An Automated Solution for Controlling Random Fires on Coal Yards

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Abstract

In spite of recent moves to wean the world of fossil fuels, coal remains the main source of power in many countries. Coal yards are prone to spontaneous ignition, a problem faced in every country that stores or transports coal. Depending on the environment – temperature, ventilation, and the rank of the coal – heating and self-ignition can be a longer or shorter process, but the possibility can never be entirely dismissed. A plethora of studies have modelled this oxidation behaviour and proposed countermeasures. Most often, human intervention is necessary, which is both slow and dangerous for the firefighters involved. In this study, we propose to build a complete firefighting solution which is mounted on a number of towers sufficient to cover the area of an open coal yard, complete with redundancy. Each tower includes an inexpensive infrared detector, software to identify areas of elevated temperature, and a water dispenser. The heat detection software calculates the parameters to position the water dispenser so that it covers the area. A prototype has been built from inexpensive components to demonstrate the effectiveness at detecting and extinguishing arising fires. This work has been conducted in collaboration with the managers of the coal yard of a power plant.

Keywords: Coal yard fire, fire detection, internet of things, spontaneous combustion detection, infrared heat detection

1. Introduction

Coal is a leading energy source among non-renewables which can be burnned for energy or heat. About two-thirds of the coal mined today is burned in power stations to make electricity. Coal is first milled to a fine powder, which increases the surface area and allows it to burn more quickly. In these pulverised coal combustion (PCC) systems, the powdered coal is blown into the combustion chamber of a boiler where it is burnt to drive a steam turbine. Pricing and a deliberate reduction of sulphur content have led to a shift from traditional bituminous coal to subbituminous coal, which is of a lower rank than traditional coal. The lower the rank, the higher the risk of oxidation, as the coal contains more moisture and higher amounts of volatile matter [1]. Oxidation generates heat, and if the heat does not dissipate fast enough, self-ignition occurs. Therefore, ventilation and ambient temperature play an important role in the self-ignition of coal. Ventilation provides oxygen but also dissipates heat. The most dangerous conditions arise under high ambient temperatures and low continuous air flow.

Coal is exposed to spontaneous combustion in mines, storage and during transport. The spontaneous ignition is a constant danger in every country that runs coal facilities, from South Africa [2] to the US, many European countries, India and China [3]. In Australia, the Hazelwood open cut mine was ablaze for weeks in February 2014, incinerating 45 houses and necessitating the evacuation of the town of Morwell in Victoria [4].

To monitor the coal facilities for developing fires, most often heat sensing is applied, alternatively the levels of combustion-related gases like CO_2 levels are monitored [1]. Fire prevention relies on the reduction of available oxygen, targeted ventilation for heat reduction or special measures such as the application of gels. Water, foam or nitrogen (in closed, airtight facilities) are used to extinguish fires [5].

Coal yards or open cut mines allow a good visual overview of large areas, which opens the opportunity for video surveillance. Although UAV-based infrared sensing has been proposed [6], the method does not provide any automated response, although it uses intelligent algorithms to identify the location of potential fires.

In this study, infrared sensors are used to monitor the heat emanating from the coal storage. The location of the heat source is determined and water pumps are pointed into its direction using actuators. This avoids the need for human fire fighting, which is is obviously a hazardous task close to a burning coal fire, but also slow, as the responder first has to get to the fire. In essence, the contribution of this paper is a complete solution for the cost effective control of random fires on coal surfaces as they are found in coal yards, open containers and open-cut mines.

2. Background

Coal fires are a constant hazard in coal production and consumption. The extent of the problem in China, the largest producer and user of coal, has been documented by Song and Künzer [7]. They also provide a comprehensive overview of detection and firefighting methods applied in the context of coal fires. Numerous detection methods have been applied under ground, on ground level, from the air and even from space. Many of these approaches are suitable for large areas, such as Künzer et al. [8]. Thermal imaging from UAVs has been proposed for landscapes difficult to access [9]. A theoretical model to predict the most susceptible areas has been presented [10]. The electrical potential, arising from oxidation and/or the change in temperature, have also been explored as indicators [11, 12], as have electromagnetic [13] and electrical [14] imaging, as well as ground-penetrating radar [15].

Clearly, most of these approaches focus on natural deposits of coal that may catch fire in often remote areas. Underground coal seam fires and their prevention have been the topic of many studies [16]. As the conditions are quite different, these methods are generally not applicable in coal yards. A few articles investigate combustion suppression in coal storage facilities. Kim and Sohn [17] modelled the temperature and ignition behaviour of a – roughly pyramid-shaped – heap of coal and verified it against and actual coal storage in Korea. According to their observations, heat travels from the aerated sides of the pile towards the middle over a period of 100 days. The authors experimented with a 2m high wall 5m from the edge of the pyramid to separate the coal on the sides into compartments. This was shown to delay ignition by about 15 days. Ventilation of the pile through holes in the ground below was also investigated, and found to have a detrimental effect at flow rates below 100 l/s. A dual wind barrier produced the best effect, delaying the ignition by 28 days given a wind speed of 10 m/s.

Using computational fluid dynamics, Taraba et al.[18] investigated the effect of wind on the heating of coal, finding that the heat shifts toward the centre of the pile with increasing wind speeds. In similar work, Zhu et al. [19] simulated fluid dynamics for bituminous coal, concluding that an oxygen concentration of 5% and sufficient wind velocity can balance the heat in a pile. A considerable number of studies that model the ignition behaviour exists [20, 21, 22, 23]. A few laboratory-based experimental studies have also been published [24, 25].

In addition to the mitigation strategies discussed by Kim and Sohn [17], nitrogen has been used to extinguish fires in closed spaces [1], tight coal layering is often practised [5] and gel is sometimes spread on the surface to prevent exposure to oxygen [5]. Water from fire hoses is recommended as an easy solution, but only has effect on the top layers [1].

Figure 1: Surface of coal yard in Norocholai.

The use of sensors in firefighting is not new. Commonly, the area to monitor is too large to cover with sprinklers, and sensors are used to inform the firebrigade [26, 27]. Recently, Eltom et al. [28] introduced an IoT solution for home fire protection, where the detector primarily alerts the owner while shutting down power, it can also be programmed to actuate a Sprinkler system. A great number of studies, e.g. [29, 30] propose robotic fire fighting systems. In practice, these face numerous challenges, which make them costly and of limited use [31].

Based on the alternatives available, the following solutions were considered for implementation:

The following options were considered for implementation:

1. Converting the storage location to a more controlled environment with less oxygen.
2. Importing coal of a higher grade which is less likely to ignite.
3. Deploying fire-fighting robots on the yard.
4. Develop a solution of moving water containers suspended on support grid.

5. Using a fire detection system that controls sprinklers.

Solutions 1 and 2 were dismissed as too expensive. Option 3 was not pursued due to the problems an uneven ground would pose for robots. As our case study example in Fig. 1 shows, coal yards are not flat, but contain heaps as well as depressions where coal has been extracted to feed the power plant. Solution 4 faces similar problems. The metal grid envisaged as a rail structure to move along may bend under the weight of the container unless supported at short intervals. In addition, the container may take a long time to traverse its designated area, and fires may have time to take hold in the meantime, if they ignite at the 'wrong time and place'. Given this topology of an open coal yard with limited depth of coal, it was decided to explore a solution based on option 5. Several visits were made to the coal yard and the solution was discussed with its representatives.

3. Pole-mounted firefighting system

Spontaneous ignition can lead to fires burning out of control, endangering human life, incurring financial losses and releasing harmful gases into the atmosphere. Fighting fires before or immediately after they occur is a pressing priority. Water sprinklers are inexpensive, environmentally friendly and effective. Infrared heat sensing is inexpensive and reliable. For a fast and reliable response, each sensor is equipped with an actuator that can point a water valve to the best location. A water pump delivers the flow needed to extinguish or prevent the fire at the position from which the heat emanates.

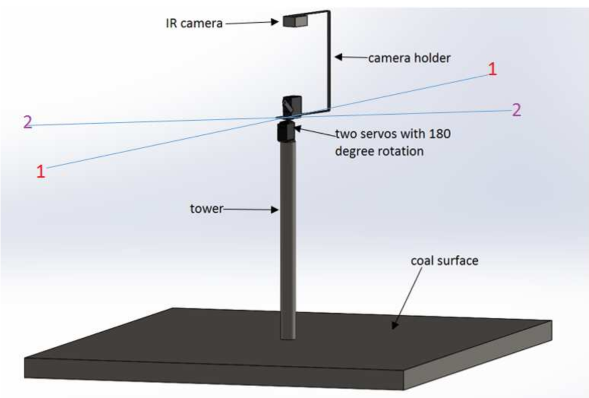

Figure 2: Pole design used in the solution.

A single system consisting of sprinkler, detector and the pertinent actuator and detection software cannot cover an entire coal yard. A coal storage unit is covered in a grid of firefighting systems, which also provides redundancy. The following sections explain the system in detail.

3.1. Detection

For the fire detection, a number of sensor options have been developed for home and industrial use. One of the most prevalent solutions is smoke detection, which can use either the ionisation or photoelectric methods. Both rely on chambers where smoke concentrates, by detecting the changes in either the lighting or the ionisation of the particles in the chamber. As such, they are badly suited for open, ventilated spaces. Similarly, RGB images have difficulty capturing smoke that dissipates fast in open areas. Heat detection is problematic in warm countries, and the problem is exacerbated by the natural variations in temperature across the coal yard. Fires can also start as a smoulder, creating little heat until the fire intensifies. Temperature sensors have to be installed at a distance from the surface, which introduces further delays in detection. In contrast, Infrared (IR) sensors can detect heat reliably from a distance. They are also inexpensive, as normal webcams can be used after removing the IR filter. This solution was trialled in the prototype.

With the IR filter removed, a video of the coal surface was recorded by a camera overseeing part of the area. The frame rate was set based on the time it takes to process each image and initiate appropriate action: Sufficient time has to be allowed between two frames to allow the processing of the image to detect a fire, determine the coordinates in case of a fire and communicate with the actuator that triggers a response.

Given a single frame, the controller interprets the brightness of the pixels and identifies potential areas of heat, based on a threshold provided. The image processing uses the OpenCV[1] library.

The algorithm is shown in listing 1. Each image is processed by initially removing noise and areas not lit brightly. This means after this step, only self-ignitions are visible on the image. Then these self-ignition regions are converted to contours and their areas are calculated. In the next step, the contour with with the largest area is determined, as this identifies the area where the self-ignition event is spreading the most at that moment. If there are several self-ignition events on the same frame, priority is given to this location. The coordinates of the centre point of this contour are calculated and used to determine the angle for the water jet, as well as the voltage needed to create the water spray.

[1] https://opencv.org/

Algorithm 1: Detection of self-ignition area

```
Data: Frames from IR camera, frame rate,
      brightness threshold
while Next frame available do
    remove noise;
    select areas brighter than threshold on grey
      scale ;
    if areas exist then
        construct contours around bright regions;
        calculate areas of bright regions;
        determine largest area ;
        calculate centre coordinate of largest
          area;
        calculate angle of coordinate from jet;
        calculate voltage needed for pump;
        call modules for water dispensation;
    end
end
```

The routine ends when the controller calls other modules to trigger the water jet for response.

3.2. Water dispensation

To adjust the water dispensation valve, servo motors were selected which rotate the nozzle to the required coordinate. Servo motors do not require a motor driver and can be connected directly to a power supply, and they provide precise angle control. They also have a good stall torque, meaning the position of the motor arm is sufficiently stable against external torques applied on the motor arm. This will ensure, after rotating the motor arm to calculated position, that the arm does not move due to weight of the water hose, or due to the jerks induced from rapid flow rate variations of the water jet.

3.3. Prototype

A simple webcam was used for the IR imaging, with the IR filter removed. The camera was mounted on a movable support as shown in Fig. 3a, because the camera orientation may likely have to be adjusted once the system is installed in the coal yard. Fig. 3 illustrates the prototype installation.

The MG996R servo motor was chosen due to its accurate position control. Mounting two motors on top of each other, it is possible to cover a 360°area using 180°rotation servo motors. The lower servo motor rotates 180°, while the upper servo motor is attached to an arm which carries it up to a further 180°as the lower servo rotates. For each position of lower servo between 0°and 180°, the upper motor is capable of covering series of points which lies on a straight line going through two quadrature making it possible to shoot water at any point that lies on any quadrature within the field of view of the camera.

For the water pump, the Anself Ultra-Quiet Mini DC 12V model was chosen, an IP68 grade fully submersible pump with 30,000 hours of working life with a flow rate of 300l/h and a maximum head of 4.5m, meaning it can lift the water up to this height.

A circuit board had to be created to connect all components, which were powered through regulators to ensure a safe environment. Also, a 5V/12V relay was used to switch the water pump following a signal from the Arduino. Fig. 4 shows the completed electronics.

Arduino provides an API for the rotation of servo motors, however without the option of setting a rotation speed. Therefore, a separate function had to be written to turn the motor smoothly and slowly to the required position.

3.4. Cost

The components used for the prototype were chosen to be sufficiently robust for a practical installation at a coal yard, yet very inexpensive.

Item	Cost ($)
Webcam	15.00
Vero board + connectors	10.00
2 MG996R motors	20.00
Anself Ultra-Quiet Mini DC 12V	10.00
Arduino MEGA controller	40.00
Hoses, arms, equipment	15.00
Total	110.00

Even though we did not quote the lowest prices available, all required items cost $20 or less each, except the Arduino controller. Therefore, at a conservative estimate, the prototype is worth around $110 in total.

4. Case Study

4.1. Coal yard site

The only coal yard currently in operation in Sri Lanka services the Lakvijaya Power Station, situated in Norocholai, Puttalam, on the southern end of the Kalpitiya Peninsula. Due to its location, the plant is also known as the Norocholai Power Station. The $450 * 150m^2$ yard is supplied twice a year by ships which moor at a distance and unload to boats which land at a purpose-built jetty. Three conveyor belts distribute the coal across the yard, from where bulldozers push it onto underground

(a) Complete pole with camera and first version of dispensation (b) Detail of water dispensation, revised version

Figure 3: Details of the prototype built, with camera on top of the pole and water dispenser at the lower level. The water dispensation was revised after experiments

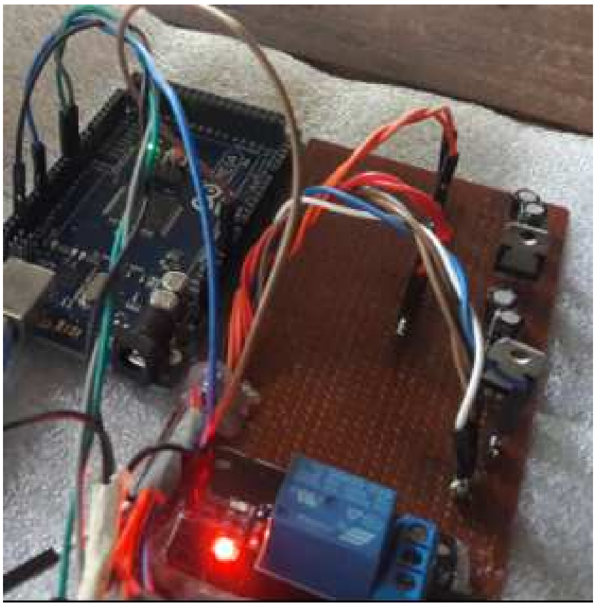

Figure 4: Completed circuit board

conveyor belts that transport it to the power plant. The conveyor belts are equipped with sprinklers to prevent ignition in transit. About a quarter of the coal stored is under cover to keep it dry. The ambient temperature of a tropical region, the internal energy of the coal and the coastal wind providing ample oxygen are all factors that increase the combustion hazard. In addition, Puttalam is one of the hottest regions in Sri Lanka. Areas of oxidation are invariably going to emerge over time, and these tend to build heat over several days until self-ignition. To alleviate this risk, three measures have been put in place at the plant:

- Sprinklers over the conveyor belts ensure the coal is moist on arrival.
- Wind barriers were installed on the shore side.
- Bulldozers compress the coal in the vicinity of fires. This poses a hazard to the drivers of the bulldozers.

Although the yard is the only coal storage in Sri Lanka at present, increasing power demands and limited availability of hydro power may lead to the introduction of new plants in the future.

4.2. *Installation at the coal yard*

For the purpose of the installation of towers equipped with detectors and water jets as trialled in the prototype, the area of the coal yard at Norochcholai Lakvijaya Power plant is subdivided as shown in Fig. 5. Each

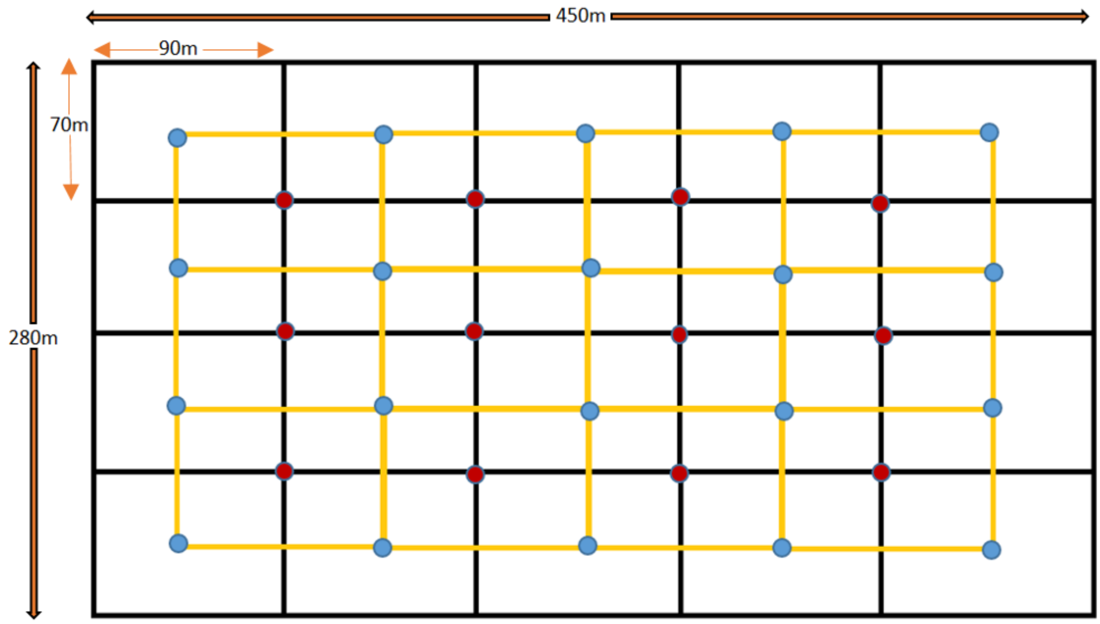

Figure 5: Pole coverage of Lakvijaya coal yard. The blue dots are the towers to cover each of the 20 rectangles. The red dots show the location of supplementary towers which cover the bases of the first set of towers.

camera and water jet cover a rectangular shape having with a width of 70m and length of 90m, which leads to 20 towers placed at the blue dots. The equipment of each tower cannot reach the very base of the tower. Therefore, a second set of towers are placed at the locations marked by red dots, where they can also serve as backup for the region between the first set of towers. This means that the area covered by yellow rectangles is monitored by two towers. This provides robustness through redundancy: If one tower becomes inactive, a backup tower can still fight an emerging fire. The area outside the yellow rectangle is monitored only by one tower. This region is at the boundary of the coal yard and automatically monitored by personnel moving around the area performing tasks. Therefore, the absence of dual coverage in this area is not considered as dangerous.

The height of the poles needed to cover the rectangles was calculated based on the movements of the cameras that can cover a 120° angle. As the pole is in the middle of the area, the longest distance has to fit into a 60° angle. The longest distance the camera has to cover is 57.008m, which is the diagonal of each of the four quadrants ('sub-rectangles') of the tower's rectangle, whose sides are 70m x 90m. Each of the four right triangles measures 45m x 35m, leading to a diagonal length of 57m. Hence, we obtain the height $h = 32.9$ of the pole by Eq.1, and determine the pole height as 33m.

$$h = \frac{57}{\tan 60} \quad (1)$$

Given the layout in Fig. 5, 12 base towers are needed, as well as 20 additional ones for redundancy in the middle of the rectangles. Disregarding the 33m pole construction with its anchoring, the electronic parts for this system would therefore cost \$3,520 at \$110 each as detailed in Table 3.4.

5. Discussion

A few improvements had to be made during the prototyping stage. The base on which the lower motor was mounted was square, and the corners of the square obstructed the path of the hose in some positions. The square was exchanged for a circular base, that fitted the motor exactly, which solved the problem.

The hose is fed through the bottom of the pole and comes out through an opening in the side of the pole.

Initially, the opening was too narrow, twisting the hose during some turns of the motors. The opening was widened, which prevented the twisting. Initially, saline hoses were used for the purpose. They did not prove very durable and were broken by the wear and tear of the movements during the experiments, so they had to be replaced with an industrial purpose pneumatic tube.

Another issue was the turn speed of the motors, which became stuck at the extreme positions if arriving there at full speed. The Arduino controller had to be programmed to take the motors to their positions slowly.

After these improvements, the prototype of the fire-fighting system worked well, identifying simulated heated areas. The system was tested by simulating the fires in all quadrants, and also at varying distances from the pole. Also, several fires were simulated simultaneously, and verified the ability of the system to extinguish all of these within a short time. The tests were repeated 50 times and only failed to extinguish a flame at the first attempt in 6 cases. Fig. 6 illustrates how one candle (of four burning) is extinguished. In Fig. 6a, the jet is still on the right of the flame, about to be turned into it. Fig. 6b shows the jet streaming at the high end of the flame. Figs. 6c and 6d see the jet reduce pressure to move lower towards the wick, which it hits in Fig. 6e. In Fig. 6f, the flame has been extinguished.

Initially, the water dispensation was planned as a point-shaped jet. This requires considerable precision in the coordination of camera and motors as well as the construction of the support pole. The unevenness of the ground is a further cause for error in the precision of the water dispensation. Eliminating these errors is time-consuming and error-prone, as unexpected shifts in the final installations could potentially compromise the effectiveness of the system. Therefore, the Arduino controller was programmed to instruct the two servo motors to move in circles around the coordinates of the centre of the detected ignition area. Initially, the jet is pointed at the centre of the area. The distance to each new circle – the step size – was determined experimentally based on the extinguishing effect. The successively larger circles were drawn until the radius of the current heating area was reached.

6. Conclusion

Once the coal has been mined, spontaneous combustion remains a problem as oxidation proceeds with a speed that depends on ambient temperature, ventilation, moisture and volatile matter. Constant observation and intermittent intervention are indispensable if catastrophic fires are to be prevented. An inexpensive solution has been explored in the current work and shown to react to building heat reliably with targeted water dispensation, which is also the most environmentally friendly solution.

The IR heat sensing solution does not require dangerous proximity to potential fires, and the automated actuation of the response is both quick and safe for humans. The testing was conducted under more difficult conditions than the actual ignition areas pose, as candles are very small and require higher precision than larger areas of coal. The water jet will rarely miss such an area entirely, rather skip small spots which may be no more than a few centimetres in diameter. These spots will be picked up by the analysis of the next frame, and also by the detector of the additional tower.

One of the remaining tasks is to correct for the effect gravity has on the water dispensation. The accuracy decreases with increasing distance from the pole. As a quick fix, the water pressure was increased to counteract the gravity. A mathematical solution that models the change of impact location as a dependency of the amount of water and the distance from the dispenser is planned as further work.

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(a) Location has been found and jet is initiated

(b) Jet is beginning to hit the flame

(c) Jet is hitting the flame but not the wick

(d) The jet is lowered towards the wick

(e) The flame is nearly extinguished

(f) The candle has been extinguished

Figure 6: Test that demonstrates how the prototype extinguishes a single flame the detector has identified as a heat source

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Competing Interests

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Authors' contributions

Jeevan Jayasuriya	: Conceptualization, Methodology, Software, Investigation, Resources
Irene Moser	: Formal analysis, Validation, Writing - Original Draft, Visualization
Ravi de Mel	: Writing - Review & Editing, Supervision

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Author's Information

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