A large distributed digital camera system for accelerator beam diagnostics

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Optical diagnostics, providing images of accelerated particle beams using radiation emitted by particles impinging a radiator, typically a fluorescent screen, has been extensively used, especially on electron linacs, since the 1970’s. Higher intensity beams available in the last decade allow extending the use of beam imaging techniques to perform precise measurements of important beam parameters such as emittance, energy, and energy spread using optical transition radiation (OTR). OTR-based diagnostics systems are extensively used on the superconducting TESLA Test Facility (TTF) linac driving the vacuum ultraviolet free electron laser (VUV-FEL) at the Deutsches Elektronen-Synchrotron facility. Up to 30 optical diagnostic stations have been installed at various positions along the 250-m-long linac, each equipped with a high-performance digital camera. This paper describes the new approach to the design of the hardware and software setups required by the complex topology of such a distributed camera system. © 2005 American Institute of Physics. [DOI: 10.1063/1.1946667]

I. SYSTEM DESIGN

The optical diagnostic system for the TESLA Test Facility (TTF) vacuum ultraviolet free electron laser (VUV-FEL) at the Deutsches Elektronen-Synchrotron facility (DESY, Hamburg, Germany) is an upgrade of the analogous system1,2 designed for the TESLA Test Facility-Phase1 (TTF) that provided, throughout the TTF operation (1994-2002), a tool for electron beam monitoring and high-quality beam analysis by means of optical transition radiation (OTR).

When defining the specifications for the TTF VUV-FEL accelerator, major new requirements for the optical diagnostic system have emerged, and therefore a redesign of the complete system has been necessary. First, the number of diagnostic stations, and, as a consequence, the number of digital cameras, have been increased (around 30 in total). Second, they are distributed over longer distances due to the increased length of the accelerator. Furthermore, because TTF VUV-FEL will become a full-fledged user facility, improved optical diagnostics has to be provided both for reliable routine operation and for high-quality beam measurements.

Because the transverse size of electron beam for TTF VUV-FEL can be as small as a few tens of microns, the whole imaging system, therefore both the optical system and the CCD camera, must be designed and the components carefully selected in such a way as to obtain the quality and performance needed for such a cutting-edge application.

For the CCD camera system we focused our attention on digital IEEE1394 (also known as firewire) cameras and re-designed the camera system accordingly. Digital cameras offer, at a cost comparable to that of their analog counterparts, a number of important features, namely, full frame resolution, region of interest (ROI) selection, electronic control of gain and shutter, triggered acquisition mode, etc. Among the most significant advantages of digital cameras with respect to standard analog ones, at least for scientific application, is their ability to provide noninterlaced images. The possibility to have beam images with full frame vertical resolution significantly improves the quality of the measurement. Although noninterlaced analog cameras exist, their implementation in such a large scale and for such an application introduces an unavoidable complexity in the cabling of the camera system that makes this option impracticable.

A single computer, providing it is equipped with appropriated software drivers and an imaging tool, can control one or more digital cameras. Multiple camera control is accomplished either by using multiple IEEE1394 ports on the computer or by using a single IEEE1394 port on the computer with an external hub. With respect to standard analog cameras, cabling can be significantly simplified because the IEEE1394 bus carries both data from and commands to the cameras, although the limitation of the maximum cable length (4.5 m) needs to be taken into account. This maximum cable length introduces a problem, which can be solved by adopting two main (and different) approaches.

The first solution is to use IEEE1394 bus extenders that allow an overall length of the computer-camera link to extend to up to 10–20 m or even much longer by means of fiber-optic links. This makes it possible to adopt a star topology, i.e., a single computer controlling all the cameras in the

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system. However, the cost of a single point-to-point extender device makes this solution inconvenient. A second approach is to have more than one camera controller, i.e., computers, distributed in such a way that the cable length is limited to the maximum allowed.

The best solution, at least in our case, is a compromise between the two alternatives (see Figs. 1 and 2) since the second option can be convenient only when the geographical distribution of controllers, adapting to the position of digital cameras along the accelerator, is such that more than one camera can be connected to each single computer.

In the case of TTF VUV-FEL (see Fig. 1) the amount of camera control computers along the linac can be reduced to a reasonable number (eight) if the allowed IEEE1394 cable length can be increased up to 10 m. This is possible with the use of special IEEE1394 cables that extend the standard specifications using high-quality cable and connectors without degradation of performance. At TTF VUV-FEL each controller computer controls two to six cameras.

Note that a similar topology can be adopted also for the first solution based on IEEE1394 fiber-optic bus extenders. In this case, although the number of bus extenders can be comparable to that of the camera controllers, the cost of a single extender (approximately 2 k€ at the time of the project design) is still higher than the cost of an industrial personal computer used as a camera controller (~1 k€).

In addition, the cost of fiber-optic cables must be added to that of the first solution (~0.5 k€ per 200 m fiber-optic cable), while camera controllers of the second solution are interconnected using the existing network infrastructure. Finally, we shall see that local controllers are not simply used as hubs for digital cameras but that one can make use of their computational power.

For such a large distributed system it is important to define a way to exchange data and commands between the cameras, via their controller, and a single operator interface in a control room situated far away from the accelerator. The Ethernet network and TCP/IP communication protocol is the natural candidate for this purpose provided it can guarantee the needed performance in terms of frame rate, i.e., number of images per second, at the operator interface.

In our implementation the “image server” that will be described in detail later plays the role of central image repository collecting data from remote cameras via the network. It also provides a user interface with image manipulation and analysis tools as well as single-point access to all remote cameras settings. Furthermore, it supplies an application server running high-level measurement programs and an interface to other clients of the optical diagnostic system, either from local or remote networks.

The image server, located in the main TTF VUV-FEL control room, has two network interfaces: one for communication with the camera controllers, the second for the other network services. Operators and experimenters normally use control panels on its local display to operate the camera system. The image server also distributes images and measurement results to both local consoles of the accelerator control system and to remote users, as described in the next paragraph.

II. FEATURES AND PERFORMANCE

From the operational point of view, the TTF VUV-FEL optical diagnostics camera system must be capable to distribute beam images provided by the camera system in different formats and for different purposes, such as remote beam monitoring and documentation, online beam analysis, and
The camera controllers continuously listen to the TCP/IP port defined for command transfer until the image server requests to open a transfer session. As soon as a transfer session is established, the camera controller initiates a data transfer to the image server and starts to read images from the camera indicated by the image server. When the operator, or a high-level application running on the image server, decides to switch to another camera connected to the same camera controller or to another camera controller, a command is sent to the active camera controller, setting it to idle. After that the next camera controller is asked to start to send images from the selected camera to the image server.

The camera controllers are compact industrial personal computers from Axiomtek. They are equipped with a 1.13-GHz Pentium III processor, a local disk, network interface, graphic card, and I/O ports. Two IEEE1394 interface cards, installed on the PCI backplane, provide three firewire ports each. Their compact sizes, 164 mm × 255 mm × 197 mm, simplify positioning in the accelerator tunnel. Because camera controllers are not directly controlled by operators, but communicate with the image server using the communication protocol, they are not equipped with monitor. They can be completely and efficiently remotely controlled, when needed, using remote desktop protocol (RDP).

For local maintenance we use a “portable” LCD-monitor + keyboard unit that can be easily transported and connected to any of the camera controllers.

The operating system and LabVIEW™ installations are identical for all the camera controllers by cloning the same disk image. The installation does not contain the camera system applications software nor configuration files, which are instead made available to the camera controllers from a shared network disk hosted by the image server. This simplifies greatly the installation and maintenance: camera controllers, being all identical, are identified by their network name, which is the only setting that is customized for each installation.

A configuration file in the shared disk, thus available to both camera controllers and image server, is used to assign each camera (identified by a serial number that can be read by the software) to its controller. This information is sufficient for a camera controller to configure itself at startup and for the image server to identify the controller in charge of the selected camera.

Online analysis and image manipulation routines developed for the previous version of the optical diagnostics camera system for TTF have been easily imported into the image server applications, although the user interface had been completely redesigned (Fig. 4). The image server (a 2 GHz Pentium IV computer) supplies beam images in two different modes: a full resolution mode for high-precision measurements and a low-resolution one for beam monitoring and documentation purposes. The image server also provides data from online analysis routines, such as beam root-mean-square (rms) (center of mass, standard deviation on x and y) and full width at half-maximum (FWHM) sizes, x and y projections, total intensity.

Background subtraction can be done automatically. Selection of the region of interest (i.e., the portion of the total high-quality measurements. As the main development tool for both image server and camera controller applications, we have chosen the National Instruments LabVIEW™ software package, a choice based on our previous experience with the package in imaging applications. The operating system is Windows™ XP. Useful features provided by the LabVIEW™ package are as follows:

- powerful image analysis library IMAQ™;
- support for IEEE1394 cameras (IMAQ™ add-on);
- multiplatform compatibility;
- TCP/IP tools for communication based on standard network protocols.

The image server software provides three main services:

- communication with the remote camera controllers;
- online image analysis and image distribution to local or remote client applications;
- automatic or quasiautomatic procedures for precise beam parameter measurements.

The software running on remote camera controllers along the linac (eight camera controllers have been installed so far) preanalyzes online images from locally connected cameras and transmits the results to the image server.

Control and readout of IEEE1394 compliant digital cameras can be easily implemented by means of the LabVIEW™ IEEE1394 tools library. So far, we have successfully tested its drivers with different kinds of cameras, whether they are low-cost webcams or high-quality ones.

For our application at TTF VUV-FEL we have chosen a high-quality Basler 301f camera. For this camera its producer also supplies a low-level API library that can be used to implement special functionalities not covered by the LabVIEW™ standard tools by taking advantage of the possibility to directly import DLL or shared libraries into the LabVIEW™ code. A custom TCP/IP-based communication protocol has been developed for communications between the image server and the camera controllers (Fig. 3).
image area that contains the beam spot) uses morphology analysis tools that automatically adjust the ROI following the beam spot even if it is jittering in size and position inside the image frame. Both low-resolution images and statistical information on the beam transverse distribution are accessible from either local or remote consoles, in the form of HTML pages served by the LabVIEW™-based HTTP server. High-resolution images can be saved as raw picture files and stored in the image server shared disk. Applications running on other computers can access these files, and read out data to perform special measurements or image analysis through the network file services.

A dedicated trigger line provides a TTL trigger to all cameras to synchronize image acquisition (i.e., the start of the CCD integration time) with the electron bunch passage time. Integration time as well as electronic gain and image brightness can be controlled via software by means of the IEEE1394 interface.

In the TTF VUV-FEL switched network, full frame images of 640×480 pixels are transferred from the digital camera to the operator interface on the image server at an average frame rate of 10 Hz, a frequency value depending mainly on the time needed for image transfer over the network, adequate for both beam monitoring and online measurements. Beam image display programs running on local consoles of the accelerator control system also use comparable image refreshing rates. Because online analysis of images does not influence the frame rate significantly, it is done by default on the camera controllers on all transferred images.

Higher frame rates can be obtained selecting the ROI transfer mode. Once the automatic ROI selection tool has been instructed, it sends to the image server only the portion of the pixel map containing the beam spot, typically containing 10%-35% of the total number of pixels. The full-size pixel map is then reconstructed at the image server by superimposing the ROI to a black pixel map in such a way that it reproduces the original arrangement in the CCD frame. Even in the ROI transfer mode, the RMS/FWHM and image projections are computed, by the camera controllers, from the original image and not from the selected subset.

The image server HTTP server provides an HTML inter-
are more robust against this kind of failure with respect to digital ones because of their much simpler electronics. The vulnerability of digital compared to standard analog cameras is the only relevant disadvantage in this kind of application.

In order to reduce failures or even damages due to radiation, all cameras and camera controllers are shielded against gamma rays by a lead shield. However, they cannot be easily shielded against neutrons, which might cause an instant, yet recoverable, failure. When this occurs, the normal operation of either the digital camera or the camera controller can be recovered by switching the power off and on again. This can be done remotely, since remote control of the power lines exists both for the digital cameras and the camera controllers.

III. DISCUSSION

The digital camera system for the TTF VUV-FEL has been operational since September 2004 and it provided an effective tool for daily beam transport operations and precise beam measurements. We have proved that accelerator optical beam diagnostics can profit from the new high-quality digital IEEE1394 cameras and that these cameras can be easily managed, even if they are numerous and distributed over long distances. The use of digital cameras and local controllers simplified very much the design of the system, especially relaxing the cabling.

Other significant advantages of the digital camera system, especially for our application, is its capability to provide beam images with higher resolution with respect to the standard video-interlaced cameras, and the possibility to have, within the same system, digital cameras of different quality and features, but still be manageable by means of the same hardware and software interface. The latter feature, though not yet employed in the TTF VUV-FEL digital camera system, makes it possible to integrate IEEE1394 cameras of different models and manufacturers into the same system, providing for physicists the possibility to optimize the performances of their diagnostic system according to the requirements of a particular measurement.

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