Blob Statistics and SVD based plasma-wall interaction detection in Tokamak

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ABSTRACT

A methodology for detecting the hot spots on the plasma facing walls during Toakmak operation is proposed. Visible imaging diagnostics are used to detect such hot spots. Image thresholding along with statistics of binary large objects (blobs) detected from the recorded videos help in identifying these hot spots from the intense radiation zone which occurs during gas puff (required for enhancing the plasma density). Singular Value Decomposition (SVD) technique is applied to determine the region of most frequent hot spots during the plasma-wall interactions.

Keywords: Image Processing, Singular Value Decomposition (SVD), Blob Statistics, Tokamak, Video Imaging.

I INTRODUCTION

Controlled thermonuclear fusion requires confinement of hot plasma. Tokamak is a device that confines hot plasma using magnetic confinement in the shape of a torus. The direct imaging diagnostics has become increasingly important for plasma physics and tokamak operation in the recent years. But, removing quantitative information from images is not a trivial task due to the complexity of the observed scenes [1]. To this end, physicists have to state methods for feature extraction from images and for matching features with physical models or visual references [2]. This requires image processing and programming skills which are not necessarily in their domain of expertise. So, a major challenge is to provide a reliable and standard environment to help physicists in the process of imaging data analysis so as to optimize the use of image databases [3].

The inner wall of the tokamak consists of plasma facing components (PFC).Damages in various ways to plasma-facing components (PFM) as a result of plasma instabilities still remains a major obstacle to a successful tokamak reactor design and operation. Loss of plasma confinements and instabilities take various forms, such as major disruptions, which include both thermal and current quench (sometimes producing runaway electrons); edge-localized modes (ELM), and vertical displacement events (VDE) [4], [5]. Most plasma instabilities may cause both surface and bulk damage to plasma-facing and structural materials [6]. Surface damage mainly consists of high erosion losses attributable to surface vaporization, spallation, and melt-layer erosion. Major bulk damage of plasma instabilities, particularly those of longer duration, such as VDE, or those with deeper deposited energy, such as runaway electrons, is the result of the high heat flux reaching the coolant channels, possibly causing burnout of these tubes [7].

II RELATED WORKS

Wu, Lingfei, et al. [8] presented a novel algorithm and implementation of real-time identification and tracking of blob-filaments in fusion reactor data. This work presents an approach for extracting spatio-temporal features by dividing the overall task into three steps: local identification of feature cells, grouping feature cells into extended feature, and tracking movement of feature through overlapping in space. Through our extensive work in parallelization, we demonstrate that this approach can effectively make use of a large number of compute nodes to detect and track blob-filaments in real time in fusion plasma.

Martin, Vincent, et al. [9] presented a qualitative imaging, which aims at delivering information for operational and critical functions of the diagnostic such as detection and identification of abnormal events without requiring absolute measurements such as true surface temperature. To this end, automatic image understanding is a real challenge, mixing plasma physics knowledge modelling, computer vision techniques, and real-time data processing.

Garrido, I., et al. [10] presents an innovative control implementation related to plasma control for the generation of electricity with magnetically confined plasma. The implementation has been carried out over a specific device of tokamak type, called Tokamak Configuration Variable (TCV). This novel hybrid control design allows for real- time implementation of an optimal model predictive control over a large scale complex system with small time constant. At each closed loop iteration, the full model is first controlled by a straight-forward controller, then, the output values are used for model reduction so that finally the discretized control system is optimized only for the variables of interest. In the case of the TCV, this novel hybrid model predictive control enhances the power availability on the actuators and extends the pulse duration.

Lee, Woong-ryol, et al. [11] had proposed a new functional digital controller based on the MTCA.4 Standard. The KSTAR Multifunction Control Unit (KMCU, K-Z35) is realized using Xilinx System-On-Chip (SOC) architecture. The KMCU is matched with a dedicated Rear Transition Module (RTM) with sites for two FMC-like analog Data Acquisition (DAQ) modules. The first DAQ systems to be implemented is the Motional Stark Effect (MSE) diagnostic and also implement a two-way steaming data transmission function for the real-time plasma control.

2.1 Motivation

Tokamak ADITYA employs about 40 different diagnostics including fast imaging vision cameras, Infrared (IR) cameras, CCD cameras, spectroscopy and bolometer among others to monitor various operating parameters and machine protection throughout plasma shots. Without any strong prior knowledge concerning heat loads localization and intensity, this demands a very high user-interaction. Besides, periodic gas-puff injections and reflections arising due to them make extraction of hot spots from videos a very difficult task. A complimentary approach is needed to alleviate this intensive user-interaction demand.

III PROPOSED METHODOLOGY

This work is purely based on the information received from a single vision camera. Frames are extracted and analyzed from a recorded video of a plasma shot. Therefore, the analysis used here is applicable in two-dimensions. Also, the vision camera employed for recording has limited view of the tokamak inner side. Naturally, it can't provide information about the events that could be happened outside its view. It is also to be noted at this point that a single sensor (i.e. vision camera) may not be able to capture changes in temperature, pressure and other such parameters which are not perceived by vision. Therefore, in order to get complete information inside the tokamak vessel, multiple sensors are employed to monitor the status and health of the tokamak. The fusion of the comprehensive information received with multiple sensors is essential to make a reliable judgement of the situation inside tokamak [12]. The methodology employed for our work is described in following paragraphs.

Each frame is cropped to equal size by removing extraneous image portion which contains no information. The cropped image is, then, converted to a binary image with an appropriate threshold level. It is very important to set the threshold level for RGB to binary conversion. Setting a too high threshold will result in an empty frame most of the time, while setting a too low threshold will make it almost impossible to distinguish hot spots from the rest as hot spots will merge with gas puffs. Intensity of over 11,000 frames was analyzed based on histograms and a threshold level of 0.7 (on a scale of 0 to 1) was found the most suitable. This level was kept fixed for all the plasma shots analyzed.

The image after thresholding contains connected components. The connected components are labelled to form blobs (Binary Large OBjects). Blob statistics are used to differentiate hot spots from gas puffs. The blob statics used are area and centroids. Since, gas puffs have much larger area in comparison to hot spots for most of the duration they appear; it is possible to effectively distinguish between hot spots and gas puffs. Moreover, from the experimental arrangement for injecting gas puffs during tokamak operations, the y-coordinate of the centroid of a gas puff blob is almost always below 180 pixels, typically, as observed for over 11,000 video frames available. Also, during the gas-puffing period temperature gets lower compare to what it was before gas-puffing. Hence, it is highly unlikely to create any new hot spots during this period.

Another tricky issue with development of the algorithm is the duration of hot spots. Many plasma-wall interactions are observed for 0.2 second and then stop while some interactions lasts for as long as 20 seconds. So, duration for classification of a persistence hot spot and transient hot spots was needed to be fixed. (Incidentally, it may be noted that this duration may vary with threshold level for binary conversion). In consultation with scientists working with vision diagnostics, time duration of 2 seconds or more of plasma-wall interaction was fixed as persistent hot spots.

All the above information lead to development of an algorithm which is capable of detecting events like persistent hot spots, transient hot spots, occurrence of gas-puff injection , plasma filed initialization phase, rise of plasma filed, disruption of plasma filed and even absence of any meaningful event with reasonable accuracy. It is also important to determine location of the persistent hot spot as soon as it is detected to prevent any irreversible damage to the plasma facing components. Successive frames are compared to find the locations of persistent plasma-wall interactions. To this end, the SVD technique is applied on the frames containing most frequent plasma-wall interactions.

3.1 Proposed Algorithm

Input: recorded video of plasma shots

Output: The region of most frequently occurring hot spots

Steps:

1. Create a video object and obtain information on height, width and number of frames.
2. Set start frame, frame increment and stop frame numbers.
3. Crop the start frame to remove borders.
4. Convert the cropped frame into binary image.
5. Set this cropped binary frame as background frame.
6. Initialize a for loop (start frame+1 : frame increment: stop frame)
7. Crop the start frame+1 to remove borders.
8. Convert this frame to binary image, displayed in a separate window.
9. if all the elements are equal to zero, display the message : NO EVENT.
10. elseif number of non-zero elements ≥ image size/2, display the message : PLASMA FIELD SET UP/COLLAPSE.
11. else label the connected binary components in the image.
12. Find the properties (centroid and area) of these connected components (BLOBS).
13. Blobs having Y-coordinate value <180 and area < 1000 (pixels) indicates plasma-wall interactions with potential to become persistent hot spots show them in separate plot.
14. Rest of the blobs are created by gas puff injection and the reflections created during the gas puff injection period, display them in separate plot.

15. if there is at least one non zero element in the above plot, do not update the background frame, else background frame is replaced by logical ANDing of background frame and current hot spot frame.
16. if ten such consecutive ANDing operations results in non zero elements, they are regarded persistent hot spots and an alarm is generated. A counter is set for this pupose.
17. Singular value decomposition (SVD) is applied to each resultant frame to find 1st principle components for the image in horizontal as well as vertical directions of the image and plotted to give location of the persistent hot spot(s).
18. If resultant frame after an AND operation has no non-zero element, the current hot spot frame becomes background frame and the counter is reset to zero. Also, if a frame number is a multiple of ten current hot spot frame becomes background frame.
19. Centroids of blobs from the resultant frames are placed on the image for convenience of finding the locations of the persistent hot spots.
20. Steps 6 to 19 are repeated for all the frames except starting frame.

3.2 Application of SVD to hot spot location detection

SVD can be viewed as a method for reducing data and identifying and ordering the dimensions along which data points exhibit the most variations [13]. In [14], SVD of imaging data has been successfully used to resolve the complex internal structures formed by the ambient gas–plume interaction. In our case it is applied on an image containing hot spots to find their locations.

Let B denote an m×n matrix of image data, where, without loss of generality, $m \geq n$ and b_{ij} is the element of image. The equation for SVD [15], [16]of B is the following:

$B = PQR^T$, where P is an m×n matrix, Q is an n×n diagonal matrix, and R^T is also an n×n matrix. The columns of P are called the left singular vectors $\{p_k\}$ and form an orthogonal basis for the intensity profiles so that $p_i \cdot p_j = 1$ for $i = j$ and $p_i \cdot p_j = 0$ otherwise. The rows of R^T contain the elements of the right singular vectors $\{r_k\}$ and form an orthogonal basis for the gene transcriptional responses. The elements of Q are only nonzero on the diagonal and are called the singular values, i.e., $Q = \mathrm{diag}(q_1, q_2, \ldots, q_n)$. By convention, the ordering of the singular vectors is determined by high-to-low sorting of singular values, with the highest singular value in the upper left index of the Q matrix. Singular values and corresponding singular vectors contain complete information about the image block, and most of the image energy is grouped in the higher singular values. Thus, replacing the original matrix B by its rank-k approximation tends to reduce dimensionality, decrease the effects of noise, and enhance the desired signal. Therefore, SVD is used to approximate the matrix, decomposing the data into an optimal estimate of the signal and the noise components

$$B = p_1 q_1 r^T_1 + p_2 q_2 r^T_2 + \cdots + p_k q_k r^T_k .$$

As mentioned earlier, there exist a certain number of singular values that signify the image components, and the remaining singular values represent the noise. Therefore, various principal images can be obtained by the SVD, and the first three principal images, for example, can be described by $p_1q_1r^T{}_1$, $p_2q_2r^T{}_2$ and $p_3q_3r^T{}_3$, respectively. The first, second, and third principal components are defined by $q^1r^T{}_1$, $q_2r^T{}_2$, and $q_3r^T{}_3$, respectively. In this paper, only first principal component is used to determine location of the persistent hot spot as it carries the most significant information and other principal components does not add any meaningful information to our requirement. Use of more than one principal component is redundant and computational demanding and hence, we use only first principle component in our analysis.

IV RESULTS AND DISCUSSION

In this section we present the results obtained with our algorithm on recorded plasma shots of tokamak ADITYA and relevant discussions on the success and failures of our algorithm along with its usefulness. It is appropriate to briefly introduce the data set (videos), the parameters for analysis and the system used for analysis at this stage.

TABLE 1: Data Set

Plasma shot number	Number of frames	Number of frames detected wrongly	% of wrong detection
28802	1700	78	4.59
28816	2940	309	10.51
28980	2200	87	3.95
29029	2600	218	8.38
29180	2210	114	5.16
Overall	11650	806	6.92

TABLE 2: Common Properties of the video shots

Property	Value
Width	450
Height	400
Frame rate/s	5
Bits per pixel	24
Video format	RGB24

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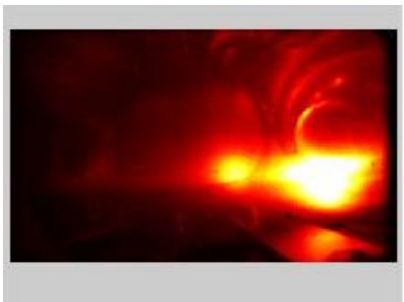
TABLE 3: Parameters used for analysis

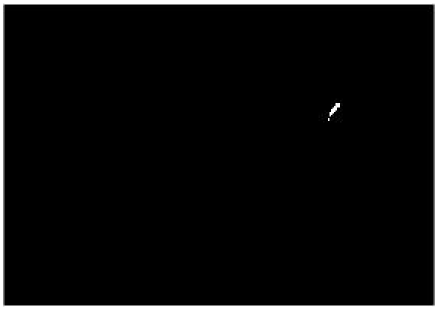
Binary conversion threshold	0.7
Blob area threshold for separating hot spots from gas puffs	1000 pixels
Blob centroid value to distinguish between hot spots and gas puffs	185
1 pixel equivalent physical area	10 mm × 10 mm
Duration fixed to separate persistence hot spot and transient hot spots	2 s
Number of principle components for SVD	1

Our algorithm is developed with the aim to detect abnormal events during Tokamak operation with focus on detecting plasma-wall interaction (hot spot) with the use of single vision camera. Fig.1 represents a typical case of hot spot detection. Fig.1 (a) shows frame number 1343 from video shot 28980. Fig.1 (b) shows the cropped-binary image for the same frame having blobs. The gas-puff reflection is observed as small blob at the bottom. The hot spot is differentiated from the gas-puff and its reflection by using area and centroid statistics of the blobs as per our proposed algorithm. The detected hot spot and gas-puff with its reflection are presented in the binary images in Fig.1(c) and (d), respectively. Finally, the SVD is applied on the hot spot and its location along x-axis and y-axis is found from the width of the pulse seen in Fig.1 (e) and (f). The height of the pulse represents the value of first principle component along specified direction. For this frame, the pulse exists between 33 and 33.5 along x-axis means it exists between 330th and 335th column of the original frame. Similarly, for y-axis the pulse exists between 101th to 110th rows of the original frame.



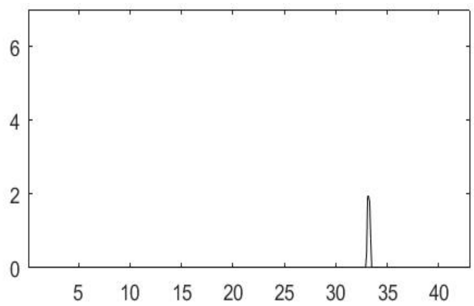
(a)

(b)

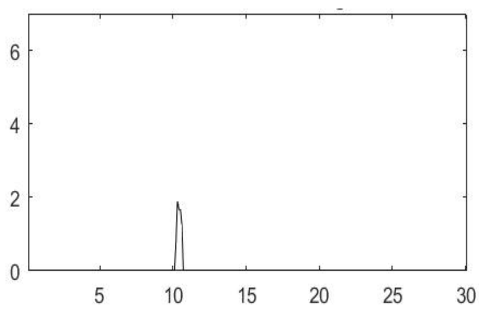


(c)

(d)



(e)



(f)

FIGURE.1. (a) Original Video frame (b) Cropped- binary image of the original video frame (c) hot spot (d) Gas-puff with its reflection (e) First principle component of hot spot along x-direction (f) Firs principle component of hot spot along y-direction.

Fig.2 shows pairs of video frames with other events detected with the proposed algorithm. On the left we have shown original video frames. On the right we have the events detected (or no events at all). All the frames shown in Fig.2 are taken from video shot number 28802 of tokamak ADITYA. It may be noted, however, that the events detected in Fig.2 are not all abnormal. They do occur in most of the video shots during tokamak operation.

Our algorithm successfully detected plasma-wall interactions on most of the frames available for analysis. However, no algorithm is perfect and this one is also not an exception. The statistics for erroneous detection of frames are gives in TABLE.1. The overall percentage of frames detected wrongly is about 7%. In Fig.3 we have summarized some frames where our algorithm failed to detect the events as either area or centroid value thresholds were not met. All the images are taken from shot 28816 of Tokamak ADITTYA. Images in Fig.3(a) to (d) shows how a plasma-wall interaction is misjudged as gas-puff cloud. While images in Fig3(e) to (f) depict the case where reflection from a gas-puff is misjudged as a hot spot while a plasma-wall interaction is merged with gas-puff and misjudges as gas-puff only.

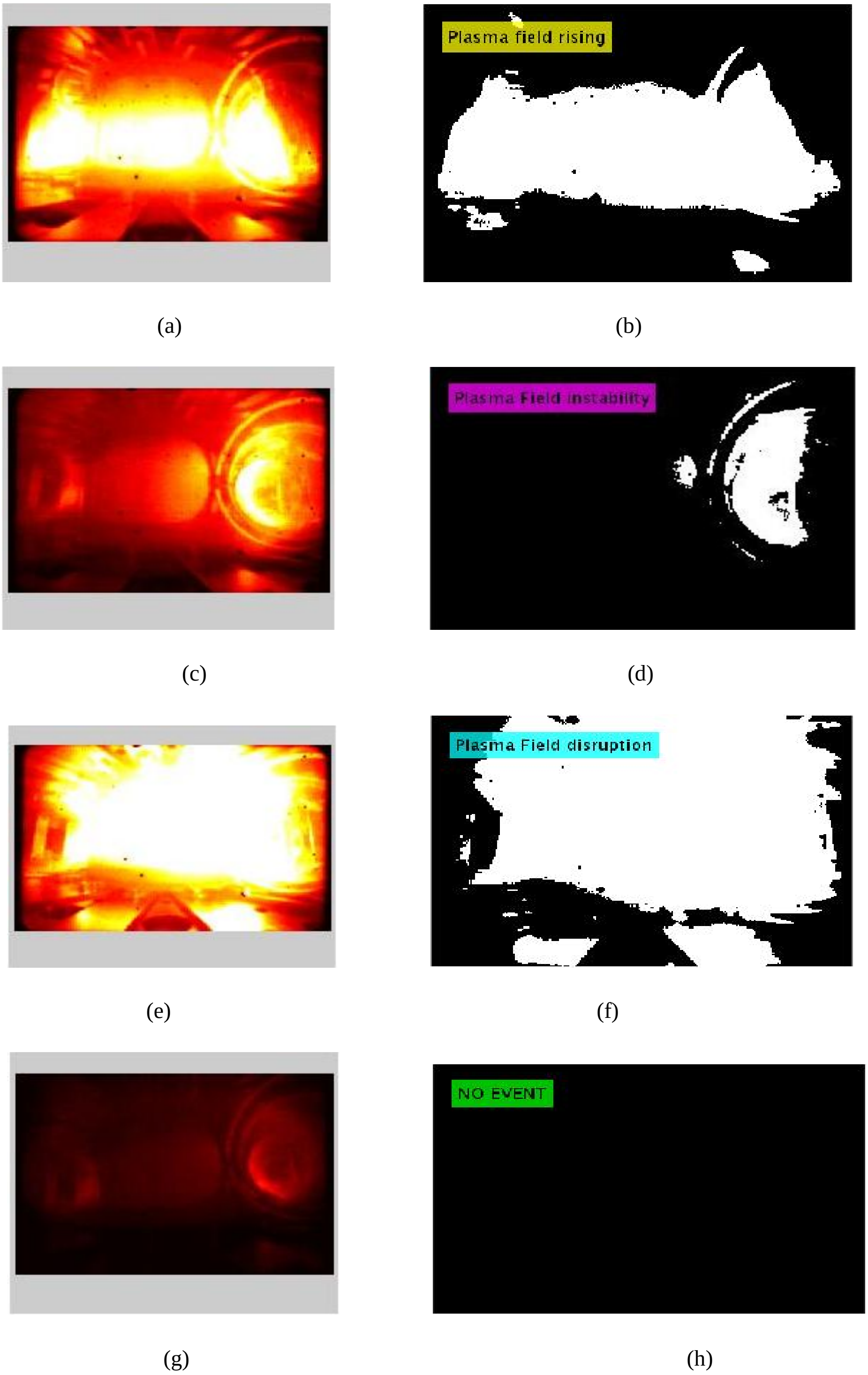
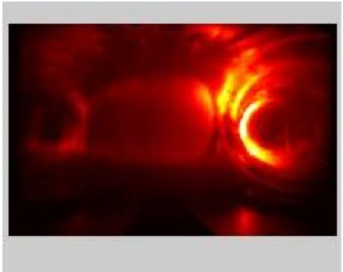
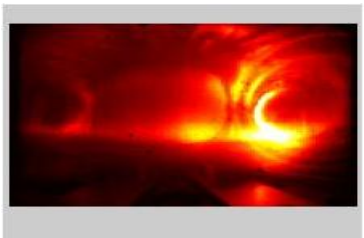


FIGURE. 2. (a) and (b) Original video frame number 12 and event detected is plasma field rise during initial phase, respectively. (c) and (d) shows original video frame number 120 and the event detected is plasma field instability while field is set up. (e) and (f) original video frame number 1617 and the corresponding event detected as plasma filed disruption. (g) and (h) original frame number 242 with no event.

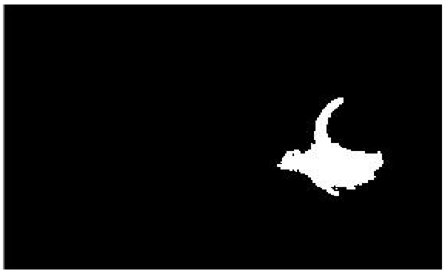



(a) (b)


(c) (d)




(e) (f)

(g) (h)

FIGURE. 3. (a) Original video frame number 1244. (b) copped-binary image for the same frame. (c) Image containing plasma-wall interactions (hot spots). (d) One of the plasma-wall interactions detected wrongly as gas-puff. (e) Original video frame number 1283. (f) Cropped binary image for this frame. (g) Image containing hot spots also shows reflection of gas-puff as one hot spot, wrongly. (h) A hot spot merged with gas-puff cloud and detected as a large gas-puff.

V SUMMARY

Blob statistics with SVD was successfully applied on recorded videos to detect the event of plasma-wall interactions during tokamak operation. The area and centroid of blobs provide a reliable base for analysis and detection of plasma-wall interactions and other events. SVD helps locating plasma-wall interactions as well as its dynamic nature in the given frame effectively. The proposed algorithm reduces high demand of user-interaction by detecting abnormal events and generating alarm as well as providing information about the location of the abnormal event. However, it should also be noted that this algorithm is sensitive to the parameter value and its performance may vary significantly with changes in parameter values.

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