Remote Laboratories in the Cloud
A Digital Holographic Microscope

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Keywords: Remote Laboratory, Remote Metrology, Virtual Laboratory, Cloud Computing, Comparative Digital Holography, Optical Shape Measurement, Master-Sample-Comparison.

Abstract: Cloud computing introduces a new paradigm for using IT resources, the often quoted "everything as a service", where resources are leased and paid for on a time-limited ad-hoc basis. Related advances in information technology open up the potential of combining optical systems with net based infrastructures, allowing for remote inspection and virtual metrology. Coupling the cloud to physically existent laboratories provides universal access to non-virtual resources. In this paper, we report our recent work on building a remote laboratory for digital holographic metrology. We describe the architecture and the techniques involved in setting up the remote controlling metrology system. Further consideration will be given to the integration into an advanced infrastructure for remote experimentation, data storage and publication.

1 INTRODUCTION

Cloud computing can be defined by the following three aspects: "The illusion of infinite computing resources, available on demand", "the elimination of an up-front commitment by the cloud user", and "the ability of paying for use of computing resources on a short term basis as needed" (Amburst et al., 2009). The goal is to provide virtual computing resources as a utility over the net. Three basic levels of service can be distinguished, defined by the types of capabilities provided (Wang et al., 2008)":

1. Hardware as a Service (HaaS): Access to complete computer systems, grids or data centers is provided, the user can install and run his own system and software as needed (e.g. Google App Engine (Goo, a) or Amazon EC2 - Amazon Elastic Compute Cloud (Ama,)).

2. Software as a Service (SaaS): Software or applications are provided, the actual hardware and platform remains completely transparent for user (e.g. Google Doc (Goo, b)).

3. Data as a Service (DaaS): Access to data for storage and semantic access over the net is provided (e.g. Google's Bigtable (Chang et al., 2006))

In our work we are extending this paradigm, or, more precisely, Software as a Service, to include non-computational hardware, in our case a physi-
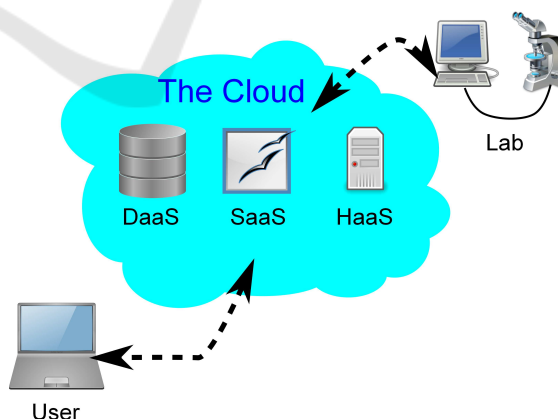

Figure 1: Accessing a remote lab through The Cloud.

cally existent laboratory for optical metrology (see Figure 1). However, the restrictions of such an implementation are obvious: the access is limited to computer resources (computing power, software, data storage, and service). The embedding of external, non-computational facilities is not addressed in the above concept. Therefore our approach extends this paradigm by adding non-computational hardware, in our case a physically existent laboratory for optical metrology (see Figure 1).

The idea of remote and virtual metrology has been reported as early as 2000 (Osten, 2000; Osten et al., 2001) with a conceptual illustration by use of comparative digital holography (Osten et al., 2002) , aimed at

the comparison of two nominally identical but physically different objects, e.g., master and sample, in industrial inspection processes. In a first step, a digital hologram of the master is generated and stored, allowing transmission through the Internet. This provides instant, global access to the complete optical information of the master object. For comparison, the master hologram is optically reconstructed using a spatial light modulator (Osten et al., 2002; Baumbach et al., 2006; Kohler et al., 2008) and projected onto a sample under inspection, resulting in interferometric patterns that can be analyzed to retrieve the difference between the master and the test object. However, the concept of remote and virtual metrology can be extended far beyond this. For example, it does not only allow for the transmission of static holograms over the Internet, but also provides an opportunity to communicate with and eventually control the physical set-up of a remote metrology system. Furthermore, the metrology system can be modeled in the environment of a 3D virtual reality using CAD or similar technology, providing a more intuitive interface to the physical setup within the virtual world. An engineer or scientist who would like to access the remote real world system can log on to the virtual system, moving and manipulating the setup through an avatar and take the desired measurements. The real metrology system responds to the interaction between the avatar and the 3D virtual representation, providing a more intuitive interface to the physical setup within the virtual world. The measurement data is stored and interpreted automatically for appropriate display within the virtual world, providing the necessary feedback to the experimenter. Such a system opens up many novel opportunities in industrial inspection such as virtual remote testing (Osten, 2000) and controlling.

With the development of broadband Internet and software for remote control, we are able to make progress toward this goal: to build a remote metrology system based on digital holography. Our prototype, being developed within the framework of the BW-eLabs project(Jeschke et al., 2011) , does not intend to implement all the functionality stated above in the current project phase. Instead, we are building a remote experimental system that can perform deformation measurement on small objects such as MEMS under various loads on nanometer scale, and 3D holographic microscopic imaging of (biological) samples on micron scale (Kemper and von Bally, 2008; Schnekenburger et al., 2007) 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 compared to intensity in trans-

parent objects such as biological samples to numerical focusing in arbitrary reconstruction planes (Langehanenberg et al., 200y; Kühn et al., 2009). The physical hardware is controlled through LabView (lab,) and will be connected to a 3D virtual reality, based on the Open Source project Wonderland (Won,) . Data storage and retrieval, including a search engine and meta data generation are handled through the Open Source project eSciDoc(eSc, ; Razum et al., 2009) . 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. In the field of chemistry and chemical engineering, such weblabs have been widely employed for education of various curriculum at many international leading universities including MIT in USA and University of Cambridge in the UK (Selmer et al., 2007) . We will not address the details of the security aspects implemented in the infrastructure, instead focusing on the technical aspects of the actual experiment, the remote control and the storage of the results.

2 APPLICATIONS FOR REMOTE LABORATORIES IN OPTICAL METROLOGY

In the following we will provide two examples for remote laboratories. The first, an application of comparative digital holography demonstrates how two objects in very distant places can be compared on a micrometer scale while the second is a proof-of-principle implementation of a digital holographic microscope.

2.1 Remote Comparative Digital Holography

Holographic interferometry offers a method for shape control with interferometric sensitivity. However, the need of matching microstructures results in an important consequence for the conventional procedure: the limitation to the comparison of an object with itself in different states, such as deformation from mechanical or thermal loading. 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 Moir Interferometry, was introduced by

Rastogi(Rastogi, 1984) and Simova et al(Sainov and Simova, 1989). The method is based on the incoherent superposition of the involved interferograms and the evaluation of the resulting Moir pattern. The appearing Moir fringes provide a direct indication of the difference between the both objects. However, the sensitivity of this method is limited due to the poor signal-to-noise ratio in the Moir image. D.B. Neumann published a completely new holographic technique in 1980, which enables the direct detection of the deviations of two objects with different microstructure. He called it Comparative Holography (Neumann, 1980). The innovative aspect of this method was the coherent illumination of every state of the sample with the conjugated wave front of the corresponding state of the master. The wave front of the master plays the role of a coherent mask for the adaptive illumination of the sample. Although the procedure has interferometric sensitivity its practical relevance is still low because of the complicated experimental background. A series of valuable contributions with respect to the improvement of this technique were made by Fzessy and Gyimesi(Füzessy and Gyimesi, 1984) who introduced the application of the double reference beam technique for the independent storage and reconstruction of both object states. In the following we describe the basic principles of Comparative Digital Holography(Osten et al., 2001) and show the advantages of this new procedure in examples dealing with issues of optical shape control. Furthermore the possibility of remote shape control by making the coherent masks globally by data transfer via the Internet is discussed. Comparative Digital Holography is a new method for direct holographic comparison of the shape or the deformation of two nominally identical but physically different objects(Osten et al., 2002). It is not necessary for both samples to have the same microstructure or to be simultaneously present at the same location. Consequently, remote shape or deformation comparison between a master and a sample is possible(Baumbach et al., 2006). In contrast to the well known incoherent techniques based on inverse fringe projection this new approach uses a coherent mask that is imaged on the sample object having a different microstructure, called holographic illumination. The coherent mask is created by digital holography to enable the instant access to the complete optical information of the master object at any place wanted. The transmission of the digital master holograms to the relevant locations can be done with a broadband digital telecommunication network.

The availability of the complete optical information of the master object in the form of a digital hologram offers two ways of comparing its shape and/or
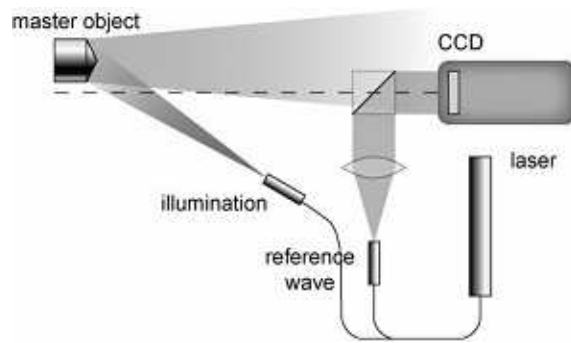

Figure 2: Recording of the coherent mask with the master object.

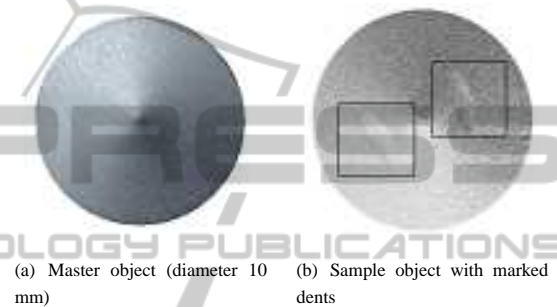(a) Master object (diameter 10 mm) (b) Sample object with marked dents

Figure 3: Master and Dented Sample Object.

deformation with those of a sample object having a different microstructure:

- numerical comparison of the respective phase distributions of the relevant digital holograms or

- optical comparison of both interferograms by Digital Comparative Holography.

In the case of a numerical comparison the difference phases of the master object and the sample object are subtracted directly in the computer. This results in the elimination of the basic shape of the object and the enhancement of differences between the two objects. In case of the optical technique the digital interferogram of the master object has to be reconstructed
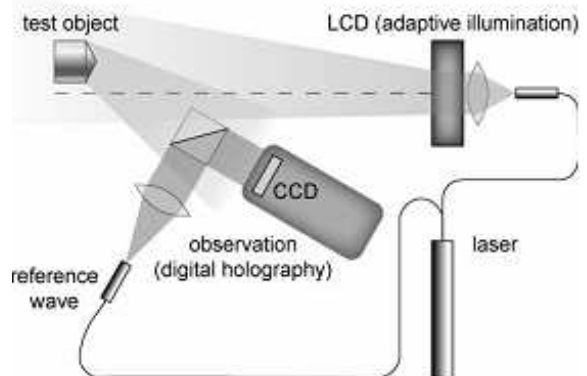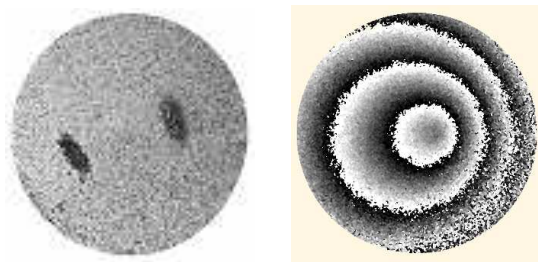

Figure 4: Coherent illumination of the sample by the conjugated wavefront of the master.

(a) Result of the coherent illumination with the conjugated wavefront of the master

(b) Result of conventional two-wavelength contouring

Figure 5: Shape comparison between a master and a sample object by comparative digital holography.

Figure 6: Experimental setup of the digital holographic microscopic system.

by a suitable spatial light modulator such as a liquid crystal SLM or a digital micro mirror device. Fig. 2 shows the setups for recording the master-hologram, Fig. 4, and for investigating the sample/test object by the comparative technology, Fig. 3(b). For that purpose the sample object is coherently illuminated by the conjugated wavefront of the master object. To reconstruct the conjugated wavefront of the master the master-hologram is written to the SLM and the SLM is illuminated by the conjugated reference wave that was used for making the master-hologram. This 2step procedure leads to an interferogram of the sample that indicates only the difference in shape or deformation between master and sample, Fig. 3 and Fig.5 . In our example the objects to be compared are two macroscopically identical aluminum cylinders with a cone at their upper end, Fig. 3(a). One of the cylinders has 2 small dents of some micrometers in the cone, Fig. 3(b). For the experiment a synthetic wavelength of = 0,326 mm was adjusted by the two single exposures with 1=579,41 nm and 2=580,44 nm. Due to the holographic illumination of the sample with the conjugated wavefront of the master the indicated difference phase (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. 5(a). 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 microns. Using the SLM, misalignment between the master and the sample can be compensated by a corresponding phase shift of the reconstructed master wavefront. A comparison of Fig. 5(a) with Fig. 5(b), 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 with various microstructure is
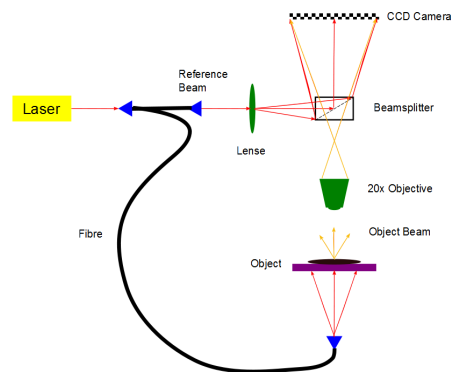
displayed. The high level of noise is justified by the relatively large pixel size of the used LCD-modulator compared to the available CCD-sensor (CCD 9m, LCD 18m).

2.2 Digital Holographic Microscopic System

In this section we describe the functional implementation of the architecture, focusing mainly on the setup of the holographic system and the configuration of the remote control (i.e. the components in the box on the right in Fig. 7). The experimental setup of the digital holographic microscopic system is shown in Fig. 6. A laser beam of is first coupled into a fiber and subsequently divides into a reference arm and object arm. 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 20x/0.5 microscopic objective. The reference beam is coupled into the system using a beam splitter, to interfere with the object wave. The sample is mounted on an electric-driven 3D positioner (Physical Instrument), allowing the user to shift the field of view at sub-micron precision. A CCD camera (SVS16000) records the hologram and transfers the data to the computer for sbsequent processing. The camera has a large sensing area of 43.3 mm diagonally with 16 M (4896×3280) pixels of 7.4×7.4 microns in size. The provides a transmitting rate of as high as 1 gigabit per second, with effective frame rates of $3 fps$. It is connected to the host computer through a PCI(e) network interface card with 82541 chip set (for example, Intel Pro/1000 GT PCI card in our case) using an RJ45 network cable.

Reconstruction of the object wave is performed numerically. The intensity pattern $f(\xi, \eta)$ recorded is first filtered in the spatial Fourier-Domain(M. et al.,

1982) , 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 the object plane (x, y) at distance z using the Fresnel transformation $\mathcal{T}(z)$ (approximation of the wave propagation for distances $z \gg \lambda$)

$$\begin{aligned} g(x,y,z) \quad &:= \quad \frac{\exp(ikz)}{i\lambda z} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(\xi, \eta) \cdot \\ &\quad \cdot \exp(\frac{ik}{2z}((x-\xi)^2 + (y-\eta)^2)) \, d\xi d\eta \\ &= \quad \mathcal{T}(z)(f(\xi, \eta)) \end{aligned}$$

The whole reconstruction process can thus be expressed as

$$g(x,y,z) \quad := \quad \mathcal{T}(z)(\mathcal{F}^{-1}(h(\mathcal{F}(f(\xi, \eta)))))$$

where $\mathcal{F}$ denotes the Fourier-Transform and h the spatial filtering in the Fourier-Domain.

3 SYSTEM ARCHITECTURE FOR THE HOLOGRAPHIC MICROSCOPy

The system architecture for the remote lab is schematically shown in Fig. 7. At the heart of the architecture is the digital holographic microscopic system, which is hidden behind a proxy server and can be accessed directly only by an operator at our 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 an SSH tunnel for encrypted, secure data exchange. Users access the experiment through the BW-eLabs portal, which authenticates against an eSciDoc user data base. On successful authentication, an SSH tunnel is opened to the SSH server running on the proxy, with authentication passed on using PAM ("pluggable authentication modules"). eSciDoc also provides storage and access to experimental data, passing data for automatic configuration of the experiment, and access to the publication infrastructure of OPUS(Opu,) . From the user's perspective, the functionality of eSciDoc is mostly transparent, working automatically in the background. The coordinator has to provide a script defining the data, format and metadata to be stored. 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 our case, the position of the object under investigation, the focusing of the microscope, the parameters requires in the reconstruction
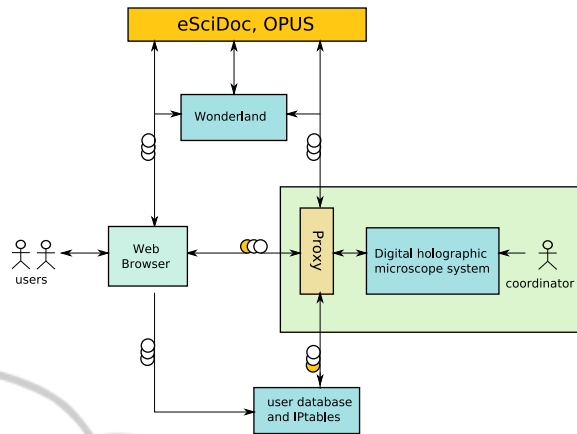

Figure 7: Schematic architecture for the remote experimental system.

of the hologram). 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 set-up and each set of data (if desired), protecting against undesired third party access while enabling collaboration between privileged partners.

3.1 Setup of the Remote Controlling System

Many techniques can be used for remote controlling. The choice for our project, Virtual Network Computing (VNC) used by MIT (Selmer et al., 2007) allows in principle for complete control of a host computer by a remote client. While somewhat slower and very open compared to alternatives like "LabVIEW Remote Panel" (lab,) (LRP) developed by National Instruments Inc, it offered some fundamental advantages within the framework of the project as a whole. VNC can connect through a proxy using an SSH tunnel, adding standard authentication through PAM and encryption for security, based on existing software such as Java-Portlets running on the BW-eLabs Portal server and Python modules on the proxy server. As a result, authentication is left very flexible and does not require local accounts, any number of different authentication methods are possible (e.g. the whole system, including eSciDoc, could authenticate against a trusted identity provider using Shibboleth (Shi,) or similar). The second argument for VNC was the easy integration of proprietary software for remote control, an aspect vital in future expansions of the project. Any existing remote control can be easily integrated into BW-eLabs through VNC, shifting the focus of development to the interaction with eSciDoc for auto-
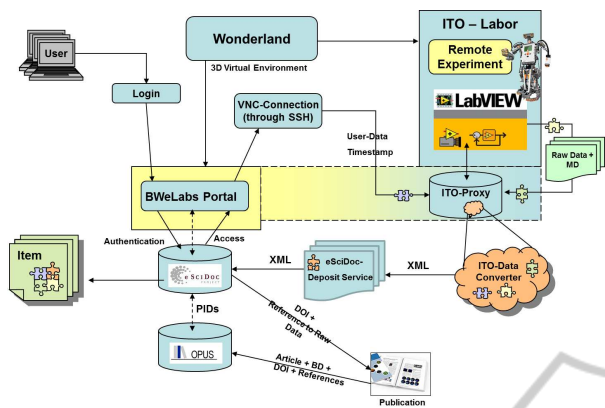
Figure 8: Architecture and Components for the Remote Laboratory.

matic storage and access to experimental data.

The major advantage of this setup lies in the minimal effort demanded from the provider of the experiment. User authentication, secure connection, user management, scheduling of experiments, storage, publication and retrieval of data are all provided by the infrastructure and can be located anywhere, either on specific systems or within the cloud (although the publication process does require long-term accessibility to the stored data, though not necessarily on the same, permanent location).

3.2 Data Flow and Integration into the Infrastructure

Fig. 8 shows a schematic representation of the data flow within BW-eLabs, with the remote controlled experiment described above being represented in the upper right corner and the connection through the BW-eLabs portal using VNC in the center. This section will be concerned with the integration into the infrastructure, mainly, the connection to the eSciDoc repository.

The data transfer between the experiment and eSciDoc is very generic. A daemon (a small program running continuously in the background) called eSciDoc Deposit Service is installed on the controlling computer and adapted to watch a specific directory. If a file is written to this directory, it will be automatically copied and send to a specified eSciDoc instance. In the transfer process the data is extended with certain metadata, including, but not limited to:

- Description of the experiment and the object under investigation (maunally created by the experimenting scientist)

- Parameters describing the physical state of the setup, including positioning of the object, focusing

of the microscope, a blind measurement needed to compensate for the curvature of the reference wave in the phase reconstruction (generated automatically by the controlling LabView program)

- Parameters needed in the analysis and interpretation of the raw data, in our case a description of the laser (type, wavelength), optical path length for the Fresnel reconstruction, filter parameters used in the Fourier domain, algorithms used etc (generated automatically by the controlling LabView program)

- Administrative metadata, specifying institution, project, investigation, measurement series and similar (usable in billing, parts created automatically in eSciDoc).

- Time stamp and user id (created automatically in eSciDoc).

This metadata serves in support of semantical search as well as in restoring a specific, physical state of the experimental setup or in the numerical analysis and interpretation of raw data (in our case, the reconstruction of the hologram and the measured deformation of the object). The first three types of metadata are laboratory-specific and have to be defined in a Python/Perl/shell script (see below). The last two generated automatically by eSciDoc.

The data itself can be anything, ranging from raw, binary data to complex structured data. Transfer to eSciDoc is performed using HTTP. On the eSciDoc server, the data is passed on to an eSciDoc depository service that in turn calls a pre-defined script (Ito Data Converter) to build an eSciDoc item, consisting of raw data and XML metadata. These items are stored in eSciDoc, with the metadata being used for indexing search functionalities. Loading an item is again performed using HTTP, with the returned data being identical to that originally saved. The whole process is completely symmetrical and transparent for the user performing the experiment.

eSciDoc provides a multitude of functionalities to handle experimental data, ranging from hierarchical organization of datasets into projects, versioning and even "publication" through the assignment of a persistent identifier like a DOI. Upon publication, the DOI marked data set can be published on the OPUS document server utilized by several German public and university libraries.

4 CURRENT RESULTS AND FUTURE WORK

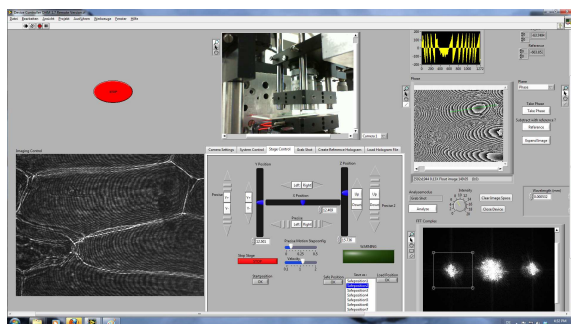Figure 9 shows the frontpanel of the LabView VI

Figure 9: The current Labview front panel, showing a sample of onion cells.

("Virtual Instrument", the LabView term for a program) with the image of a webcam showing the physical setup on the top left, with the numerically reconstructed hologram, in this case, a biological sample, onion cells, on the far right. The hologram was filtered in the spatial Fourier-Domain previous to reconstruction (M. et al., 1982) , removing the DC component and the twin image in the reconstruction to improve the utilization of the spatial bandwidth of the camera. The other two display below show the phase retrieved from the hologram and the phase difference between the currently investigated hologram and a reloaded, previously recorded hologram for comparative metrology. Phase unwrapping (Huntley, 2001; Ghiglia and Romero, 1994; Ghiglia and Romero, 1996) provides a 3D reconstruction of the deformation of the object, displayed on the bottom left.

The dials control the set-up, move the stepper motors of the 3D positioner and select a region of interest for the numerical reconstruction of the hologram. One useful feature and used to demonstrate the interaction with eSciDoc is the "save current position" and the "restore saved position" buttons. The position of the positioner is stored in an XML file and restored, positioning the system in the original configuration. This function is very useful in bringing a given region of a sample back into focus, an otherwise slow and tedious process, since the full reconstruction of the hologram takes a couple of seconds.

The current implementation includes the actual experiment, the controlling LabView software, the VNC connection and the login through the BW-eLabs server. The next steps in the ongoing work of this project will consist of the connection to the eSciDoc system, saving and loading data into the repository and in the integration of the system into a virtual 3D world, first as a simple solution displaying the VNC interface within the 3D environment, then in a more direct manner, controlling the LabView VI directly from and displaying the recorded holograms directly within virtual world.

While some provisions have been made towards access to the laboratory from the cloud, additional work is required. Authentication and access to the set-up are flexible enough to accommodate access from the cloud, as long as they are connected to a specific eSciDoc instance. eSciDoc itself is quite flexible in the location of its data, so could be adapted to use a DaaS paradigm, as long as long-term access to the data is guaranteed for the DOIs. Analysis of the data can be either performed remotely on the lab computer, or, given an installation of the proper LabView VI, within the cloud under the SaaS paradigm, retrieving the data from the eSciDoc storage.

5 CONCLUSIONS

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 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, among them advanced approaches to documenting, 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 test 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, 3D-user interfaces, data structures, data archiving, ...), and last but not least the convention and implementation of safety standards for the remote access to the infrastructure (the continuous availability, the facility and personal protection, the access rights and authentication).

ACKNOWLEDGEMENTS

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