to analyze the collected data online and upload the results to a repository (Use Case: Data Analysis), maintaining a link to the original data or to download directly to the user's local hard drive (Use Case: Access Library). In addition, the system also needs to have a function that accepts user registration (Use Case: Create Account) and reservation (Use Case: Request Reservation) for his or her experiments with security issues taken into account. Finally, the coordinator needs to be able to manage user registration information (Use Case: Manage Account), to schedule an experiment upon request (Use Case: Schedule Reservation), and, most importantly, to prepare the experimental setup (sometimes according to the user's special requirements) (Use Case: Prepare Experiment). The system also has additional interfaces to be integrated into a broader framework of the project, which are ignored in this use case.

8 Exemplary Applications

In this section, we describe selected applications for the remote optical metrology laboratory. In principle, the remote laboratory allows a wide variety of applications and services (see Fig. 4) including

- *e-Sharing*: Shared use of expensive facilities by partners in collaborative projects (for instance, the cooperation between experts coming from different fields such as optical metrology and artwork conservation with the objective to create more efficient technologies for artwork restoration and inspection[45–48]),
- *e-Comparison*: remote master-sample comparison (see Sec. 8.1),
- *e-Assembling*: measurement and digital joining of parts that are fabricated at different locations, but have to be joined at one place,[1,49]
- *e-Documenting* and *e-Publishing*: a new way of documentation and publication by addition of real-world experiments to publications providing remote access to the metadata and to the experimental setup via the Internet,[50]
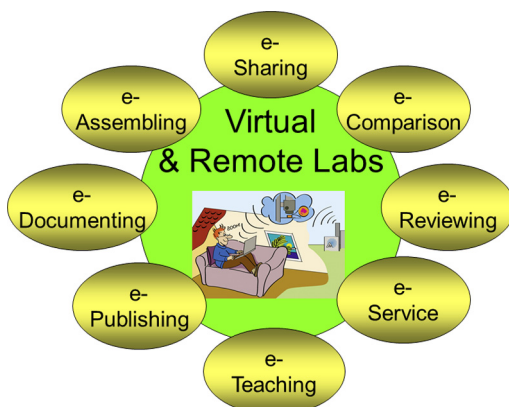
- *e-Reviewing*: reviewing datasets cited in publications by direct access to the experiment via the given URL and the delivered metadata,
- *e-Service*: remote testing of equipment, facilities and services for potential customers (tele-service[6]) prior to and after the purchase, and
- *e-Learning* and e-*Teaching*.[33,51]

Here, we limit our explanations to various aspects of the e-comparison referring to different basic technologies such as inverse fringe projection and comparative digital holography. Finally, we describe our digital holographic microscope for remote experiments.

8.1 Remote Master-Sample Comparison (e-Comparison)

The comparison of the shape of two nominally identical but physically different objects is a standard task in industrial inspection, the so-called master-sample comparison. In the case of objects having optically smooth surfaces, such as lenses and mirrors, holographic techniques have been applied for many years by implementing the so-called null test.[52] However, the optical comparison of industrial components having rough surfaces is a more complicated task. The application of interferometric techniques is limited to rather simple objects such as cylindrical shells. The difficulty consists in the difference of the microstructures of the objects to be compared. Due to the strong decorrelations of the interfering wave fronts, only a statistical intensity distribution will be recorded. Therefore, grazing incidence of light was preferred to reduce the interferometric sensitivity of the setup.[53,54]

In recent years, various methods have been developed that are based on fringe projection using conventional light sources.[55] An elegant comparison between master and sample can be performed if the inverse fringe pattern of the master object is used for the structured illumination of the sample object.[3,4,56] The inverse pattern can be calculated, for instance, by a special ray-tracing method that is based on a correspondence between the pixels of the CCD-sensor and the LCD/DMD-projector. If the sample object completely fits the shape of the master piece, the inverse projection delivers an equidistant and nondistorted fringe pattern. Every deviation between master and sample causes local distortions in the fringe pattern, which can be detected very fast by means of correlation and Fourier processing techniques, respectively. One example is shown in Fig. 5. The objective of the inspection process consists of the control of the settings of the valves in a cylinder housing [Fig. 5(a)]. The result with conventional structured illumination by an equally spaced linear grating is shown in Fig. 5(b), while Fig. 5(c) shows the calculated inverse mask that is fed to a spatial light modulator to generate the undeformed intensity distribution as shown in Fig. 5(d). This inverse pattern projection is applied to detect tiny misalignments of the valve heads [Fig. 5(e)]. A shift of only 50 μm [Fig. 5(f)] that is unseen by the unaided eye can be detected clearly by use of an optical correlator [Fig. 5(g)].[3,57] The inverse mask of the master can be simply used for comparison with a distant sample. For that purpose, the mask is transmitted through the Internet to the lab where the actual comparison with the sample is being performed. After loading the mask

Fig. 4 Potential applications for e-labs.
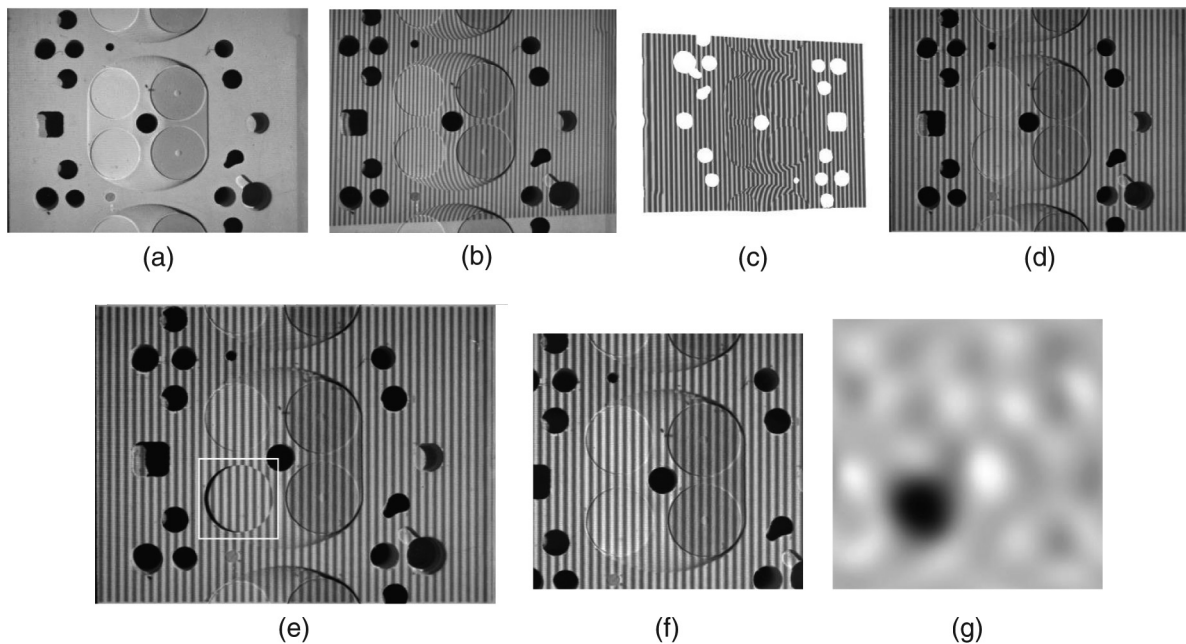
Fig. 5 Principle of inverse fringe projection using incoherent masks as the basis for the incoherent and remote master-sample comparison. (a) Cylinder housing with valve heads. (b) Structured illumination with an equidistant fringe pattern. (c) Calculated inverse mask. (d) Result after projecting the inverse pattern. (e) Displaced valve head (strongly exaggerated). (f) Slightly shifted valve head. (g) Display of the shifted valve head after correlation.

into a spatial light modulator and projecting onto the sample, only the differences between master and sample are displayed.

8.2 Remote Comparative Digital Holography

In contrast to the projected fringe technique (see Sec. 8.1), holographic interferometry offers another approach for shape control with interferometric sensitivity. However, the need for matching microstructures results in an important consequence for the conventional holographic procedure: the limitation to the comparison of an object with itself in two or several different states. Therefore, for the comparison of the shapes or the responses to a load of two nominally identical but physically different objects (master-sample comparison), it was necessary to evaluate the resulting interferograms independently and to compare the resulting data numerically. A more elegant approach, the so-called

Comparative Holographic Moiré Interferometry, was introduced by Rastogi[58] and Simova and Sainov.[59] The method is based on the incoherent superposition of the involved interferograms and the evaluation of the resulting Moiré pattern. The appearing Moiré fringes provide a direct indication of the differences between the both objects. However, the sensitivity of this method is limited due to the poor signal-to-noise ratio in the resulting Moiré image.

Comparative Holography[60,61] enables the direct detection of the deviations of two objects. Comparative digital holography[5] is a new method for direct holographic comparison of the shape or the deformation of two nominally identical but physically different objects. It is not necessary for both samples to be simultaneously present at the same location, consequently, remote shape and/or deformation comparison between a master and a sample is possible.[20,62] In contrast to the well-known incoherent techniques based on inverse fringe projection, this new approach uses a coherent mask
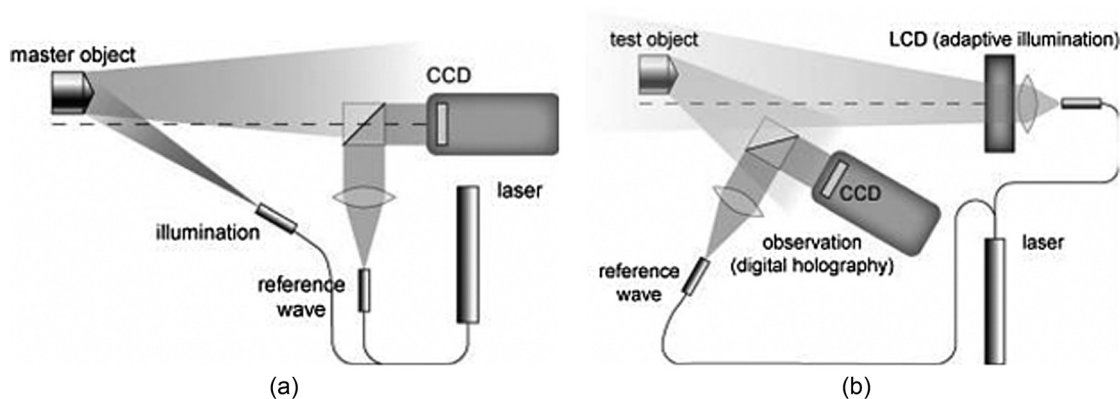
Fig. 6 Schematic setup for comparative digital holography. (a) Recording of the coherent mask of the master object. (b) Illumination of the test/sample object by the conjugate wavefront of the master object.
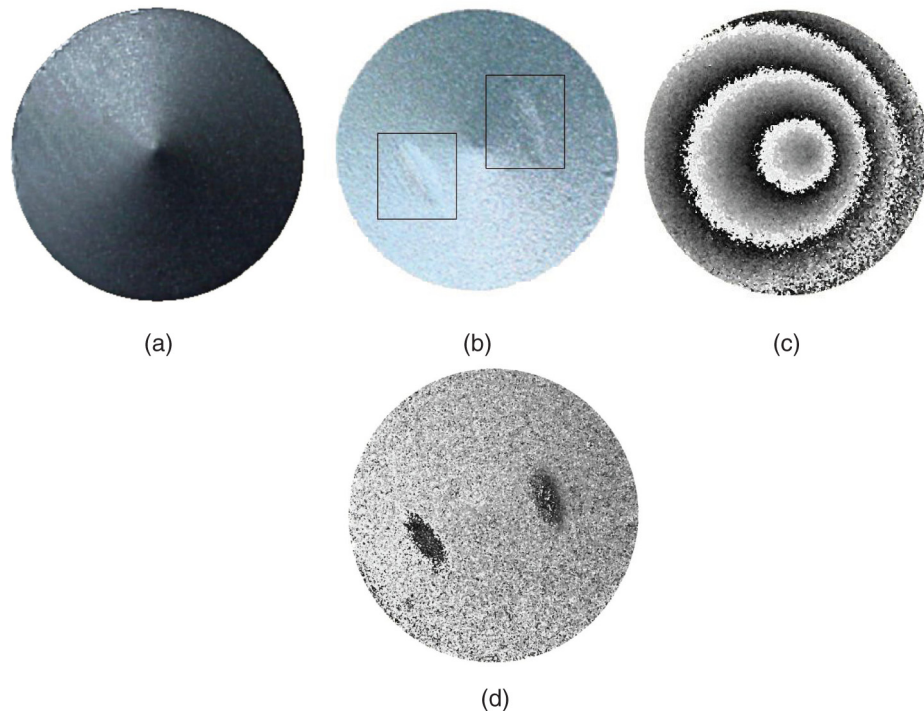
Fig. 7 Shape comparison between a master and a sample object by comparative and conventional digital holography. (a) Master object: cone without surface defects. (b) Sample object: cone with two surface defects. (c) Result after the comparative holography procedure, only the faulty parts are displayed. (d) Conventional holographic multiwavelength contouring of the sample object.

(hologram of the master) that is imaged on the sample object (holographic illumination). The digital availability of the complex amplitude enables the instant access to the complete optical information of the master object at any place needed. The transmission of the digital master holograms to the relevant locations can be done with a broadband digital telecommunication network.

At the place where the comparison takes place, the digital holograms of the master object have to be reconstructed by a suitable spatial light modulator such as a liquid crystal SLM or a digital micro mirror device.[57] Figure 6 shows the setups for recording the master-hologram [Fig. 6(a)], and for the holographic illumination of the sample object by the coherent master wavefront [Fig. 6(b)]. To reconstruct the conjugated wavefront of the master object, the master-hologram is fed to the SLM and the SLM is illuminated by the conjugated reference wave that was used for making the master hologram. This two-step procedure leads to an interferogram of the sample that indicates only the difference in shape or deformation between master and sample (Fig. 7).

In our example, the objects to be compared are two macroscopically identical aluminum cylinders with a cone at their upper end [Fig. 7(a)]. One of the cylinders has two small dents of some micrometers in the cone [Fig. 7(b)]. For the experiment, a synthetic wavelength of $\Lambda = 0.326$ mm was adjusted by the two single exposures with $\lambda_1 = 579.41$ nm and $\lambda_2 = 580.44$ nm. Due to the holographic illumination of the sample with the conjugated wave front of the master, the indicated difference phase $\delta(P)$ corresponds directly to the difference of the height deflections between master and sample in every object point. Consequently, the registered phase distribution indicates only the deviation between master and sample [Fig. 7(c)]. The

size of the detected deviations depends as well on the resolution of the used SLM and CCD and the size of the synthetic wavelength. In the described experiment, we detected height deviations of several 10 μm. Using the SLM, misalignment between the master and the sample can be compensated for by a corresponding phase shift of the reconstructed master wave front.[63]

A comparison of Fig. 7(c) with 7(d), the result of conventional holographic contouring, shows the advantage of comparative digital holography for shape comparison: only the difference in shape of two nominally identical objects
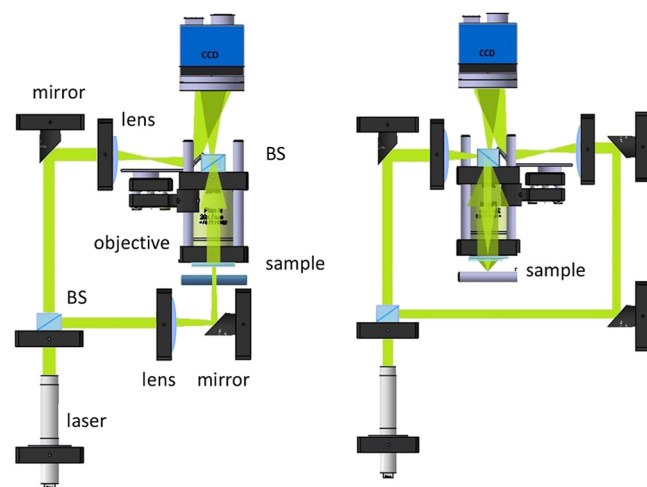
Fig. 8 Schematics of the experimental setup for the digital holographic microscopic system in the remote laboratory.
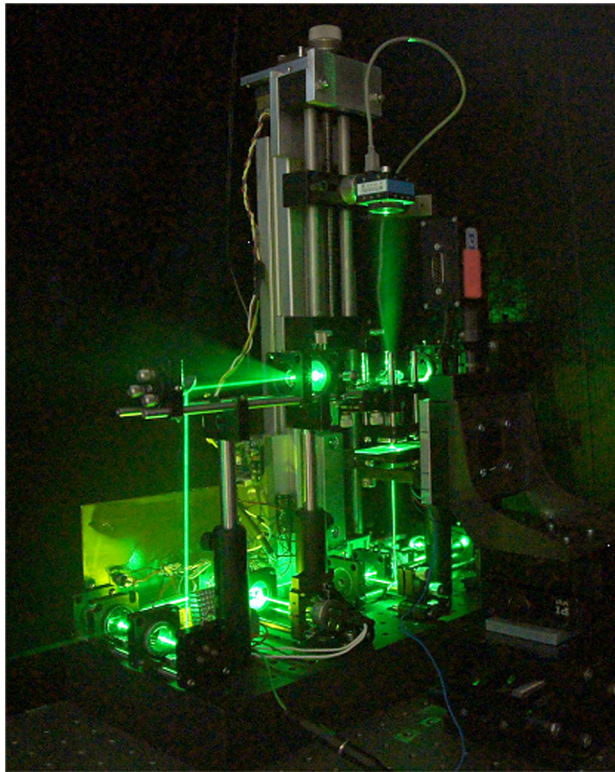
Fig. 9 Photo of the digital holographic microscope.

with various micro structures is displayed. The high level of noise is justified by the relatively large pixel size of the used LCD-modulator compared with the available CCD-sensor (CCD 9 μm and LCD 18 μm). The application of the principle for nondestructive testing (comparison of the response of two objects to the same load) is shown in Ref. 11.

9 Remote Laboratory for Digital Holographic Microscopy

In this section, we describe the functional implementation of the architecture focusing mainly on the setup of the holographic system for digital holographic microscopy and the configuration of the remote controlling (i.e., the "rig" in Fig. 2).[64] A digital holographic microscope was chosen as a proof-of-concept prototypical implementation. The requirements for controlling the setup are rather low, while providing useful functionality. The system already implements the complete holographic process, recording and reconstruction, including phase and depth reconstruction, necessary in the aimed for comparative holography. The experimental setup of the digital holographic microscopy system is shown in Figs. 8 and 9. The laboratory is embedded into the entire system BWeLabs for the data acquisition, storage, communication, and user interaction (see Fig. 3). A laser of wavelength $\lambda = 532$ nm is first divided into reference and object arms. The object arm fiber can be switched for different illumination modes, i.e., transmission mode or reflection mode, depending on the property of the object to be investigated. The object is imaged through a 20× /0.5 microscopic objective. The reference is coupled into the system using a beam splitter to interfere the reference beam with the object wave. The microscopic table is mounted on an electric-driven 3-D positioner (physical instruments) allowing the user to shift the field of view at submicron precision. A CCD camera (SVS16000 from SVS-Vistek) is placed above the microscopic table to record the hologram. The hologram is captured by the camera and is transferred to the computer for subsequent processing. Reconstruction of the object wave is performed numerically. The intensity pattern recorded in the CCD-plane is first filtered in the spatial Fourier domain removing the DC component and the conjugate twin image in the reconstruction. The filtered signal is inverse Fourier transformed, and then propagated and focused in
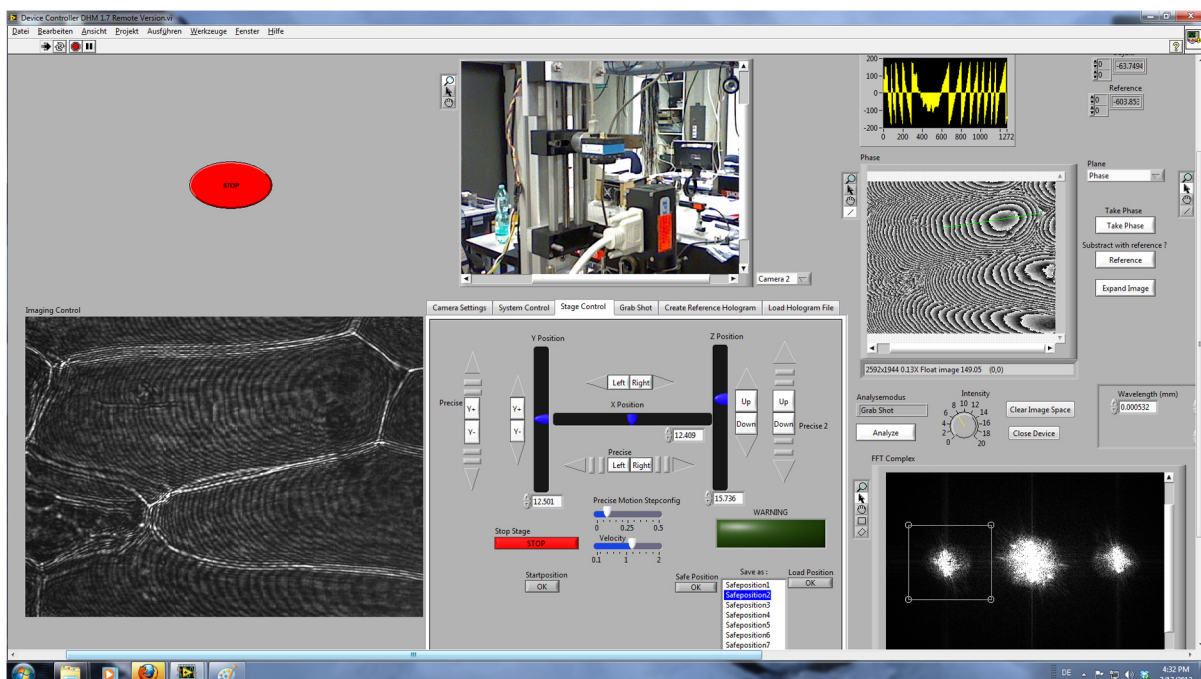

Fig. 10 Screenshot of the graphic user interface.

the object plane. A screenshot of the graphic user interface that is displayed on the remote computer to run the remote holography lab by the distant user is shown in Fig. 10.

10 Summary and Outlook

We have shown a possible extension of the cloud-computing concept by adding real-world facilities to the cloud. The facilities are embedded in a remote laboratory that provides the complete infrastructure for the remote access and data exchange. Such a system opens up many novel opportunities, e.g., in industrial inspection such as the remote master-sample comparison and the virtual assembling of parts that are fabricated at different locations. Moreover, a multitude of new techniques can be envisaged, and among them advanced approaches to documenting, the efficient methods for metadata storage, the possibility for remote reviewing of experimental results, the adding of real experiments to publications by providing remote access to the metadata and to the experimental setup via Internet by simply quoting the uniform resource locator in the reference list, the presentation of complex experiments in classrooms and lecture halls, the sharing of expensive and complex infrastructure within international collaborations, the implementation of new ways for the remote testing of new devices, for their maintenance and service, and many more. However, there are still several problems that have to be solved before the full potential of the remote laboratory approach can be realized. Among these is the need for the clarification of a series of legal questions such as IP rights, the definition and agreement of standards (protocols, 3-D user interfaces, data structures, data archiving, etc), and last but not least, the convention and implementation of safety standards for remote access to the infrastructure (the continuous availability, the facility and personal protection, and the access rights and authentication).

To match the remote laboratory concept to the cloud paradigm as closely as possible, certain provisions have to be made. Access to the actual laboratory should be as generic as possible. If there is more than one identical laboratory available, they should be indistinguishable to the user. Authentication should be similarly generic, not requiring local accounts. This is already provided for in the authentication against eSciDoc using Shibboleth, which allows for multiple eSciDocs as identity providers, thus allowing eSciDoc to move into the cloud. Data storage and access should be as flexible as possible with provision for either local storage under strict control of the user or on a global, transparent system for publication, a requirement also fulfilled by the option of multiple eSciDoc installations.

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