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A. Murari, J. Vega, D. Mazon, P. Arena,T. Craciunescu, L. Gabellieri, M. Gelfusa,
D. Pacella, S. Palazzo, A. Romano and JET EFDA contributors

Latest Developments in Image Processing for the Next Generation of Devices with a View on DEMO

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A.Murari[1], J.Vega[2], D.Mazon[3], P.Arena[4],T.Craciunescu[5], L.Gabellieri[6], M.Gelfusa[7], D.Pacella[6], S.Palazzo[4], A.Romano[6]
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Associazione EURATOM-ENEA per la Fusione, Consorzio RFX, 4-35127 Padova, Italy
[2]Asociación EURATOM/CIEMAT para Fusión, Madrid, Spain
[3]Association EURATOM-CEA, CEA Cadarache DSM/IRFM, 13108 Saint-Paul-lez-Durance, France
[4]Dipartimento di Ingegneria Elettrica Elettronica e dei Sistemi-Università degli Studi di Catania, 95125 Catania, Italy
[5]EURATOM-MEdC Association, National Institute for Laser, Plasma and Radiation Physics, Bucharest, Romania
[6]Associazione EURATOM-ENEA sulla Fusione, ENEA C.R. Frascati, C.P. 65, I-00044 Frascati, Roma, Italy
[7]Associazione EURATOM-ENEA - University of Rome "Tor Vergata" , Roma, Italy
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ABSTRACT

In magnetic confinement fusion devices the use of cameras, both visible and infrared, has increased very significantly in the last years. The large amount of data and the difficulty of the analysis tasks (ambiguity, ill posed problems etc), require new solutions. The technology of Cellular Nonlinear Networks CNNs has been successfully applied to various tasks, from the real time hot spot detection to the automatic identification of instabilities. The accuracy obtained is comparable to the one of more traditional serial algorithms but the CCNs guarantee deterministic computational times independently from the image contents. Moreover the latest developments have allowed obtaining these results also in the case of space variant image analysis. The method of the optical flow permits to derive information about the speed of the objects moving in the frames of a single camera. The results of previous applications have been so successful that the approach has been extended to videos in compressed format (MPEG) to reduce the computational time, preserving the accuracy of the results. Since the next generation of devices will emit a lot of SXR radiation, also from the edge, new technologies are being developed to perform imaging over this region of the spectrum for a global view of the entire plasma column.

1. IMAGE PROCESSING IN SCIENCE AND NUCLEAR FUSION

The increasing penetration of cameras in scientific fields is a clear and uncontroversial trend of the last decades. This tendency is particularly evident in large fusion devices, in which many more camera based instruments have become routine diagnostics. In the Joint European Torus (JET), for example, in the last campaigns many experiments relied on IR and/or visible cameras and about 15 new cameras are being installed for the next experiments with the new ITER-like wall. One of the main characteristics of cameras as diagnostics is the large amount of data that they produce. Data compression techniques and pattern recognition methods have allowed reducing the amount of data to store and retrieving the required information efficiently [1]. On the contrary, the interpretation of the video contents remains a challenging task. Another important difficulty task in image processing resides in the fact that, very often, the analysis of images consists of inverse problems which are typically ill posed (in the mathematical sense of Hadamard).The aforementioned two main issues are particularly challenging in the case of real time image processing, in which the analysis must be performed in well defined and normally limited amount of time. The new computational paradigm of Cellular Neural Networks (CNNs) has been investigated since, being based on morphologic operators, guarantees deterministic computational time. The approach of the CNN has been extended to space variant problems, meaning to situations which require processing different parts of the images in different ways (see section 2). To determine the velocity of objects such as pellets or instabilities, the approach of the optical flow has been implemented quite successfully. In addition to providing quite good results, new developments allow the use of compressed MPEG images, improving processing speed (see section 3).

In reactor relevant devices, such as DEMO, traditional diagnostics can have difficulties to

perform in all conditions and could be integrated by other diagnostics. Imaging in the Soft X-Rays (SXR) energy range could indeed provide a holistic view of hot reactor relevant plasmas and new technologies, such as GEM (Gas Electron Multiplier) detectors and polycapillary lenses are being developed for this purpose (section 4). Conclusions and directions of future research are the subject of the last section of the paper.

2. CELLULAR NONLINEAR NETWORKS FOR REAL TIME, SPACE VARIANT IMAGE PROCESSING.

CNNs constitute a computational scheme alternative to the more traditional serial machines [2]. They consist of multidimensional arrays of cells. The output of each cell depends on the value of the cell itself and of the other cells in a predefined neighborhood. CNNs plus a memory are equivalent to universal Turing machine and therefore have the same computational power as traditional serial computers based on the von Neumann architecture. The main competitive advantage of CNNs, in applications to real time image processing, is their parallel computational approach. Moreover, they use morphological operators, called templates, which are very powerful nonlinear tools and render CNNs very competitive in terms of computational capabilities. The combination of these two aspects typically results in very short computational times. Finally the output of these morphological operators can be calculated in deterministic time, i.e. without exceeding a maximum time known in advance and independent from the contents of the images. This of course is a very important property for hard real time applications (and essential in DEMO and the reactor).

For the scope of the applications described in this paper, a Cellular Nonlinear Network can be considered a rectangular cell array C(i,j), where each cell is modelled by a nonlinear dynamic system, defined mathematically by two main elements: the state equation and the output equation. In the space variant implementation used presently at JET, the discrete-time version of the CNN state equation becomes:

$$x_{ij}(n+1) = (1-h)\,x_{ij}(n) + \\ + h\left(\sum_{C(k,l)\in S_r(i,j)} A(i,j;k,l)\,x_{ij}(n) + \sum_{C(k,l)\in S_r(i,j)} B(i,j;k,l)\,u_{kl}(n) + z_{ij}\right) \tag{1}$$

where n is the iteration number, uij represents the intensity level (mapped in the [-1,1] interval) of the ij-th pixel in the input image, whereas xij is the intensity level of the ij-th pixel in the output image. A and B are the 3X3matrixes, called templates, which implement the various operations to be performed on the corresponding part of the image. It is worth mentioning that, in the past, CNNs were typically implemented using Application Specific Integrated Circuits (ASICs). To improve the flexibility and accessibility of the image processing tools developed for JET, they have now been implemented using FPGAs [3]

On JET the most interesting InfraRed (IR) cameras for the development of real time algorithms are installed on a dedicated endoscope providing a wide-angle view (field of view of 70 degrees)

in the infrared range (3.5 to 5μm). The wide angle view of the system includes the main chamber and the divertor. The diagnostic consists of an endoscope formed by a tube holding the front head mirrors, a Cassegrain telescope, and a relay group of lenses, connected to the camera body. A typical frame acquired by JET wide angle camera is shown in Figure 1. The white pixels indicate the regions of the first wall with stronger emission and therefore correspond to hot spots, locations of higher temperature than the surrounding structures. For machine protection purposes, it is obviously very important to determine whether these locations reach dangerous temperatures during the discharge. Thanks to the intrinsic parallelism and the core-array layout of the Falcon architecture, used to implement the CNNs described in this paper, it has been demonstrated offline that it is possible to completely process an image in less than 10ms, allowing the system to reach a processing frame rate of 100fps with only one core [4]. This is considered adequate for the thermographic applications but in any case, by increasing the number of cores and therefore the parallelism, even higher frame rates (up to 1000 fps) can be reached, to satisfy stricter real-time requirements.

3. OPTICAL FLOW

As mentioned in the first section, very often deriving the required information from video movies implies solving ill posed problems. A typical example is the attempt to derive quantitative information about the 3-D movements of objects seen by a single camera. To attack this issue, the method of the optical flow has proved to be particularly effective [5]. The optical flow, or "projected motion", technique consists of a dense representation of visual motion important for dynamic scene understanding and can be defined as the (perspective or orthographic) projection of the 3-D motion in the real world scene on the 2-D image plane. The basis assumption, used by most optical flow algorithms, is the brightness constancy: when an object changes position in subsequent frames, its intensity or colour does not vary. This assumption implies that any change in the image is caused by the translation of brightness patterns leading to the gradient constraint equation:

$$\vec{f_s} \cdot \vec{v} + \vec{f_t} = 0 \tag{2}$$

where $f_s = (f_x, f_y)$ and f_t are the spatial and temporal gradients respectively and ν is the optical flow velocity. The brightness constancy assumption provides just one constraint on the two unknowns at each pixel and therefore, as mentioned, the problem is ill-posed and requires additional constraints. The most effective regularization approach tested at JET so far consists of minimizing a Combined Local-Global (CLG) functional [6]. Recently the JET implementation of the optical flow has been upgraded to use compressed images. Since video streams are usually compressed to reduce the storage requirements, MPEG-2 compressed domain information is manipulated to obtain a very fast and reasonably accurate 2-D motion estimation of the video scenes. This reduces significantly the computational costs. These methods can be used for the manipulation of the large JET video databases and, in specific cases, even for real-time data processing. An example is the detection of MARFEs in a movie captured by JET fast visible camera and shown in figure 2. MARFEs are

thermal instabilities, which consist of an annular region of high emissivity moving along the high field side of the inner wall. Figure 2 shows clearly how a set of simple and fast image processing steps succeed in dividing the image sequence into semantically meaningful regions along the time axis [7]. The MARFE detection and tracking is achieved with very good quality. The procedure is very fast since the processing time per frame is 6.9ms.

4. GEM DETECTORS AND POLYCAPILLARY LENSES FOR X-RAY IMAGING

In future generation of devices, of the DEMO class, the diagnostics will have to perform different duties with respect to their main goals in present day purely experimental devices. For example, they will have to operate in a much harsher environment, with limited opportunity for maintenance. One of the challenges which will be posed by reactor relevant devices is the determination of the magnetic configuration and particularly the plasma boundary at steady state, in the very high radiation field dominated by 14 MeV neutrons. The present technologies of magnetic pick-up coils are indeed expected to have some difficulties already in ITER. One possible alternative is to rely more on X ray emission. Indeed, in DEMO class plasmas already the top of the pedestal will have a temperature of several KeV and therefore the plasma is expected to strongly emit in the X ray part of the spectrum even from the edge. In this perspective, new GEM detectors and polycapillary lenses are being developed to measure the SXR emission and to perform imaging in the SXR region. The layout of a triple GEM detector being developed at present is reported in figure 3. The radiation to be detected generates electrons in the gas. The electrical field is properly shaped by the GEM foils to provide the required amplification, preserving the spatial resolution of the detector. The pads at the anode can be considered equivalent to pixels in cameras. These detectors are very flexible (since there are many parameters to adjust from the gas mixture to the voltage of the foils and geometry). They therefore guarantee high count rate, versatility and robustness. Contrary to their original scope in high energy physics, in fusion the boundaries of this technology are being extended in the direction of detecting lower energy radiation, in the KeV range for spectroscopic and imaging applications.

To improve the optical properties and to locate the detectors away from the plasma if necessary, they can be combined with polycapillary lenses, which consist of 104-106 hollow glass channels bundled together. The X ray photons propagate in the hollow spaces of the polycapillary channels and the reflection, which occurs at the boundary between the two media, allows guiding them. To test the optical properties of these lenses specific experiments have been performed. The layout of the experiments to test the astigmatism is reported in figure 4. Experiments performed with a focusing lens demonstrated that images can be obtained at large distances (much larger than the focal length), with progressively larger magnifications and with a very low astigmatism (see figure 4), revealing therefore the good optical properties of these polycapillary lenses.

CONCLUSIONS AND DIRECTION OF FUTURE INVESTIGATIONS

Images and in general bidimensional measurements are the new frontier in fusion diagnostics. They already produce the largest amount of data collected in each shot. The wealth of information they contain can contribute significantly not only to further understanding of the physics but also to control and machine protection. On the other hand, traditionally the community is more prepared to handle time series and therefore the richness of images and videos is not always completely exploited. To remedy this situations significant innovation is required in a wide variety of fields, which range from information retrieval to machine learning, from real time computation to the development of new radiation hard detectors and optics. Moreover a complete revision of the traditional architecture for data storage is to be performed. Various aspects, from data retrieval to relational databases, will have to be reconsidered in the perspective of data production dominated by video cameras.

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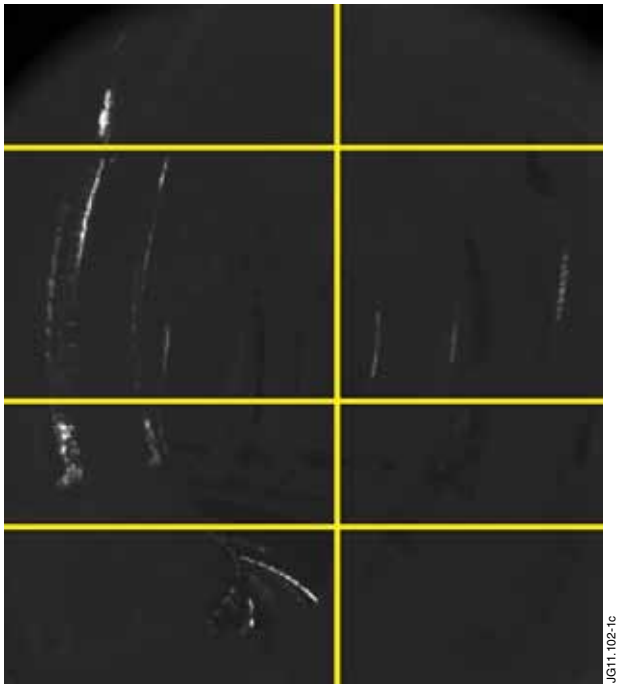

Figure 1: Typical view of the IR wide angle camera. The field of view has been segmented in regions to show the capability of the CNN implementation to perform space variant image processing.

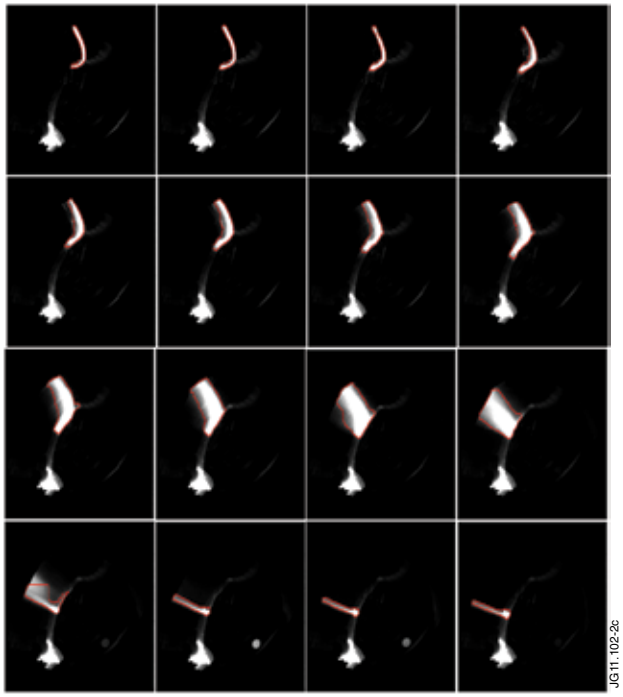

Figure 2: Evolution of a MARFE as seen by JET fast visible camera (white annular region). The red line is the region identified by the algorithm using the MPEG images as a MARFE.

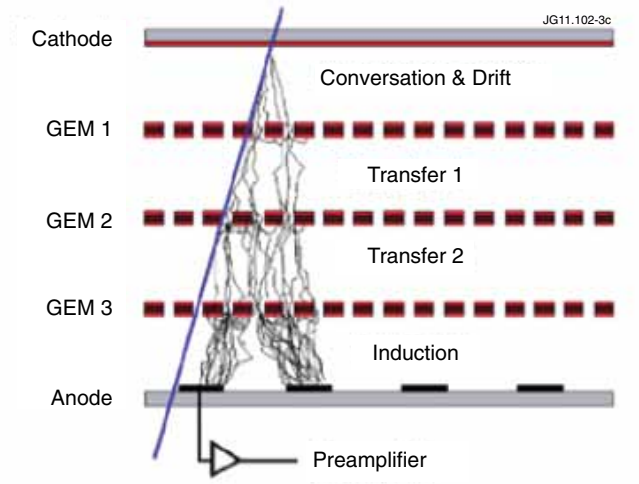

Figure 3: Layout of a triple GEM detector. The radiation to be detected ionises the gas and the electrons generated are accelerated, mulitplied and finally collected by single pads at the anode.

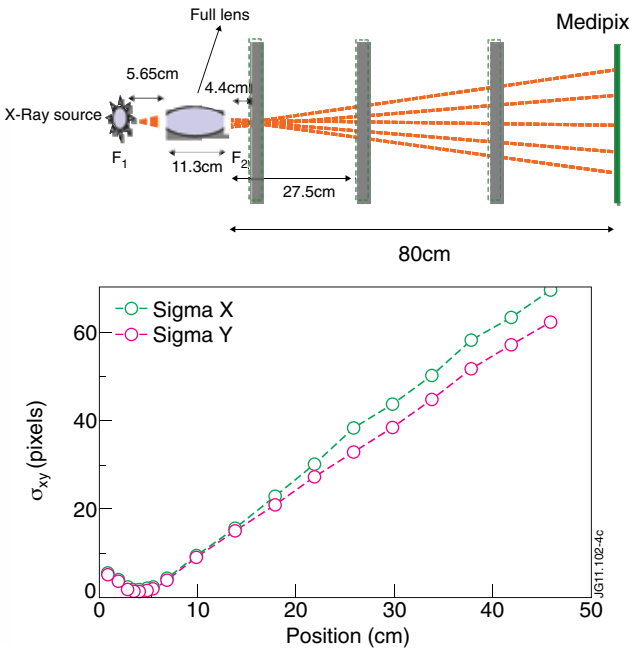

Figure 4:Top: layout of the imaging of a point SXR source. Bottom: diameter f the source in the x and y directions at various distances