Application of digital imaging techniques to flare monitoring

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Abstract. This paper presents a technique for detecting and monitoring flares in harsh industrial environments with the use of an imaging sensor combined with digital image processing. Flare images are captured via an imaging fibre and analysed to detect the flare’s presence and region of interest. The flare characteristics are then determined using various image processing algorithms. A prototype system is designed, constructed and evaluated on a purpose built laboratory scale flare test rig. Results indicate that the imaging based technique has potential for the detection, monitoring and analysis of flares amidst various background conditions in the chemical and oil industries for plant safety, pollution prevention and control.

1. Introduction
In oil refineries and chemical processing plants it is a common practice as a part of the plant process to release gases via a stack to burn [1] in the atmosphere, when more fuel gas is produced than the actual requirement and for emergency events due to plant malfunctions [2]. These flares are produced at a considerable height above a stack [3] to elude the possibility of plant area ignition for human safety and to avoid hazards due to heat releases. The flared gases are ignited by a pilot flame, which is located at the root of the flare, so that purge gases and the vent gases can be readily combusted [4]. The pilot flame should be continuously “ON” and has a continuous fuel gas supply to do so [5]. It is mentioned [6] that the chemical process used for flaring is high temperature oxidation that burns hydrocarbons which reacts with atmospheric oxygen to form CO₂ and water. The environmental regulations indicate that the requirement is for smokeless burning [7], whereas the safety requirement is the issue of thermal radiation [6]. The smokeless burning of a flare is considerably obtained by assisting it with steam [7] that causes turbulence but creates some sound levels.

Traditionally flares are monitored for abnormalities by an operator on a 24x7 observation, which is not reliable [8]. Other sensing techniques have been used to monitor flares. These include infrared spectroscopic sensing [9] that is generally very inaccurate due to environmental interferences [3]. A thermocouple approach has also been used but has problems of failures due to corrosive effects of the environment, high maintenance requirement, and limitations of single point measurement. To replace a thermocouple requires an expensive shutdown [10]. CCTV cameras have also been used to monitor flares [11]. Similarly, a colour video camera [2],[8] has been used to detect and analyse the characteristics of a flare. Apart from this work, there is little report of the use of imaging sensors for flare monitoring. It is hence recognised that there is a demand for an imaging based flare monitoring system that could be easily viewed from the control room, have least maintenance requirement and could also assist by monitoring the presence of the flare and presenting certain important flare characteristics on a graphical user interface. This paper presents a demonstration system that is designed for flare monitoring through the application of an imaging sensor in conjunction with an imaging fibre.

2. System Description
Figure 1 shows the basic concept of the imaging based flare monitoring system. It consists of an imaging fibre of 6k resolution and an objective lens with a 90 degrees field of view (Figure 2). The objective lens is mounted with a focus directed towards the flare on the platform whilst the imaging sensor, a 640x480 pixel C-mount colour camera, is placed at the ground level. The image signal is sent through USB (or Ethernet) to a microcomputer that incorporates flare analysis and monitoring software. An alternative configuration of the system is to use an embedded system instead of a microcomputer, indicating whether the flare is present and its approximate size, i.e. low, medium or high.
Since gas is available in abundance, a single layer cooling jacket, as shown in Figure 2, will be deployed to prevent the fibre view port and the front end of the fibre bundles from excessive heat from the flare. The view port of the fibre has a protective window to avoid contamination of the objective lens. The fibre from the platform level to the camera at ground level would have a protective shield.

3. Image Processing Principles
The flare images captured from the imaging system (Section 2) are processed using a novel method for detection and a combination of various existing image processing algorithms to quantify the characteristics and behaviours of the flare.

3.1. Flare detection and visual dynamism
The first flare frame is captured and saved for a fixed time, depending on the camera frame rate, until the next frame is captured. The two frames $F_x$ and $F_{x+1}$, which represent the first and second frames, respectively, in a video sequence, are subtracted to obtain the difference image wherein the like-pixel regions of no change within the frames $F_x$ and $F_{x+1}$ will result in the $R$, $G$ and $B$ values of the difference image to ‘0’, i.e.

$$X = \sum_{n=1}^{N} \sum_{k=1}^{C} (F_{(n-1)c} - F_{(n-1)c+1})$$

Where $N$ and $C$ are the number of frames/processing set and the maximum frame rate of the camera, respectively. Similar to frame subtraction, the two frames are also added to obtain the summation image:
Here the flare dominated regions within the respective frames $F_x$ and $F_{x+1}$ will result in the R, G and B values to its maximum, i.e., ‘255’. The value ‘N’ in this research is taken to be two frames out of twenty-five frames per second that the camera can capture. The higher the value of N at a higher frame rate, the better the difference image. For every check of the condition that two consecutive frames are captured, the first data set is processed until C=25fps after which the cycle repeats.

The above processing technique in turn relates to the flare background information and the flare (size/shape) identification, respectively. The two processed images (X and Y) are further used to obtain the disparity visualisation (Z) in absolute, which displays the dynamism of the flare by overlapping the two images over each other and assisting in obtaining the region of interest, i.e., the pixel areas cover the flare dynamism in the video images for the two frames, respectively.

$$Z = \left| (X+Y) \right|_{F_{x+1}}$$

Where $\left| (X+Y) \right|_{F_{x+1}} \geq 0$ and $\left| (X+Y) \right|_{F_{x+1}} = 0$ if and only if $(X+Y) = (F_{x+1})_c$.

This is dependent on the camera frame rate ‘C’, as a higher frame rate would represent a closer disparity visualisation of the two frames in time, thus indicating rapid changes of the flare.

### 3.2. Flare analysis

Image processing techniques are then used to convert the image frames to gray-scale images ($F_{gx}$ and $F_{gx+1}$) and binary images ($F_{bx}$ and $F_{bx+1}$), where $F_{gx}$ and $F_{gx+1}$ will have values between 0 to 255 for gray-scale while $F_{bx}$ and $F_{bx+1}$ will have values of ‘0’ or ‘1’. A logical ‘OR’ operation is then performed for reliable and robust processing of the binary images of the two frames as one of the preliminary steps prior to edge detection and contour identification. This process can be summarised as follows:

$$F_x(R,G,B) \rightarrow F_{gx}(0 \text{ to } 255) \rightarrow F_{bx} (0,1)$$

$$F_{x+1}(R,G,B) \rightarrow F_{gx+1}(0 \text{ to } 255) \rightarrow F_{bx+1} (0,1)$$

$$P_b = F_{bx} (0,1) \text{ OR } F_{bx+1} (0,1)$$

Where ‘$P_b$’ denotes the processed binary image. Edge detection using the Canny algorithm and contour identification is then performed for the purpose of flare analysis. All the algorithms are developed and tested within the Matlab environment.

### 4. Experimental Results and Discussions

To evaluate the image processing algorithms for flare detection and analysis, experiments were carried out on a purpose built laboratory-scale test rig that can replicate industrial flares. The flare images were captured at a rate of 25 frames per second using the imaging system (Section 2). However, the images presented in this section are straight from the camera firmly angled towards the flare. The fuel used was propane. The image processing algorithm was tested under different background conditions, including day and night conditions as well as steam assisted flares and air assisted flares.

#### 4.1. Flare detection and visual dynamism

The two frames $F_x$ and $F_{x+1}$, as shown in Figures 3(a) and 3(c) were captured from a stream of images by the camera under day and night conditions, respectively. The application of equations 1 and 2 has resulted in the difference image and summed image as shown in Figures 3(b) and 3(d) that are then used for flare detection and determination of the visual dynamism and region of interest.
The processed images are significant as frame subtraction indicates that the like-pixel regions of almost no change or very slow change within frames $F_x$ and $F_{x+1}$ that includes the background and a part of the stack will result in the R, G and B values of the difference image to ‘0’ which is displayed as black colour. Similarly, on performing frame addition the pixel regions of the flare dominated regions or the fast moving regions for the two consecutive frames $F_x$ and $F_{x+1}$ will result in the R, G and B values to its maximum, i.e., ‘255’ which is displayed as white colour. The second processed image is also used to determine the size, shape and region of interest of the flare. The algorithm then takes these images and performs the disparity visualisation $(Z)$ calculation as per equation (3). The absolute of the two processed images is used to find the difference from the most recent image, thereby displaying the image that assists in visualizing the dynamism of the flare.
Figure 4: Visual dynamism and region of interest detection under day and night conditions

Figure 4 shows the visual dynamism of the flare that assists in identifying the direction of the flare, the spread within the atmosphere, the flare shape and the energy or rapid changes of the flare. The result confirms that the technique as described is simple and effective for flare detection that also indicates the dynamism, shape and structure of the flare. The region of interest is obtained reliably by finding the max height of the flare which is obtained by locating the lowest and highest vertical pixels with a maximum R, G, B value of ‘255’, respectively, and the width, which is obtained by locating the lowest and highest horizontal pixels with a maximum R, G, B value of ‘255’, respectively. These maximum pixel values are then taken as a reference to draw a rectangle automatically within the software GUI indicating the region of interest of the flare. This technique, however, requires the viewing end of the imaging fibre to be securely installed and any movement of the fibre while capturing two consecutive frames could result in false detection as the algorithm would underperform.

4.2. Flare Analysis

Out of the flare images obtained in time that depends on the camera frame rate, every two successive image frames were converted to gray-scale images as shown in Figure 5. These images illustrate the observations for one set of images captured under different conditions of flaring, both assisted and non-assisted. There was consistency in the observations for a particular condition and to analyse these effects such as missing combustion spots and soot formations for various assisted conditions on the flare that are fairly random due to the highly dynamic nature, the gray-scale images of the two frames were then converted into binary images. When the binary images were observed, changes in the flare characteristics are clearly evident due to fuel addition, air assistance and steam assistance. To obtain accurate and reliable results a logical ‘OR’ operation was performed on the binary images after which edge-detection using the Canny algorithm and contour identification techniques were applied. It was observed consistently for images due to respective conditions that the non-assisted flare produced a brighter image with missing combustion spots indicated by the contour identification that were observed inside the outer edge of the flare; this could be due to the lower cracking of the fuel (propane) hydrocarbons as there is limited supply of air. The air-assisted flare did not have significant changes, but it is larger in size due to the richer supply of oxygen for cracking down the hydrocarbons, thus the contour indicating lesser spots of incomplete combustion. The steam assisted flare has the least brightness and is a turbulent flare with clean and leaner combustion as observed from the contours and binary images. This result indicates that image processing techniques can be applied to obtain significant information about a flare and suitable for both online or offline flare analysis.
5. Conclusion

A flare monitoring system using a colour imaging device and an imaging fibre has been proposed. The novel algorithm for the detection and visual dynamism observation of a flare has been tested successfully for reliability and robustness assessment on a laboratory scale flare test rig under real atmospheric background conditions. Image processing techniques have been applied effectively to obtain relevant information for the purpose of analysing the effects of assistance on the flare. Future work will include the identification of different constituents of the gas flaring and continuous tracking of the type of gas being flared. It is envisaged that the proposed flare monitoring technique will assist the oil, gas and chemical industries to achieve cost-effective maintenance, enhance plant safety and reduce harmful emissions.

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