A DISTRIBUTED DIGITAL CAMERA SYSTEM FOR ACCELERATOR OPTICAL DIAGNOSTICS

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Abstract

Optical diagnostic, providing images of accelerated particle beams by using radiation emitted by particles impinging a radiator, typically a fluorescent screen, has been extensively used, especially on electron linacs, since the seventies. 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 etc. by using Optical Transition Radiation (OTR). OTR-based diagnostics systems are extensively used on the superconducting TESLA Test Facility (TTF) linac driving the VUV-FEL free electron laser at DESY. Up to 30 optical diagnostic stations have been installed at various positions along the 250 meters long linac, each equipped with a high performance digital camera. This paper describes the new approach to the design of the hardware and software set-up required by the complex topology of such a distributed camera system.

SYSTEM DESIGN

The Optical Diagnostic System for TTF VUV-FEL at DESY (Hamburg, Germany) is an upgrade of the analogous system [1, 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. Firstly, the number of diagnostic stations, and that of digital cameras as consequence, has been increased (around 30 in total). Secondly 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 few tens of microns the whole imaging system, therefore both the optic system [3] and the CCD camera, must be designed and the components carefully selected in such a way 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 (a.k.a. firewire) cameras and redesigned 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 resolutions, region of interest (ROI) selection, gain and shutter control and triggered acquisition mode and others. Among the most significant advantages of digital cameras with respect to standard analog ones, at least for scientific application, is their ability to provide non-interlaced images. The possibility to have beam images with full frame vertical resolution significantly improves the quality of the measurement. Though non-interlaced analog cameras exist, their implementation in such a large scale and for such 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 imaging tool, can control a number of digital cameras using one or more IEEE1394 ports. In the former case a IEEE1394 hub is needed. 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 meters) needs to be taken into account. This maximum cable length introduces a problem, which can be solved adopting two main different approaches.

The first solution is the use of IEEE1394 bus extenders to allow an overall length of a computer-camera link up to 10-20 meters 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 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 controllers, 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 (Fig.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 (Fig.1) the amount of camera control computers along the linac can be reduced to reasonable number (8) if the allowed IEEE1394 cable length can be increased up to 10 meters. This is possible by using special IEEE1394 cables that extend the standard specifications using high quality cable and connectors without degradation of performances. At TTF VUV-FEL each controller computer controls 2-6 cameras.

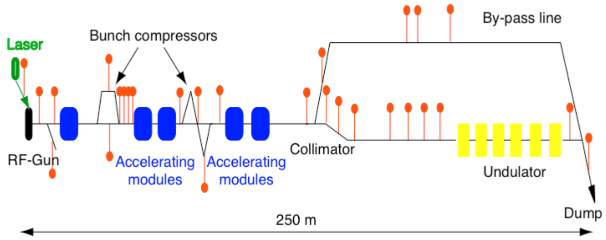


Figure 1: Schematic overview of the TTF VUV-FEL linac (not to scale). Dots indicate the position of optical diagnostics stations (digital cameras).

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 performances in terms of *frame rate*, i.e. number of images per second, at the operator interface.

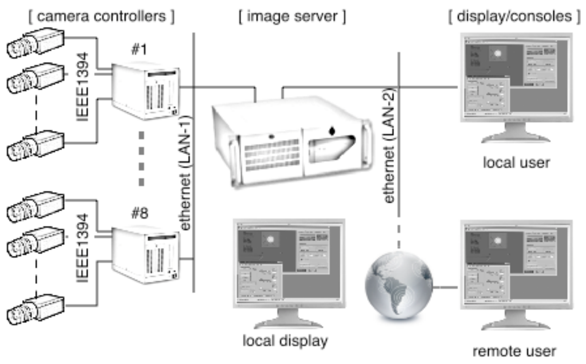


Figure 2: Layout of the TTF VUV-FEL Optical Diagnostics Camera System.

In our implementation the “Image Server” that will be described in details later has the role of central image repository collecting data from remote cameras via 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.

FEATURES AND PERFORMANCES

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, on-line beam analysis and high-quality measurements.

As main development system we have chosen the National Instruments LabVIEW™ software package. This choice is based on our previous experience with it in imaging applications. The operating system is Windows™ XP. Useful features provided by the LabVIEW™ package are:

- powerful image analysis library IMAQ™;
- support for IEEE1394 cameras (IMAQ™ add-on);
- multi-platform compatibility;

TCP/IP tools for communication based on standard network protocols.

The image server software supplies three main services:

- communication with the remote camera system controllers;
- on-line image analysis and image distribution to local or remote client applications;
- automatic or quasi-automatic procedures for precise beam measurements.

The software running on remote camera controllers along the linac (8 Camera Controllers have been installed so far) controls the locally connected cameras performing on-line image pre-analysis and their distribution to Image Server.

Provided that digital cameras are IEEE1394 compliant, their control and read out can be easily implemented by means of the LabVIEW™ IEEE1394 tools library. So far, we have tested these drivers with different kinds of cameras, being either low cost web-cam or different high quality cameras.

For our application at TTF VUV-FEL we have chosen a high quality camera Basler 301f. For this camera the producer provides a low-level API library which can be used to implement special functionalities, not covered by the LabVIEW™ standard tools, 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 the communications between the Image Server and Camera Controllers (Fig.3). The latter continuously listen the TCP/IP port defined for the 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 an high-level application running on the Image Server, decides to switch to another camera connected to the same 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 of the selected camera to the Image Server.

The Camera Controllers are compact industrial Personal Computers, equipped with a local disk, network interface and up to six IEEE1394 ports. Their compact sizes simplify the positioning into the accelerator tunnel.

The Operating System and LabVIEW™ installation are made identical for all the camera controllers by cloning the same disk image. The installation doesn't contain the camera system applications software and configuration files that are instead made available to Camera Controllers from a shared network disk hosted by the Image Server. This simplifies very much installation and maintenance: Camera Controllers, being all identical, are identified by means of their network names that is the only setting to be 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 its serial number that can be read by software) to its controller. This information is sufficient to a Camera Controller to configure itself at startup and to the Image Server to identify the controller in charge of the selected camera.

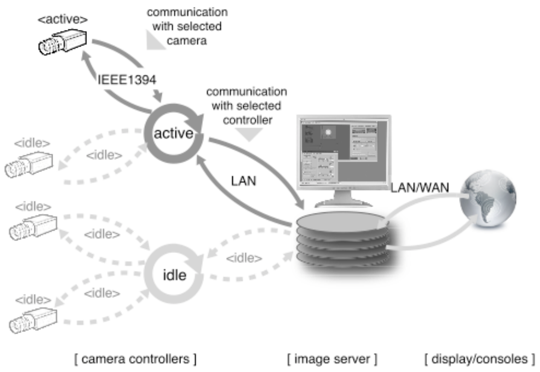
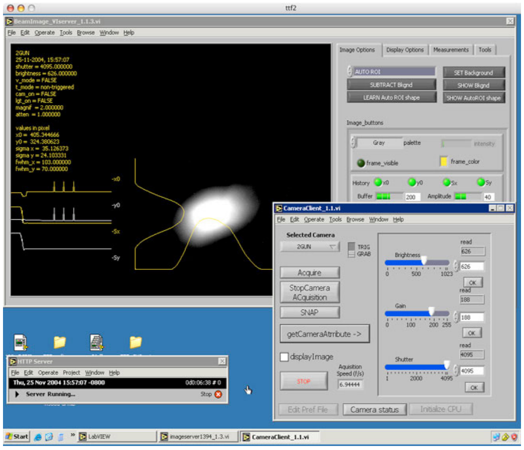


Figure 3: Communications and data/commands transfer in the Optical Diagnostics Camera System.

Although the user interface has been completely redesigned (Fig.4), on-line analysis and image manipulation routines developed for the previous version of Optical Diagnostics Camera System for TTF have been easily imported into the Image Server applications. The Image Server (a 2 GHz PentiumIV 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 latter mode provides also outputs from on-line analysis routines, such as beam RMS or FWHM sizes, total intensity, centre of mass position and x and y projections.

Background subtraction can be done automatically. Selection of the region of interest (i.e. the portion of the total image area that contains the beam spot) take advantage of morphology analysis tools that automatically adjust the ROI following the beam spot even if it is jittering, varying its size and position inside the image frame with time.



```
2GUN
25-11-2004, 15:57:07
shutter = 4095.000000
brightness = 626.000000
v_mode = FALSE
t_mode = non-triggered
cam_on = FALSE
lgt_on = FALSE
magnif = 2.000000
atten = 1.000000

values in pixel
x0 = 405.344666
y0 = 324.380623
sigma x = 35.126373
sigma y = 24.103331
fwhm_x = 103.000000
fwhm_y = 70.000000
```

Figure 4: Local user interface on the Image Server. The camera control panel (front most) and the image display and analysis panel are shown.

Both low-resolution images and statistical information of 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 a local shared disk. Applications running on other computers could access these files, and read out data to perform special measurements or image analysis, through the network file services.

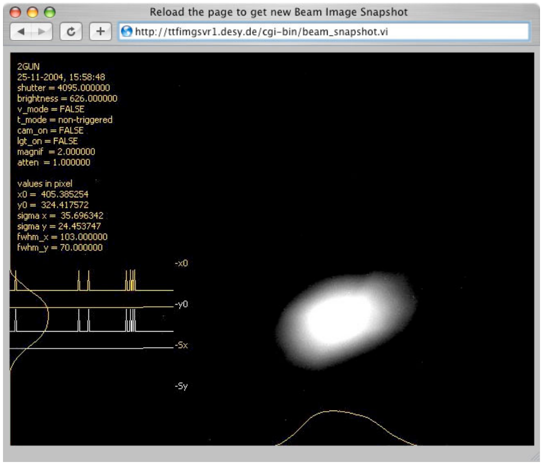
A dedicated trigger line provides to all cameras a TTL signal that synchronize the image acquisition (i.e. the start of the CCD integration time) to the beam pulse. Duration of integration time, as well as electronic gain, image brightness etc. can be controlled via software by means of the IEEE1394 interface.

In the TTF VUV-FEL switched network, full frame images of 640x480 pixels are transferred from the digital camera to the operator interface at an average frame rate of 10 Hz, including on-line analysis of the images. This performance is satisfactory for both beam monitoring and on-line measurements.

Higher frame rates can be obtained if one selects 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 having typically 10-35% of total amount of pixels. The full-size CCD pixels map is then reconstructed at the Image Server positioning the ROI in such a way that it reproduces the original arrangement in the CCD frame. Even in ROI Transfer Mode the RMS/FWHM and image projections are calculated from the original image, not from the selected subset.

The interface with the DOOCS control system was accomplished via WDOOCS based server. The server has been implemented as a dynamic linked library that allows embedding it in a LabVIEW's virtual instrument. The server reads data structure (cluster) from the virtual instrument and transfers it to the corresponding DOOCS server properties. The read cluster includes images bitmap coming from active camera and stored background image. Additionally the server transmits information about cameras and optical system, e.g. optic settings, camera parameters (mode, shutter, brightness and gain). The possibility to change the ODCS settings over DOOCS connection will be done by LabVIEW mailbox writing and executing commands which will come from the server.

The Image Server HTTP server provides an HTML interface to beam pictures (Fig.5). These images are mainly used for documentation and remote observation of the beam. HTML pages are created by means of dedicated CGIs developed with LabVIEW™ in such a way to directly access image data from the global variables of the application instead of image files saved on the local hard disk. As a consequence the client requests are served faster with a reduced load on the local CPU.


Reload the page to get new Beam Image Snapshot

http://ttfimgsvr1.desy.de/cgi-bin/beam_snapshot.vi

```
2GUN
25-11-2004, 15:58:48
shutter = 4095.000000
brightness = 626.000000
v_mode = FALSE
t_mode = non-triggered
cam_on = FALSE
lgt_on = FALSE
magnif  = 2.000000
atten  = 1.000000

values in pixel
x0 =  405.385254
y0 =  324.417572
sigma x =  35.696342
sigma y = 24.453747
fwhm_x = 103.000000
fwhm_y = 70.000000
```

Figure 5: HTML Interface for documentation or remote operation.

For remote beam observation a dynamic page with video-streaming features has been developed providing a continuous and smooth refresh of the displayed image on the remote browser.

Remote maintenance of the Image Server and Camera Controllers is possible by means of Remote Desktop Protocol (RDP) even from far away networks. Using this protocol the groups from INFN-Roma2 and INFN-LNF completed the configuration, debugged the system and upgraded the software from home laboratories.

The complete system has been in continuous operation since September 2004. After the first months of the operation, the only remaining relevant concern is the failures of the cameras and the Camera Controllers due to the radiation in the accelerator tunnel. When this occurs the normal operation can be recovered by switching off and on again the power.

So far remote control of power lines exists for computer controllers only but this feature will be also available for digital cameras soon.

CONCLUSIONS

The digital camera system for the TTF VUV-FEL is operative 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, taking advantage of simple low-cost computers working as Local Camera Controllers.

This solution simplified very much the design of the system, relaxing the cabling especially.

Other significant advantages of the digital camera system, especially for our application, are its capability to provide beam images with higher resolution 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 being 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 possible to integrate IEEE1394 cameras of different model and manufacturers into the same system providing for physicists the possibility to optimize the performances of diagnostic system according to the requirements of a particular measurement.

ACKNOLEDGEMENTS

We like to thank all the colleagues at DESY and INFN-LNF/Roma2 who have contributed to the development and the commissioning of the TTF VUV-FEL digital camera system. In particular we wish to thank D.Nölle and S.Schreiber from DESY and M.Castellano from INFN-LNF for their constant support and helpful suggestions. We also thank C.Eckelmann for the development of electronic equipments for the trigger distribution system and L.Cacciotti for the work on the camera system auxiliary electronics.

REFERENCE

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[2] L. Catani et.al., “A Distribuited Multiplatform Control System with LabVIEW”, PCaPAC2000, DESY (Germany)

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