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Intelligent Mine Periphery Surveillance using Microwave Radar

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and Vinod Kumar Singh*

Abstract

This paper deals with an intelligent mine periphery surveillance system, which has been developed by CSIR-Central Institute of Mining and Fuel Research, Dhanbad, India, as an aid for keeping constant vigilance on a selected area even in adverse weather conditions like foggy weather, rainy weather, dusty environment, etc. The developed system consists of a frequency modulated continuous wave radar, a pan-tilt camera, a wireless sensor network, a fast dedicated graphics processing unit, and a display unit. It can be spotting an unauthorized vehicle or person into the opencast mine area, thereby avoiding a threat to safety and security in the area. When an intrusion is detected, the system automatically gives an audio-visual warning at the intrusion site where the radar is installed as well as in the control room. The system has the facility to record the intrusion data as well as video footage with timestamp events in the form of a log. Further, the system has a long-range detection capability covering around 400 m distance with an integration facility using a dynamic wireless sensor network for deploying multiple systems to protect the extended periphery of an opencast mine. The field trial of this low-cost mine periphery surveillance system has been carried out at Tirap Opencast Coal Mine of North Eastern Coalfields in Margherita Area, Assam, India and it has proved its efficacy in preventing revenue loss due to illicit mining, unauthorized transportation of minerals, and ensuring safety and security of the mine to a great extent.

Keywords: microwave radar, FMCW, opencast mines, periphery surveillance, unauthorized vehicle intrusion detection

1. Introduction

One of the crucial challenges of the mining sector is the prevention of financial loss due to illegal mining and mineral theft through an unauthorized path. This loss inflicts severe assault on the financial health of both the mining industry and government. Safety and security lapse is another worrisome aspect of this sector. Mining production highly depends on the safe interface between mining machinery and human being. Their proper and optimum utilization helps to maximize the production and productivity of a mine. Hence, protecting both these elements from safety and

security hazards is a matter of immense importance. This calls for strict vigilance in the mine periphery to prevent unauthorized intrusion of any vehicle or person. Taking due cognizance of the stated situation, an intelligent mine periphery surveillance system (PSS) has been developed by CSIR-Central Institute of Mining and Fuel Research, Dhanbad, India, as a solution to these problems. Real-time detection of any suspected element or unwanted incidence by microwave radar and CCTV footage of the intruder is seen on the monitor, prompt alerting security personnel and thereby helps to avert untoward incidences by taking immediate action.

In recent years, microwave frequency modulated continuous wave (FMCW) radar has grown with demand in various domains. FMCW radars are found to realize the signals generated and processed in real-time for high-performance vehicle safety systems. The radar system has been employed in many safety applications, such as adaptive cruise control, crash mitigation and pre-crash sensing, to name a few. The FMCW radar can effectively detect moving and stationary target objects and are presently being marketed as safety systems for high-performance automotive applications as described by different authors [1–5]. This can also be applied in several other fields such as automotive applications, short-range radars for parking, traffic monitoring, anti-collision warning, adaptive cruise control, security, collision avoidance, defense, shipping, security, traffic, and medical imaging on under indoor and outdoor environments. The microwave FMCW radar security system is used for vehicle detection with a long detection range and high reliability, irrespective of environmental factors such as foggy weather, rain, dusty conditions etc. The range and velocity information of distinct targets may be measured concurrently in a short time for automotive safety applications. Various radar systems in use have been reported by several authors [6–14].

Unauthorized intrusion and illegal transportation of coal and minerals are significant issues about opencast mining industries. For example, in Tirap Opencast Mine, coal theft is widespread. The intrusion of illegal persons in this opencast mine is pervasive, leading to the unlawful transportation of coal and theft of mineral/coal and small mining equipment from the mine. Thus, there is a loss of revenue due to the above illegal activities, which is a grave concern and needs attention. Coal production of the mine largely depends on the safe interface between mining equipment and human beings. Protecting the assets and personnel against any possible hazards and optimizing their application by real-time location monitoring and control will improve mine safety and lead to increased productivity. The areas must be protected against unauthorized intrusion to manage the potential hazards in the sensitive areas inside the mining premises. Therefore, an intelligent mine periphery surveillance system has been developed and deployed in the mine for the first time. The developed system played a significant role in checking out these problems as this industrialized device could monitor the area efficiently.

Besides the above, the environmental conditions in opencast mining areas are dusty, full of smoke, foggy during the winter, and heavy rain during the rainy season. Thus, it raises a big challenge. These areas have different issues like soil erosion and dust coming from coal particles, leading to air and water pollution. These impact the environment and thus impact biodiversity as well. In recent years, the accumulation rate of waste dumps increased gradually, resulting in the great height of the waste dumps having a minimum ground cover area that created a danger to the environment. Illegal mining in the area marked with uneven slopes with an open pit is hazardous as it makes a warning bell for the human being and other animals living in the area. Open-pit slopes create disadvantages for mining industries as mining machinery cannot be used smoothly. There is always a chance

of damage to machines due to land conditions created due to illegal mining as there is a lack of proper planning. Thus, there is a need for continuous monitoring and surveillance in that area which is a big challenge as the atmosphere in that area is full of dust and bad weather. Microwave FMCW radar is very suitable in these environmental conditions for surveillance and monitoring. It does not impact dust, vapor or waste particles suspended in the air, foggy weather, and rain. FMCW radar signals processing is good at different weather conditions such as humidity, snow, fog, rain, and dusty conditions. The microwave FMCW radar security system, is used for vehicle detection with a long detection range and high reliability. The objective of this experimental work is to showcase the impact of using our real-time monitoring and tracking, sensing and management system using surveillance microwave FMCW radar for controlling mineral overloading, coal theft and illicit mineral transportation from the mines, improving mine safety, security, and productivity management.

Mining activities form an essential part of the financial increase of any nation endowed with mineral resources. Unauthorized mining, vehicle overloading, adequate transparencies during mineral transportation, enhancement of equipment optimization and production scheduling, downtime of shovels and dumpers, etc., are some of the main concerns in opencast mines. As an obvious outcome of searching for proper solutions to these problems, recent decades have witnessed wide applications of communication, sensing, surveillance, and vehicle detection technologies.

In this field of research and investigation, the authors have put a pretty good step forward by developing a “microwave radar-based periphery surveillance system” using the advanced vehicle tracking and surveillance technologies.

In this chapter, the FMCW radar sensor is briefly discussed. The FMCW radar is the best for accurately measuring the distance of multiple targets and identifying the intruder using a pan-tilt-zoom (PTZ) camera. The principles of FMCW radar for measuring distance change and detection of a target is presented in this paper. Its application for monitoring of transportation of coal at the Tirap coal mine in Assam, India, has been discussed. In this system, a real-time object detection technique is used to provide a clear multilevel description of the environment around it for constant vigilance. The PSS has been developed using an FMCW radar sensor to maintain high accuracy with precise range information, which helps stop illicit coal transportation through the mine lease boundary. Based on this auto-generated information, the user is free to mark any suspicious object and raise the alarm. The experimental results show that the system can accurately measure the distance of 400 m approximately along the mine periphery. The objective of the field experiment is to showcase the impact of using real-time monitoring and tracking, sensing and management system in which a developed system is used for detecting mineral overloading, coal theft and illicit mineral transportation from the mines and to improve mine safety and security. A digital oscilloscope has been used to analyze the actual performance of the FMCW radar system, and the output waveform is the raw data received from radar.

2. Related works

The development of a periphery surveillance system for detecting an unauthorized vehicle or target object has gained popularity in the mining industry in recent times. Choudhary and EI-Nasr [15] have developed an automatic target recognition system using a remote sensing system and radar sensor. The system

detects the target by reflecting an electromagnetic signal between the radar sensor and the target object. Ibanez et al. and Ganapathi et al. [16, 17] have developed a sensor-based transportation system for traffic control and vehicle tracking. The system addresses the high level of traffic control issues and improves road safety by tracking a vehicle in the respected area. Mimbela and Klein [18] have developed a vehicular detection and surveillance system. The system enhances the speed of monitoring, vehicles classification and speed of vehicle tracking. Yulianto [19] has developed a vehicle actuated control (VAC) and adaptive traffic signal control (ATSC) system for decreasing traffic congestion, object detection time and air pollution. Santi et al. [20] have developed a GNSS based multi-static radar for the detection and localization of vessels at sea. This system detects the location of a vessel in seawater. Thiel et al. [21] have carried out a case study for a car periphery supervision system for the production line in the automobile industry. Chaulya and Prasad [22] have developed a sensor-based monitoring system for hazardous areas in mines. A wireless sensor network (WSN) has been used for monitoring mine hazard parameters. Kassim et al. [23] have evaluated the performance of an acceleration sensor of the vehicle security system for movement detection. The system determines acceleration for a car using the acceleration sensor and detects the location of a vehicle using the GPS receiver. However, the said periphery surveillance systems do not have the proper architecture for detecting an intruder in real-time for controlling illegal mineral transportation and intrusion through the vast opencast mine periphery. The existing solutions do not have appropriate identification facilities to recognize the intruder, such as integrated CCTV cameras and analysis software. Further, these systems have no provision for providing automatic audio-visual warning at the intrusion site and control room and storing intrusion events with video footage for taking necessary action against the intruders with the recorded proof of the intrusion.

Considering the above limitations of the existing surveillance systems, an intelligent periphery surveillance system has been developed by CSIR-Central Institute of Mining and Fuel Research, Dhanbad, India, by integrating radar, CCTV camera, WSN, display and warning devices with application software. The main advantage of the proposed periphery surveillance system is that it detects the exact location of an intruder at the mine periphery in real-time. The system also identifies the intruder by auto-focusing a PTZ camera to the intrusion location during the incident, which detects the intruders in real-time while observing the control room. If the system detects an intrusion, it automatically gives an audio-visual warning at the intrusion site where the radar is installed as well as in the control room. The system has the facility to record the intrusion data as well as video footage with timestamp events in the form of a log for taking necessary legal action against the intruder with the proof of the intrusion. Further, the system has a long-range detection capability covering around 400 m distance with integration facility using a dynamic WSN for deploying multiple numbers of sub-systems to protect the long periphery of an opencast mine for controlling illegal mineral transportation from the mine as well as preventing the unauthorized entry into the mine. The system has suitable integrated software that adequately handles the radar and wireless devices, display unit, and warning devices.

3. Periphery surveillance system

The main components of the developed periphery surveillance system (PSS) are an FMCW radar, a PTZ CCTV camera, a wireless sensor network (WSN), a fast graphical processing unit (GPU) and a display unit.

3.1 FMCW radar

The microwave radar sensor operates in FMCW mode in the industrial, scientific and medical (ISM) K band of the transmit frequencies of 24.00 to 24.25 GHz. For short and long-range applications, the radar sensor measures the distance and displacement of a static or slow-moving target object [9–14]. The radar system consists of transmitting and receiving antenna; receiver consists of low noise amplifier (LNA) and in-phase/quadrature (I/Q) mixer, amplifier, a band-pass filter (BPF), two analog-to-digital (A/D) converters, a digital-to-analog (D/A) converter, and a digital signal processor (DSP). The output power of the radar front end is 16 dBm.

3.2 PTZ camera

The FMCW radar is combined with the commercial PTZ camera. This high-resolution network camera is powered over the Ethernet and provides PTZ capability. The PTZ camera has been installed at mines at about 12 m height, with the radar front end covering the observation area. When operating in tracking mode, the PTZ camera observes the complete area and looks for sudden changes in the data stream. As soon as an intruder is detected, the camera switches to auto-focus mode. The camera zooms into the scene (the zoom factor depends on the target distance) and follows the intruder across the monitored area. During this time, high-resolution images of the target are produced, which can be used for assortment and recognition reasons. Therefore, a background image is intended and continuously updated by the system, similar to radar detection. The investigation of visual data was performed using the application software developed.

3.3 Wireless sensor network

Using radio signals, communication can be done in a self-configuring network of tiny sensor nodes called a wireless sensor network. To sense, monitor and understand the physical world around us, a wireless sensor network (WSN) is needed to be deployed in large quantities. It is a subject of high prospective technology, which has been successfully implemented and tested in a real-time scenario and is practically deployed for many applications in different areas. Its real-time application is capable of monitoring, responding immediately to user input or controlling an external environment. Sensors play an essential role in connecting the external environment to the computer system.

3.4 Graphics processing unit

The graphic processing unit (GPU) is preferred over the central processing unit (CPU) as it has unique features of computational display operations, which are faster than the CPU. Thus, the graphical presentation of the data can be easily understood through it. The GPU devices have more active threads than existing computer resources. Radar signal processing (RSP) represents a complex task that involves advanced signal processing techniques and intense computational efforts. The computational load of modern radar signal processors is more complex. In most applications, real-time radar data processing is required with the constraints of space ever haunting. The gamut of radar signal processor hardware ranges from general-purpose hardware like PC, workstations or mainframes, and application-specific hardware such as multi-core processors to reconfigurable computing platforms such as field-programmable gate arrays (FPGA). Radar signal processing is a

data-parallel operation that also benefits from parallel processing architectures. The most promising of all high-performance computational architectures is the GPU, which can leverage hardware multithreading capabilities and single instruction multiple data (SIMD) or single instruction multiple threads (SIMT) execution schemes leading to incredible levels of performance on data-parallel based applications.

3.5 Advantages of periphery surveillance system

This developed PSS has many advantages and capabilities in the mining environment. These include the ability to filter on distance, direction, angle, and velocity measurement of object target up to 150° horizontal detection and up to 400 m (depending upon the object's size). It provides accurate incident notifications at night and in all weather conditions like foggy weather, dusty environment, rainy weather etc. The system working has been for 24 hours in seven days (24 × 7) and detects moving objects in the periphery for intruder detection at remote locations. It receives all the radar measurement data and converts it into meaningful information/reports through TCP/IP, integrated display and storing of intrusion data and video for reports and records. Audio-visual warning at the site and in the control room is received and recorded.

4. Fundamentals of radar overview

This part discusses the FMCW radar working principle, radar sensor hardware overview, signal processing, and radar signal waveform raw data measurement through a digital oscilloscope.

4.1 Principle for FMCW radar

The principle of operation of FMCW radar is simple. This radar sensor sends continuous waves with increasing frequency and receives them back after reflecting by an object or target. It is used to find the range and other information from a target using a frequency modulation technique on a continuous signal. The radar transmitter continuously transmits this modulated signal as a continuous wave (CW). The frequency modulation used by the radar can take many forms, such as triangular, saw-tooth, sinusoidal, or some other shape. The characteristic of a radar sensor is low transmitting power, ease of modulation, simple processing and ability to measure both range and velocity (Doppler) simultaneously. The radar signal processing can be used for real-time object recognition, target tracking, parameter deduction, and sometimes even signal classification of multi-target positions under all weather situations like foggy weather, dusty environment, rainy weather, etc. The advantages of FMCW radar against the other types of radar are low peak power, less sensitivity to clutter and accurate short-range measurement, which means that it is easier to integrate, a simpler algorithm for digital signal processing and cheaper to manufacture [24–26]. A continuous carrier modulated periodic function like a saw-tooth wave is transmitted to provide range data as shown in **Figure 1**, a frequency-time relation in the FMCW radar where the red line denotes the transmitted signal, the blue line indicates the received signal, ν_0 denotes the central frequency, ν_w denotes frequency bandwidth for sweep and t_w denotes period for the sweep. The modulation waveform has a linear saw-tooth sample, as shown in **Figure 1**. A signal obtained is having some delay time.

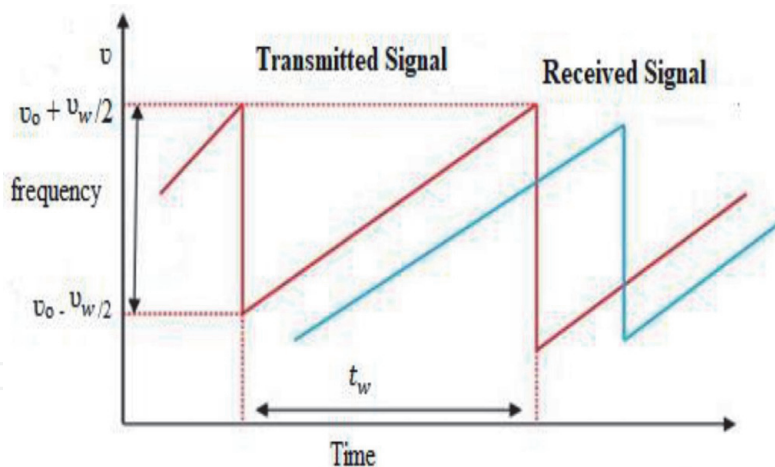


Figure 1.
 Saw-tooth frequency modulation.

In the FMCW radar system, the frequency modulated signal received at a voltage-controlled oscillator (VCO) is transmitted from the transmitter T_X terminal and the reflected signals from the targets are received at the receiver R_X . These T_X and R_X signals are multiplied in a mixer, and thus beat signals are generated. The beat signals are then passed through a low pass filter, and an output signal is thus obtained. In this method, the frequency of the input signal varies with time at the VCO.

Figure 2 shows the block diagram of the FMCW radar system. Here, D/A denotes the digital to analog converter, VCO denotes the voltage controlled oscillator, BPF indicates the band-pass filter, and A/D means analog to the digital conversion, FFT means fast Fourier theorem, T_X denotes the transmitter unit, and R_X denotes the receiver unit [26].

The frequency of the transmitted signal $V_T(v; s)$ at T_X , the transmitter unit is represented as:

$$V_T(v, s) = Ae^{j\frac{2\pi v s}{c}} \quad (1)$$

Where v indicates the frequency at a particular time, s indicates the target's distance from the transmitter where $s = 0$, A denotes amplitude of the transmitted signal, and c represents the speed of light. The frequency reflected signal $V_R(v, s)$ at the receiver unit R_X is expressed as:

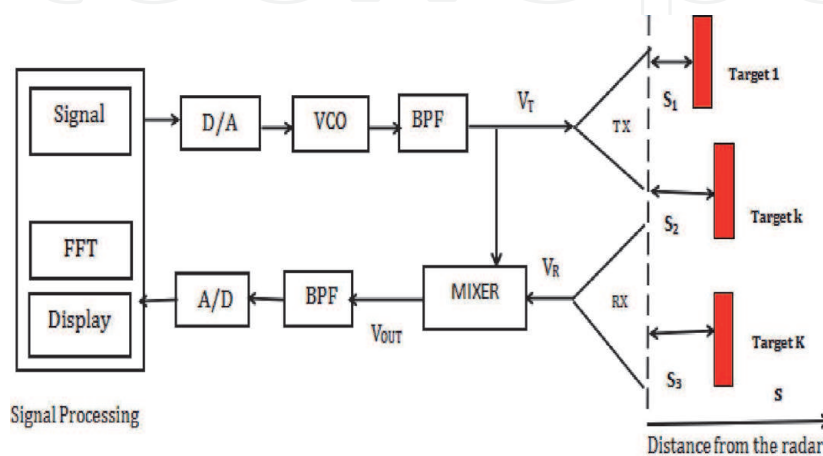


Figure 2.
 Block diagram of the FMCW radar system.

$$(V_R(v, s) = \sum_{k=1}^K A\alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{2\pi v}{c}(2d_k - s)} \quad (2)$$

Where φ_k and γ_k are reflective coefficients for the phase and amplitude of the k^{th} target, respectively. The α_k denotes the amplitude coefficient for transmission loss from the target and d_k denotes the distance between the transmitter and the k^{th} target.

At the receiver where, $s = 0$, Eq. (2) can be rewritten as:

$$V_R(v, 0) = \sum_{k=1}^K A\alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{2\pi v}{c}(2d_k)} \quad (3)$$

To get the frequency of a beat signal, the transmitted signal's frequency in Eq. (1) is multiplied by the frequency of the received signal in Eq. (3) at the position $s = 0$.

Thus, the frequency of beat signal = $V_T(v, s) \times V_R(v, 0)$.

$$= A e^{j\frac{2\pi v}{c}s} \sum_{k=1}^K A\alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{2\pi v}{c}(2d_k)}. \quad (4)$$

The output signal $V_{out}(v, 0)$ is generated by passing through a BPF is presented as:

$$V_{out}(v, 0) = \sum_{k=1}^K A^2\alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{A\pi v d_k}{c}} \quad (5)$$

The distance and displacement of the target are assumed from the generated output signal in Eq. (5) by the use of signal processing.

The distance spectrum of the output signal $P(x)$ is calculated by using Fourier transform:

$$\begin{aligned} P(x) &= \int_{v_0 - \frac{v_w}{2}}^{v_0 + \frac{v_w}{2}} V_{out} e^{-j\frac{4\pi v}{c}} dv \\ &= \int_{v_0 - \frac{v_w}{2}}^{v_0 + \frac{v_w}{2}} \sum_{k=1}^K A^2\alpha_k\gamma_k e^{j\frac{A\pi v d_k}{c}} e^{-j\frac{4\pi v}{c}} dv \\ &= A^2 \sum_{k=1}^K \alpha_k\gamma_k e^{j\varphi_k} \int_{v_0 - \frac{v_w}{2}}^{v_0 + \frac{v_w}{2}} e^{j\frac{A\pi v (d_k - s)}{c}} dv \\ &= A^2 \sum_{k=1}^K \left[\alpha_k\gamma_k e^{j\varphi_k} e^{j\frac{A\pi v_0 (d_k - s)}{c}} v_w \text{sinc} \left\{ \frac{2\pi v_w (d_k - s)}{c} \right\} \right] \end{aligned} \quad (6)$$

In this equation, the function of $\text{Sin } c(s)$ denotes:

$$\text{Sin}(cs) = \frac{\text{Sins}}{s} \quad (7)$$

The amplitude value of the distance spectrum $|P(x)|$ in Eq. (6) is given as:

$$|P(s)| = A^2 \left| \sum_{k=1}^K \alpha_k \gamma_k e^{j\varphi_k} e^{j\frac{4\pi v_0 (d_k - s)}{c}} v_w \text{sinc} \left\{ \frac{2\pi v_w (d_k - s)}{c} \right\} \right| \quad (8)$$

$$\leq A^2 v_w \sum_{k=1}^K \left[\alpha_k \gamma_k \left| \text{sinc} \left\{ \frac{2\pi v_w (d_k - s)}{c} \right\} \right| \right]$$

This is possible when the phase components $\phi_\kappa + \frac{4\pi v_0 (d_k - s)}{c}$ for all of κ are equal.

$$|P(s)| = A^2 v_w \sum_{k=1}^K \left[\alpha_k \gamma_k \left| \text{sinc} \left\{ \frac{2\pi v_w (d_k - s)}{c} \right\} \right| \right] \quad (9)$$

When the number of a target to be 1, the distance spectrum in Eq. (6) becomes:

$$|P(s)| = \left[A^2 \alpha_1 \gamma_1 e^{j\varphi_1} e^{j\frac{4\pi v_0 (d_1 - s)}{c}} v_w \text{sinc} \left\{ \frac{2\pi v_w (d_1 - s)}{c} \right\} \right] \quad (10)$$

Its amplitude value of the distance spectrum is given as:

$$|P(s)| = A^2 v_w \alpha_1 \gamma_1 \left| \text{sinc} \left\{ \frac{2\pi v_w (d_1 - s)}{c} \right\} \right| \quad (11)$$

This Equation indicates the distance of the target is specified by the amplitude value of the distance spectrum.

The phase value of the distance spectrum, $P(s)$, is represented as:

$$\angle P(s) = \phi_1 + \frac{4\pi v_0 (d_1 - s)}{c} = \theta_1(s) \quad (12)$$

Here, because $\theta_1(s)$ satisfies $-\pi \leq \theta_1(s) \leq \pi$

The displacement of the target is:

$$\frac{c(-\pi - \varphi_1)}{4\pi v_0} \leq d_1 \leq \frac{c(\pi - \varphi_1)}{4\pi v_0} \quad (13)$$

If the phase value satisfies $\varphi_1 = \frac{\pi}{6}$, and $v_0 = 24.15$ GHz in Eq. (13). Thus, it can be rewritten as $-0.0036[\text{m}] \leq d_1 \leq 0.0026[\text{m}]$ with $v_0 = 24.15$ GHz. This means a slight displacement of the target within $-0.0036[\text{m}] \leq d_1 \leq 0.0026[\text{m}]$ is generated by the phase value of the distance spectrum.

On the other hand, the maximum distance for measuring d_{max} can be calculated using the following equation:

$$d_{max} = \frac{c}{4\Delta v} [\text{m}] \quad (14)$$

Where c denotes the speed of light and Δv denotes the frequency resolution of the distance spectrum and expressed in hertz (Hz), which can be calculated using the following equation:

$$\Delta v = \frac{v_w}{t_w/t_s} [\text{Hz}] \quad (15)$$

Where t_w denotes the sweep time, t_s denotes the interval time for sampling and v_w denotes the bandwidth of sweep frequency, d_{max} denotes the maximum distance is expressed in metre (m).

Now, when sweep time, $t_w = 1024 \mu\text{s}$. Interval time for sampling, $t_s = 1 \mu\text{s}$, the bandwidth of sweep frequency, $v_w = 200 \text{ MHz}$.

Then,

$$\Delta v = \frac{v_w}{t_w/t_s} = \frac{200 \times 10^6 \text{ Hz}}{1024 \times 10^{-6} \text{ s} / 1 \times 10^{-6} \text{ s}} \quad (16)$$

$$\Delta v = 1.95 \times 10^5 [\text{Hz}]$$

Using value of Δv , d_{max} can be calculated as follows:

$$d_{max} = \frac{c}{4\Delta v} = \frac{3 \times 10^8}{4 \times 1.95 \times 10^5} = 384 [\text{m}] \quad (17)$$

4.2 Radar hardware overview

In the transmitter unit of the radar system, a 'saw-tooth' voltage sequence is generated by the 'saw-tooth' generator. It is used to control a VCO to generate a frequency modulated radio frequency (RF) signal. The receiver channel, with the help of the beam forming array, receives the signal reflected by obstructions. The fundamental frequency output from VCO is connected to the transmit antenna array and halved frequency output. Signals received from the antenna array are mixed with the transmitted signal in the sub-harmonic mixer. The intermediate frequency (IF) signal obtained from the mixer is then amplified by the variable gain amplifier (VGA) and filtered by a band-pass filter (BPF). These two components are controlled by the radars electronic control unit (ECU) unit, which also communicates with the PC host via the USB interface [27–30]. The photograph of the manufactured FMCW radar unit is shown in **Figure 3**.

4.3 Signal processing overview

The algorithm for signal evaluation is implemented on a field-programmable gate array (FPGA) to facilitate real-time processing. A parallel signal processing and control of all peripheral units such as ADC, DAC, radar, data transmission interface (USB), etc., are set up. The signal processing starts with the FMCW ramp

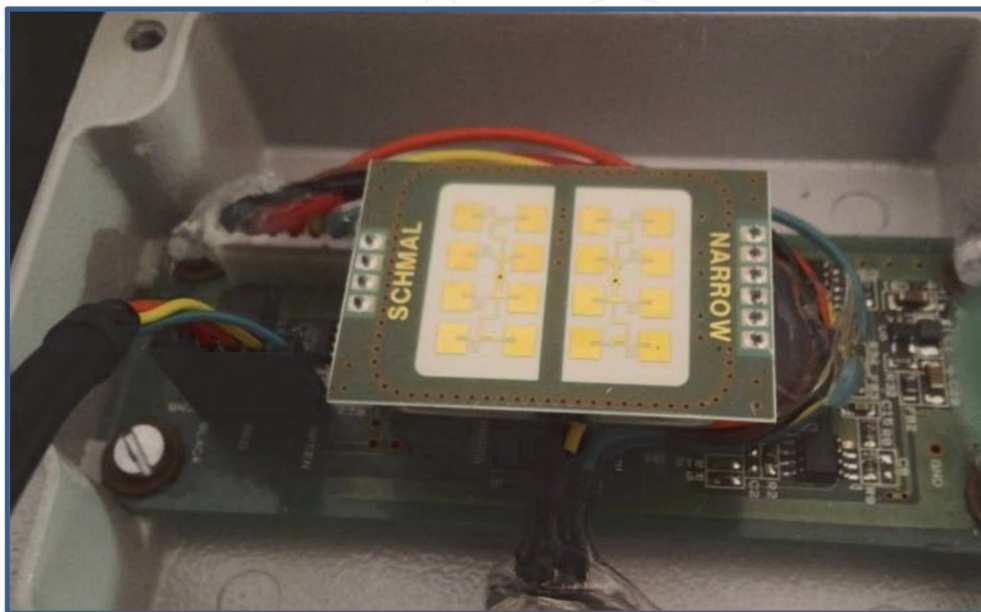


Figure 3.
View of the FMCW radar.

generation inside the FPGA using very high description language (VHDL) software. This ramp is converted from digital data to analog with a DAC and is amplified. Finally, it reaches the radar interface FMCW transceiver. The transceiver, using the ramp, generates a modulated signal to transmit it. Then the signal is reflected by some targets and is received by each receiver antenna, and then the calculation of beat signals is done. Thus, the beat signal is amplified and converted from analog to digital data with an ADC to adapt measured signals to the FPGA. This block contains digital to analog (or vice versa) conversions, amplification, and FPGA processing. The ramp generated in the FPGA is then sent to a 16 bit digital to analog converter (DAC). The FMCW radar uses the ramp information to emit a transmitted signal, which is used to obtain the beat signal by mixing with the received one. Fast Fourier transform (FFT) is primarily used for signal processing.

The presence and distance of targets are identified by identifying the peaks. The signal processing is achieved on-board entirely by the microcontroller with ARM Cortex-M4F core, a group of 32-bit reduced instruction set computer (RISC) based ARM processor cores. The cores, when intended for micro-controller use, consist of the Cortex-M4F core features SIMD type instructions (single instruction, multiple data) and the floating-point unit, which, combined with high operating frequency, 32-bit hardware multiplies with the 64-bit result, 12 cycles interrupt latency results in very efficient data handling. The FFT composed of 1024 samples of single-precision (32 bit) floating-point type is calculated slightly less than 5 ms. The ARM Cortex-M4F processor is very well appropriated for mainly deterministic real-time applications, even for low-cost platforms [30–33]. Microprocessor algorithms provide powerful digital signal processing to identify the digital signature of intruders walking, automotive, etc., through the detection range. Intruders entering the detection zone are monitored in real-time. Signal processing using application software in the periphery surveillance system is mainly consists of software design, pre-processing, computation, FFT, graphical interface, and control module [33–36].

4.4 Digital oscilloscope measurement

Figure 4 shows the radar waveform received from the digital oscilloscope. These are raw data received from the FMCW radar. There are two different lines in the

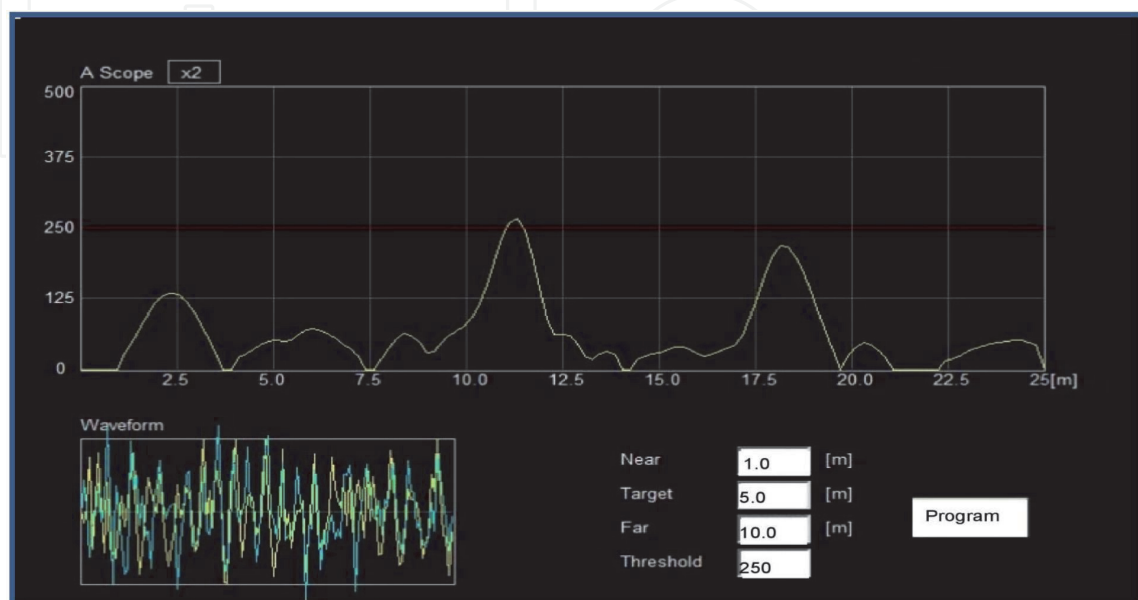


Figure 4.
Output radar signal graph from the oscilloscope.

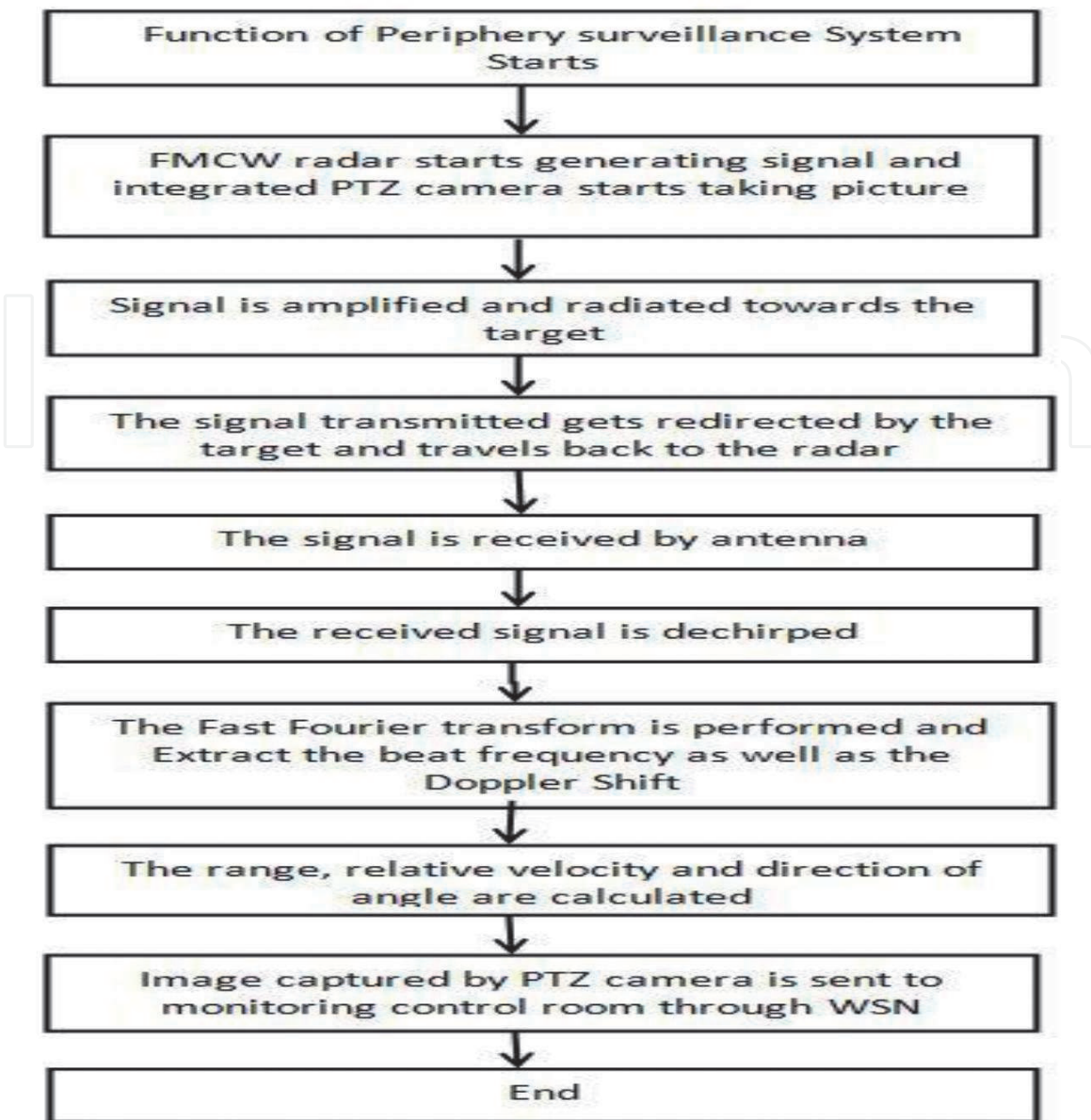


Figure 5. Flow chart of intelligent mine periphery surveillance system implementation process used in the FMCW radar.

A-scope graph, viz. the yellow line and the red line. The yellow line represents the data after DSP signal processing in the distance domain. Red line is the user configured threshold to cancel out noise detection. Based on the above, the radar application gives alarm for the distance domain. The signal program the user-configured threshold set value 250 to cancel out noise detection, and object target 5 m and distant object 10 m. The flow chart of the function of the periphery surveillance system implementation process used in the FMCW radar, PTZ camera, and wireless sensor network has been shown in **Figure 5**.

5. Field studies

The study area is Tirap Opencast Coal Mine, owned by North Eastern Coalfields (NEC) of Coal India Limited (CIL), located at the north-western end of the Makum Coalfield, Assam in India. The nearest township, Ledo, is about 3 km to the east of Margherita. The headquarters of NEC is located at a distance of about 10 km. The national highway, NH38, forms the northern boundary of this colliery. The nearby

railheads for the coalfield are Margherita, Ledo, and Baragolai on a broad-gauge line of the North-East Railway.

5.1 Field installation

Generally, mine lease covers a wide area with a long lease boundary, and most of the boundaries are not fenced. Each mine has separate entry and exit gates which are the authorized routes for vehicle transportation and mine personnel. Entry through these authorized routes is usually controlled by installing an access control system comprising radio frequency identification (RFID) tags, RFID reader, Internet protocol (IP) based motorized boom barrier, signal lights, computer and integration software. The boom barrier opens the gate for entry or exit of the authorized vehicle or person only when the access control system reads the valid RFID tag assigned to the respective vehicle or person. Entry or exit through the rest of the significant mine lease boundary is unauthorized and prohibited. However, illegal mineral transportations are found from some mines through these unauthorized routes of mine boundaries. Hence, a periphery surveillance system has been developed by integrating radar, CCTV camera, wireless network, server and software for day and night surveillance of the mine lease boundary from a remote control room.

The system detects any vehicle or person entering through the particular unauthorized routes or boundary with simultaneous CCTV footage of the intrusion location. Further, it provides a real-time warning to the system's operator in the control room regarding the intrusion along with CCTV footage of the incidence. It saves the intrusion location and video footage with a time stamp, and these records of the log can be retrieved any time for further analysis. Thus, the system detects all intrusions. The control room operator verifies each intrusion through the respective CCTV footage whether the intruder is an authorized or unauthorized vehicle or person.

Field installation of the periphery surveillance system has been conducted at Tirap Opencast Coal Mine of North Eastern Coalfields (NEC), having latitude 27° 17'35.09" N and longitude 95°46'10.29" E. The microwave FMCW radar sensor and PTZ surveillance camera installed in the mine periphery of Tirap Opencast Coal Mine has shown in **Figure 6**.

An FMCW radar sensor, an integrated PTZ camera, and a wireless sensor network have been installed on few electric poles along with railway siding of the mine roadside. After the installation of the periphery surveillance system, the selected area has been kept under rigorous vigilance. There is multi-radar connectivity with a wireless network for real-time detection. Any intruding object can be detected through the sensor. The virtual framework of an integrated periphery surveillance system for opencast mine has been shown in **Figure 7**.

Suppose any unauthorized vehicle or any object is sensed to be entering into the boundary, in that case, wireless sensor nodes trigger an alarm and also send intrusion notifications to the central monitoring computer. The vehicle's position or a target is traced by the transmitting sensor node. Furthermore, long-distance PTZ cameras installed along with the radar sensor provide actual pictures of the intruders. A centralized observation station consists of a large digital display, computer, server, GPS antenna, walkie-talkie, alarm, centralized continuous power supply, etc. The arrangement of an integrated periphery surveillance system deployment has been shown in **Figure 8**. It is also equipped with software modules to track and perform real-time assignments and operations. The radar sensor node is also attached to a central monitoring station via a wireless sensor network. This station performs various tasks such as initiation of geo-fencing for each truck, tracking vehicle movement throughout its transportation route, assigning trucks in real-time, etc. It is also responsible for monitoring operating

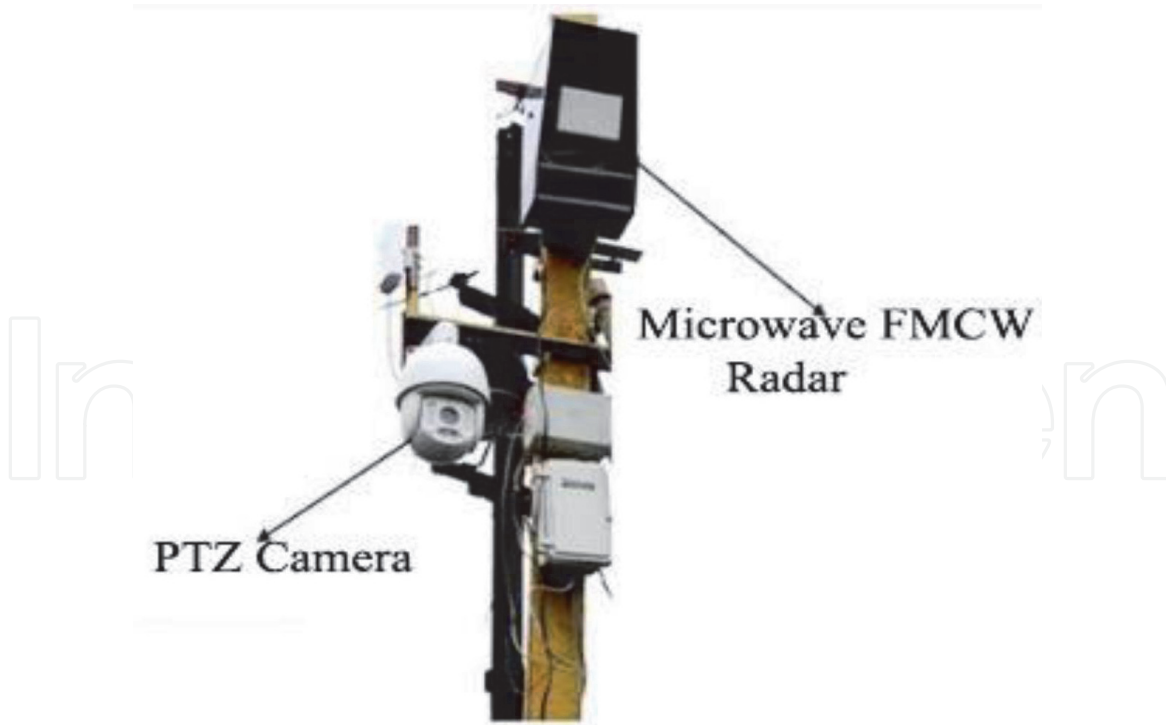


Figure 6.
The microwave FMCW radar sensor and integrated PTZ surveillance camera were installed in the mine periphery of Tirap Opencast Coal Mine.

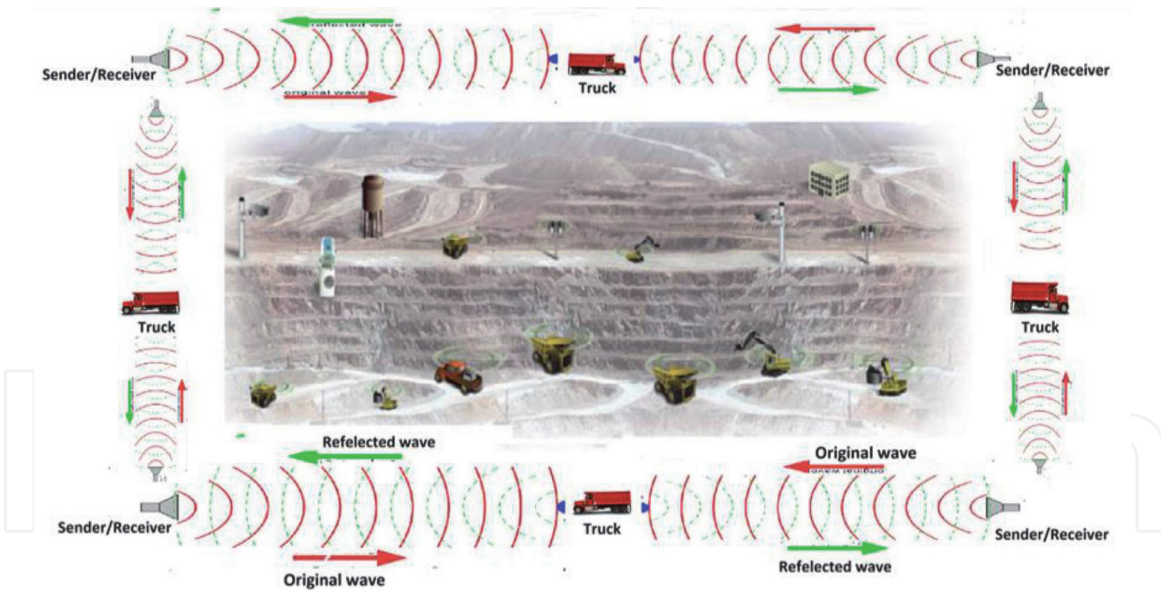


Figure 7.
Virtual framework of an integrated periphery surveillance system for an opencast mine.

threshold values for equipment and maintaining the database. The watching administrator also can communicate with the authorized supervisors about moving vehicles in the area. The central observing operator also generates an audible alarming signal in case of accidents, mineral theft, or illegal activities in the mine's excavation area. Performance of the system was also evaluated during severe weather conditions like foggy weather, heavy rain and dusty environment. It has been found that the version of the radar is not significantly affected during the said severe weather conditions.

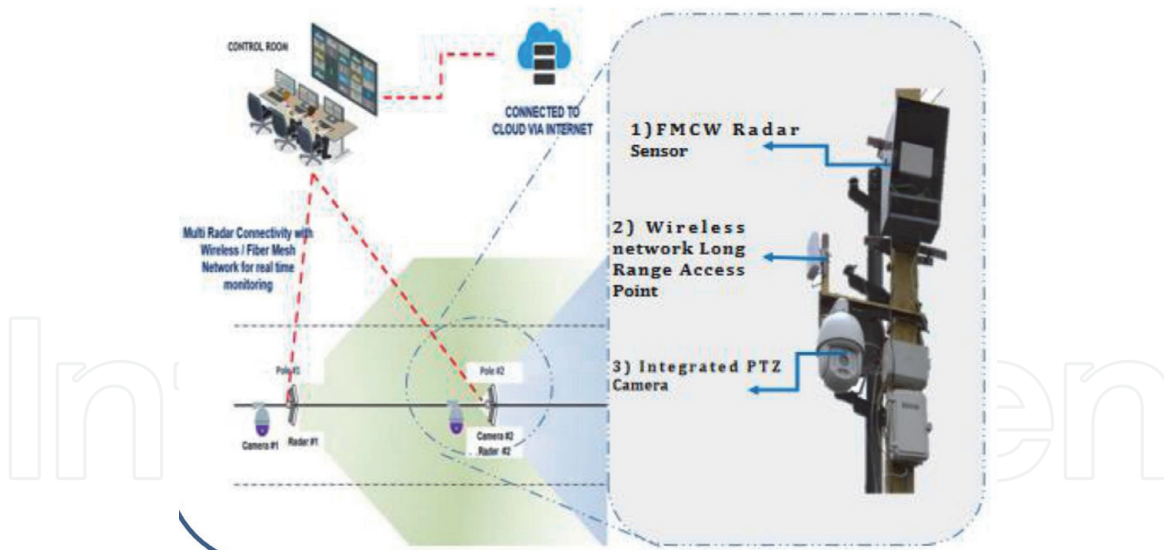


Figure 8.
Architecture of mine periphery surveillance system deployment.

5.2 Observations and discussions

Figure 9 shows a snapshot for the distance-direction graph generated by using application software and a photograph taken by PTZ camera during these detections of incidences. The actual pictures are taken from the PTZ camera, real-time radar detection and distance graphs of different objects obtained during field experiments. Photographs show the presence of trucks and many persons. The interaction between the user and the high language software system has taken place in the application layer. It is implemented through a visual system simulator for front end simulation. The radar distance graph plots the continuous detection of intrusion along the mine periphery up to 400 m. The lines in different colors in the graphs correspond to the velocity and direction of varying mining vehicles or persons concerning the radar sensor's location. The other color lines represent different moving and stationary objects. The radar sensor generates an integrated volumetric perimeter detection zone. The developed application software is set to trigger an alarm if the thing crosses the boundary lines or attempts to cross the detection zone.

Figure 9 represents screenshots of continuous radar view and CCTV video surveillance of a control room screen installed in an opencast coal mine site. Each line shows the radar detection location for a particular vehicle or person. The movement of each intruder is shown in the form of the path in the graph, i.e., X and Y coordinate concerning the location of radar and its center line, as shown in the left side graph of **Figure 9**. When an intruder is in stationery position, there will be no variation of the intrusion detection path displayed in the control room screen. Further, the respective detection line vanishes automatically from the display screen when an intruder crosses beyond the length and width of the radar detection range.

Table 1 presents various data gathered by radar regarding trucks and different objects. This experimental fieldwork showcases the impact of real-time monitoring, tracking and sensing management systems using the developed application software. The developed method can capture single, double and multiple targets placed at various locations in the different test areas of a mine. Thus, it can detect the intruders and intruding objects like trucks and other vehicles to control illegal mining-related activities in the mining area.

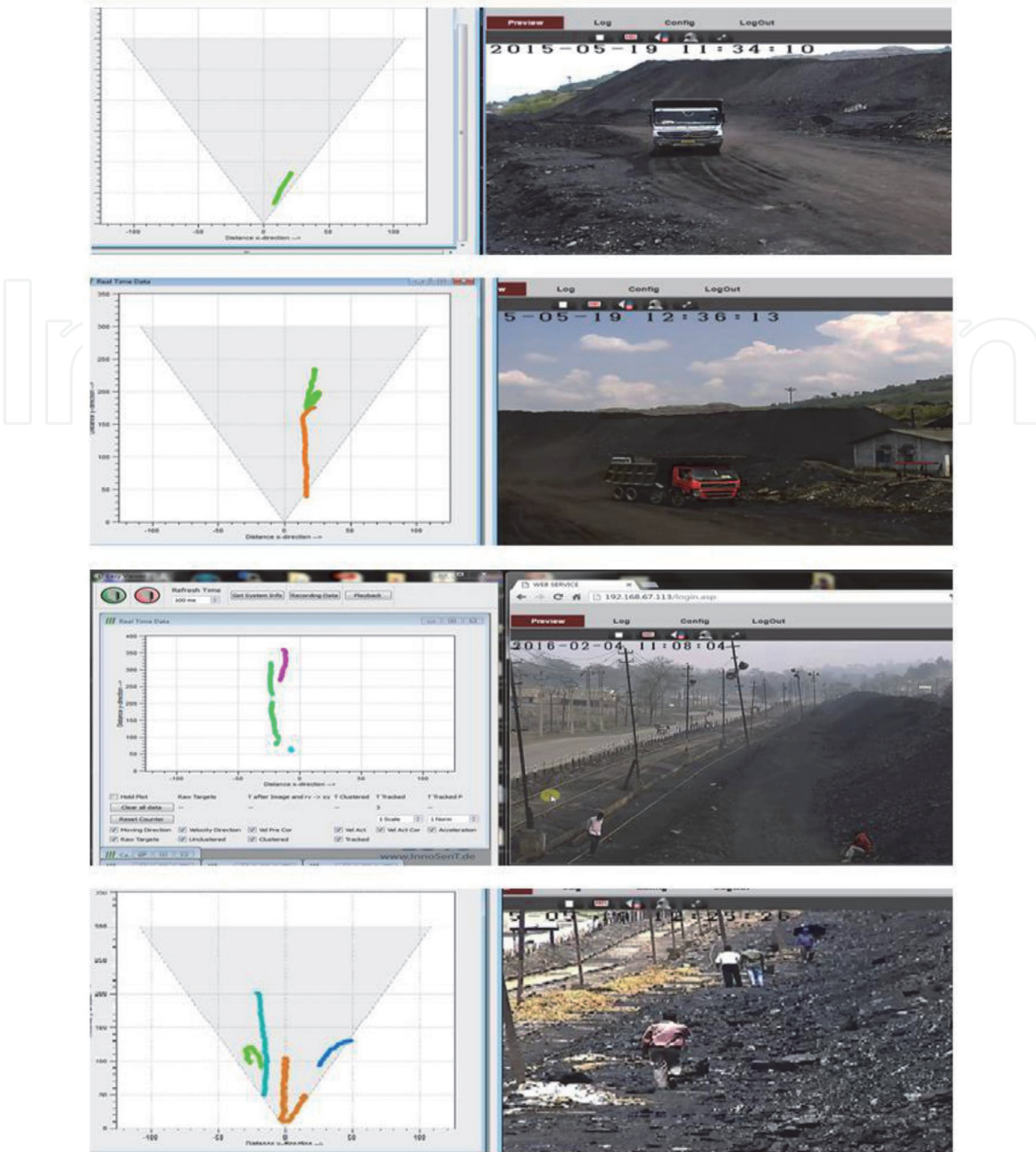


Figure 9. View of real-time monitoring of the diverse position of periphery surveillance system at an opencast mine.

Real-time data from the FMCW radar information are saved in the database by the application software and are extracted as given in **Table 1**. This object target information includes the following:

- a. Object ID is the identifier for a valid object, and it does not change during a lifetime.
- b. Quality is the indicator for the track quality that equals 10 for best quality.
- c. Distance X and distance Y denote the distance of the traced object from a reference point in X and Y-directions, respectively.
- d. Velocity X and velocity Y represent the velocity of the tracked objects in X and Y-directions, respectively.

Object ID	Quality	Distance in X-direction (m)	Distance in Y-direction (m)	Velocity of the object in X-direction (km h ⁻¹)	Velocity of the object in Y-direction (km h ⁻¹)	Object type	Distance polar (m)	Speed polar (km h ⁻¹)	Angle of direction (°)
15038	1	-50.5419	240.648	-23.397	10.6527	0	245.898	0	11.8611
150183	8	-55.6701	248.83	-2.65974	8.75161	0	254.982	0	12.611
149785	9	3.01645	58.5682	-0.167479	-6.04272	0	58.6458	0	-2.94831

Table 1.
The periphery surveillance system monitors parameters.

- e. Polar distance denotes the distance from a reference point to the tracked object in polar coordinates.
- f. Polar speed denotes the speed of the tracked object in polar coordinates.
- g. The angle of direction indicates the angle of the tracked object to the reference point in degree (polar coordinates).

6. Conclusions

The developed intelligent mine periphery surveillance system is an effective and economical device that can keep constant vigilance over a selected area or a place even in adverse weather conditions like foggy weather, rainy season, dusty environment, etc. As the system is quite capable of detecting the position and movement of an object from a long distance, it would be beneficial for preventing (i) unauthorized intrusion of a vehicle or person into the mining area and thereby avoiding many safety and security problems, (ii) illegal transportation of coal and other minerals from the mining area especially where there is no boundary wall, (iii) detection of several other incidences such as surface mine fire due to burning of coal, etc. Thus, this surveillance system would undoubtedly go a long way in preventing financial loss of the mining industry due to mineral theft, and ensuring the safety and security of the mines.

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