A Safety System for Human Radiation Protection and Guidance in Extreme Environmental Conditions

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***Abstract*—We present a safety system designed to ensure human radiation protection and provide real-time guidance in extreme environmental conditions. This system was developed and tested in the complex experimental infrastructure of the ATLAS underground cavern at CERN, where personnel safety is crucial, especially during maintenance periods. Safety in such environments is challenging and extremely important due to the high complexity of the working space, the radioactivity, and the stress that people experience. The safety system we propose consists of three subsystems: a data acquisition (DAQ) system, a control system (CS), and a remote monitoring system (MS). The DAQ system acquires data wirelessly from various environmental and biological sensors installed in the outfit of the user. The CS controls and creates alerts to warn the user in case of emergency. The MS is developed to remotely supervise the health status of the personnel and provide real-time guidance during the performance of complex activities inside the ATLAS cavern. Radiation background monitoring is also achieved through the MS via the communication of the DAQ system with a gamma camera placed in the cavern. This system is developed to supervise multiple interventions and communicate with numerous users in real time, and it is adaptable to various extreme environmental conditions.**

***Index Terms*—Control systems (CS), data acquisition (DAQ), radiation safety, remote monitoring, safety.**

I. Introduction

PERSONNEL safety, supervision, and real-time monitoring are important key parameters while performing activities in risky environments and extreme environmental conditions such as the ATLAS cavern at the European Organization for Nuclear Research (CERN). The hazardous environments are not user-friendly in terms of frequent access, performing regular or sudden interventions, monitoring, and supervision activities. The engineers and the personnel need to perform complex activities like installation and maintenance work in the heavy machinery. Those activities can be stressful mainly due to the radiation fields (gamma, beta, and particle radiation) near high-energy particle accelerators. Therefore, any visual or acoustic guidance to assist the workers on performing maintenance activities can reduce the intervention time and consequently the human exposure to ionizing radiation.

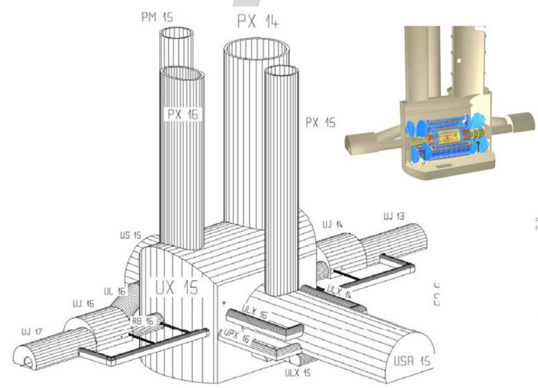

Fig. 1. Schematic view of the underground ATLAS installation including the test area USA15 [1].

The ATLAS experimental cavity (UX15) is surrounded by a variety of other caverns and access shafts. A schematic view of the underground ATLAS installation is shown in Fig. 1 [1]. The detector cavern is UX15, and the adjacent service caverns are USA15 and US15. PX14 and PX16 are the installation shafts for surface access, and PM15 and PX15 are the two elevators [1]. The USA15 cavern, of 20-m width and 62-m length, is designed to accommodate most of the electronics that are necessary for carrying out the experiment [2]. With circulating beam, the radiation doses in the large hadron collider (LHC) underground areas reach high levels and therefore access during beam operation must be prohibited for the major part of the underground structure. However, access during beam operation is required for a few underground areas (USA15, upper part of PX24, USC55, part of UX85) and therefore extensive shielding calculations had to be performed [3]. Q3

The areas inside CERN's perimeter are classified as a function of the effective dose a person is liable to receive during his stay in the area under normal working conditions during routine operation. In line with the Safety Code F (2006) [7], three types of areas are nondesignated areas, supervised radiation areas, and controlled radiation areas. The latter two are jointly termed radiation areas. The radiological classification currently used at CERN is shown in Table I.

A study was made by Ferrari *et al*. in 1995 [5], [6], concerning the wall thickness between the experimental cavern and USA15 (shielding process), the plug thickness at the top of the two vertical shafts, the dose rate in the surface buildings, and the lateral passage ducts. They concluded that the USA15 wall should be 2-m thick, providing a maximum dose equivalent rate in USA15 of approximately 3 μSv/h (see Fig. 2) to foreseen future lower

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TABLE I
CLASSIFICATION OF NONDESIGNATED AREAS AND RADIATION AREAS AT CERN [4]

Area	Dose Limit [year]	Ambient dose equivalent rate	
		Work place	Low occupancy
Non-designated	1 mSv	0.5 mSv/h	2.5 mSv/h
Supervised	6 mSv	3 mSv/h	15 mSv/h
Simple	20 mSv	10 mSv/h	50 mSv/h
Limited Stay	20 mSv		2 mSv/h
High Radiation	20 mSv		100 mSv/h
Prohibited	20 mSv		>100 mSv/h

Radiation Area (Supervised to Prohibited); Controlled Area (Simple to Prohibited)

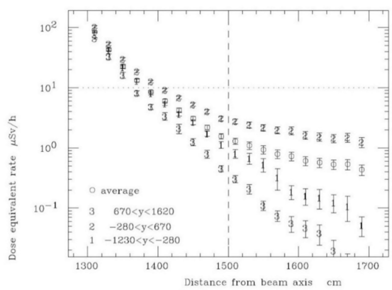

Fig. 2. Dose equivalent rate averaged over the whole wall length versus the distance from the beam line [6].

radiation dose limits. The ambient dose equivalent limit for a simple controlled area such as USA15 is currently 10 μSv/h (see Table I) [7]. The predicted dose equivalent rate of 3 μSv/h was sufficiently low at the time; considering that there were no experimental data from the today's LHC highest beam energy operation of 14TeV proton–proton interactions. In the future, radiation doses will increase mainly due to material activation and higher energy in particle collisions.

This paper proposes a safety system to ensure human radiation protection in experimental areas such as USA15 and enhance the personnel's safety against anticipated hazards described in the Section II-A.

A. Anticipated Hazards and Existing Safety Systems

The main risks are in the underground experimental area, especially in the main ATLAS cavern and the adjacent technical-service caverns (see Fig. 1) [2]. These areas are accessible to the personnel for maintenance activities, and significant risks can occur. Gases found in ultrahigh vacuum systems: H2, CH4, H20, CO, and CO2 can leak, which can cause fire incidents, local oxygen deficiency levels, and detector damages. There are several safety systems for gas leaks and fire incidents, such as Sniffer systems, hydrants, fire extinguishers, water mist systems, high expansion foam, air conditioning, sputter ion-pumps and titanium sublimation pumps. Oxygen deficiency detectors are crucial to detect possible oxygen deficiency hazard (ODH) caused due to the cryogenic technologies used in the cavern and the presence of large quantities of CF4 gas that can lead to ODH. LHC is the largest cryogenic system in the world and one of the coldest places on Earth. Cryogenic-fluid leaks can take place around the cryogenic infrastructures (super conducting magnets, LAr calorimeters). Personal protective

TABLE II
ANTICIPATED ENVIRONMENTAL HAZARDS

Environmental Hazards	Hazard Sources	Safety Systems
Radiation Hazards (Personnel Doses, Material activation/aging/ destruction)	Beam on (Prompt Ionizing Radiation), Beam off (Ionizing Radiation due to radioactivity)	Shielding, ALARA regulations, CERN's Safety Code, Dosimetry, Radiation Monitoring Systems
Gas leaks/Smoke Detection	Fire, Gases found in Ultra High Vacuum Systems: H2, CH4, H20, CO, and CO2	Sniffer Systems, Hydrants, Fire extinguishers, Water Mist Systems, High expansion foam, Air conditioning, Sputter ion-pumps, Titanium pumps
Oxygen Deficiency Hazard (ODH)	Cryogenic technologies, Presence of large quantity of CF4 gas	Oxygen Deficiency detectors
Cryogenic-fluid leaks (Helium, Nitrogen and Argon)	Cryogenic Infrastructures (Super Conducting Magnets, LAr Calorimeters)	Personal Protective Equipment (PPE), Equipment/system leak tightness, Ventilation/extraction systems, ODH detectors, Emergency procedures/ evacuation plans

equipment (PPE), equipment/system leak tightness, ventilation/extraction systems, ODH detectors, emergency procedures and evacuation plans as well as low-temperature compatible materials are safety systems that can protect the personnel from hazards linked to cryogenic-fluid leaks. A synopsis of possible anticipated hazards in the working environment and the current safety systems that are used is presented in Table II.

The radiation fields around high-energy accelerators are prompt ionizing radiation while the beam is ON and ionizing radiation due to induced radioactivity while the beam is OFF. The radiation hazards are mainly dose to personnel affecting their health (see Table III) and material activation leading to aging and destruction (for example damages in cable insulations). Radiation protection technologies at CERN include shielding like the one proposed by Ferrari *et al.* [5], compliance with CERN's regulations and safety codes, dosimeters, and radiation monitoring systems (MS). CERN's Occupational Health and Safety and Environmental Protection (HSE) Unit currently operates two radiation MSs. ARCON (ARea CONtroller), which was developed at CERN for the large electron–positron collider and has been in use since 1988, and RAMSES (RAdiation MS for the Environment and Safety), which was designed for the LHC based on current industry standards and has been in use since 2007. About 800 monitors are employed in ARCON and RAMSES. Both

TABLE III
RADIATION DAMAGE TO THE HUMAN BODY [4]

Dose (whole-body irradiation)	Human health effects
<0.25 Gy	No clinically recognizable damage
0.25 Gy	Decrease in white blood cells
0.5 Gy	Increasing destruction of leukocyte-forming organs (causing decreased resistance to infections)
1 Gy	Marked changes in the blood (decrease in the numbers of leukocytes and neutrophils)
2 Gy	Nausea and other symptoms
5 Gy	Damage to the gastrointestinal tract causing bleeding and ~50% death
10 Gy	Destruction of the neurological system and ~100% death within 24h

installations comprise data acquisition (DAQ), data storage, and the triggering of radiation alarms and beam interlocks.

CERN's radiation protection policy stipulates that the exposure of persons to radiation and the radiological impact on the environment should be as low as reasonably achievable (the ALARA principle) and should comply with the regulations in force in the Host States and with the recommendations of competent international bodies [4].

The International Commission on Radiological Protection (ICRP) has specified in its Recommendation 60 [7] that any exposure of persons to ionizing radiation should be controlled and should be based on the following three main principles.

1) Justification: any exposure of persons to ionizing radiation must be justified.
2) Limitation: personal doses must be kept below legal limits.
3) Optimization: personal and collective doses must be kept as low as reasonably achievable (ALARA).

These recommendations have been fully incorporated into CERN's radiation safety code [8].

Exposure to ionizing radiation accompanies all work at a particle accelerator and in the associated experimental facilities, and legal dose limits assure the safety of personnel working under these conditions [4]. The dose received by individuals working with ionizing radiation at CERN is monitored with personal dosimeters. The CERN dosimeter registers the personal dose from sources of ionizing radiation around particle accelerators. It combines an active detector for gamma and beta radiation based on the direct-ion storage technology and a passive detector for quantifying neutron doses [4].

The legal protection limits for radiation are not expressed directly in measurable physical quantities, resulting in the inability of quantifying the biological effects of ionizing radiation exposure of the human body. Therefore, protection limits are expressed in terms of so-called protection quantities, which quantify the extent of exposure of the human body to ionizing radiation from both whole-body and partial-body external irradiation and from the intake of radionuclides. To demonstrate compliance with dose limits, so-called operational quantities are typically used, which are aimed at providing conservative estimates of protection quantities. The radiation protection detectors used for individual and area monitoring are often calibrated in terms of operational quantities [4]. One of these operational quantities is the personal dose equivalent Hp(d) (measured in units of Sievert), which is the dose equivalent in standard tissue at an appropriate depth d below a specified point on the human body. The specified point is normally taken to be where an individual dosimeter is worn. The personal dose equivalent Hp (10), with a depth $d = 10$ mm, is used for the assessment of the effective dose, and Hp (0.07), with $d = 0.07$ mm, is used for the assessment of doses to the skin and to the hands and feet. The personal dose equivalent is the operational quantity for monitoring of individuals [4].

B. Radiation Impact on Human Health

The need for human radiation protection derives from the numerous health effects of ionizing radiation, which we will briefly describe in this section [4]. Radiation can cause two types of health effects, deterministic and stochastic. Deterministic effects, usually measured in gray units (1 Gy = 1 J/Kg), are tissue reactions, which cause injury to a population of cells if a given threshold of absorbed dose is exceeded. The severity of the reaction increases with dose. The quantity used for tissue reactions is the absorbed dose *D*. When particles other than photons and electrons (low-LET radiation) are involved, a dose weighted by the relative biological effectiveness (RBE) may be used. The RBE of a given radiation is the reciprocal of the ratio of the absorbed dose of that radiation to the absorbed dose of a reference radiation (usually X-rays) required to produce the same degree of biological effect. It is a complex quantity that depends on many factors such as cell type, dose rate, and fractionation. Stochastic effects, usually measured in sieverts, are malignant diseases and inheritable effects for which the probability of an effect occurring, but not its severity, is a function of dose without a threshold [4].

For each type of deterministic effect (erythraemia, depletion of bone marrow and blood cells, necrosis, vomiting, etc.), there is a dose threshold for the damage to become assessable or visible. The various types of damage observable after acute irradiation, and their dose equivalents in gray units, are listed in Table III [4].

Several safety systems have been designed and implemented to detect at a very early stage any possible sources of danger in the underground work environment and to activate alarms and trigger the required safety actions. These systems have been implemented under the direct supervision of the ATLAS GLIMOS (Group Leader in Matters of Safety) leading the ATLAS safety organization and of the CERN Safety Commission [9]. Any event linked with the anticipated hazards (see Table II) that might endanger the safety of the personnel, the environment or the ATLAS equipment is detected by the detector control system (DCS) [10]. The DCS ensures correct and safe operation; enables equipment supervision using operator commands; reads, processes, and archives the operational parameters of the detector; allows for error recognition, handling and alarming; manages the communication with external control systems (CS); and provides a

TABLE IV
TEST THRESHOLDS FOR THE ACQUIRED SENSOR DATA

Sensor	Unit	Upper Threshold	Lower Threshold
CO_2	ppm	600.0	100.0
O_2	%	22.0	18.5
Temperature	deg;C	40.0	10.0
Body Temperature	deg;C	39.0	35.0
Barometric Pressure	bar	1.2	0.8
Humidity	%	90.0	10.0
Dose Accumulation	mSv	0.0	0.0
Dose Rate	mSv/h	0.0075	0.0

synchronization mechanism with the physics DAQ system [11]. A more personalized safety system could potentially decrease and minimize risks involving human health. The goal of our research was to create a system that would enhance safety on a more personalized level.

II. Safety System Overview

The system we proposed first enables the DAQ from various environmental and personal biological sensors used by the employees and the technicians of the ATLAS cavern. Radiation dose measurements are acquired through personal dosimeter devices. Second, the system controls the various parameters that can cause accidents when exceeding certain predefined thresholds (see Table IV), for example, fluctuations in barometric pressure can indicate possible cryogenic gas leaks (see Table II). These values were used as thresholds for the sensors to test the sensitivity of the DAQ system. The specifications and the functionalities of the proposed DAQ System are presented in Section IV.

Whenever a sensor input measurement exceeds this threshold, alarms are triggered from the CS. These thresholds are customizable and can be configured through the configuration settings of the system. Wireless communication and real-time monitoring are also accomplished by supervisors and operators located in the surface. The personnel are therefore, guided through bidirectional optoacoustic communication during the performance of complex activities in the cavern and their safety is ensured. The specifications and the functionalities of the proposed CS System are presented in Section V.

The system is developed to supervise multiple interventions simultaneously for more than one worker in the field. Additionally, all acquired data are stored in a dedicated Database for offline analysis. An overview of the proposed system equipment is shown in Fig. 3. The worker wears a helmet with an integrated mobile personal supervision system (MPSS) for video DAQ of the environment, a personnel transmitting unit (PTU) for sensor data and a dosimeter for radiation dose measurements. A gamma camera is also placed in the field to provide radiation hot-spot images to the system. Augmented reality (AR) technology is used to provide superimposed instructions in the actual view of the working environment through a first prototype in the form of a tablet. AR glasses (final prototype shown in Fig. 3) were developed, to allow the real-time computer-based identification and analysis of the objects in the worker's environment and to project necessary information directly onto the display of the glasses.

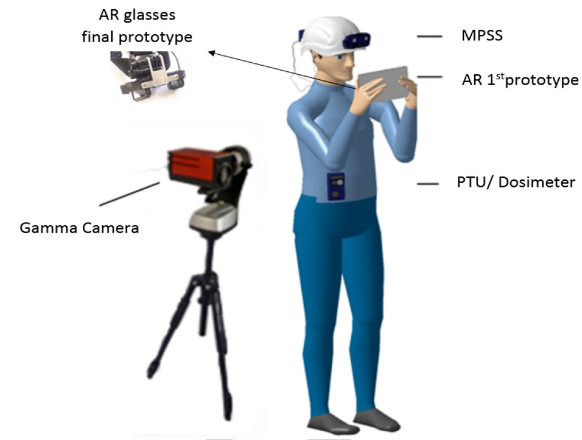

Fig. 3. System overview.

The tests that were performed during the development of this work, took place in USA15, where human radioprotection is crucial mainly due to the constant accessibility even during beam operation. This study is the main part for the CS and the DAQ System of the EDUSAFE project [12], an FP7 Marie Curie ITN project focusing on research into the use of virtual reality and AR during planned and emergency maintenance in extreme environments.

III. Safety System Architecture

The safety system we propose consists of three sub-systems: a DAQ system, a CS, and an MS. These sub-systems are integrated to provide real-time guidance to the users and enhance human radioprotection. There are four external systems that interact with the safety system, namely PTU, MPSS, gamma camera, and AR system. These hardware sources will be described further in Sections IV and V.

The DAQ system first acquires data from various safety sensors, the gamma camera (device to image gamma radiation and provide localization of radioactive sources), as well as other vision cameras that are integrated in the helmet of each technician or user that works underground (see Fig. 3). Second, it stores them in a reliable database that is created for offline analysis. Third, it displays them in a dedicated graphical user interface (GUI) of the MS (a web server is developed in this system), to enable remote supervision of workers in the ATLAS cavern, mainly for safety purposes.

Sensor and power printed circuit boards (PCBs), based on electronic miniaturization process, were developed by Prisma Electronics SA [13], to acquire the various sensor data, both biological and environmental. We will refer to the developed PCBs from now on as PTU since it collects sensor data for the person that uses each device.

The sensor data from the various PTUs are wirelessly acquired through the CERN network in JavaScript Object Notation

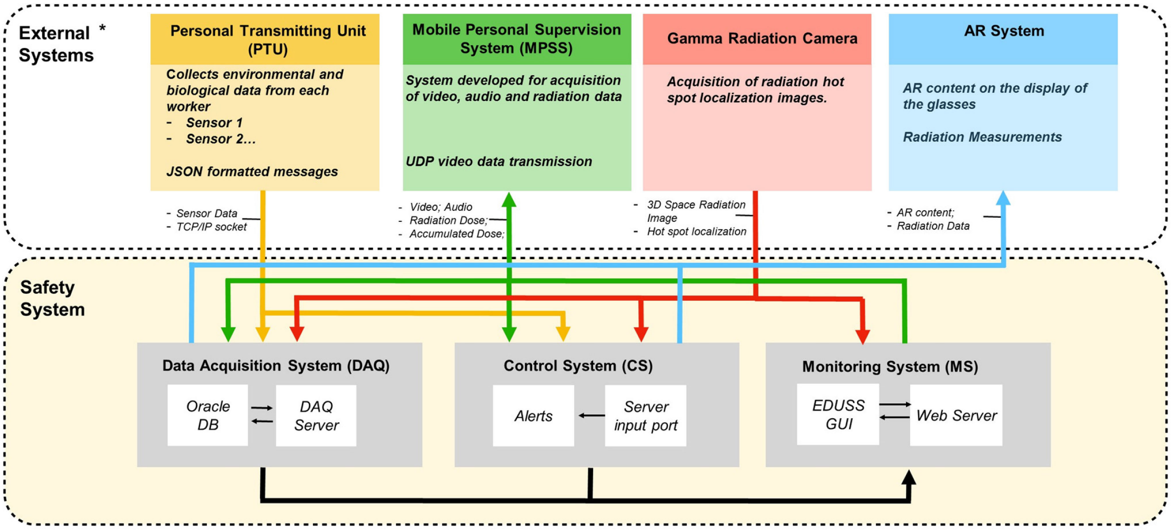

Fig. 4. Architecture design of the safety system.

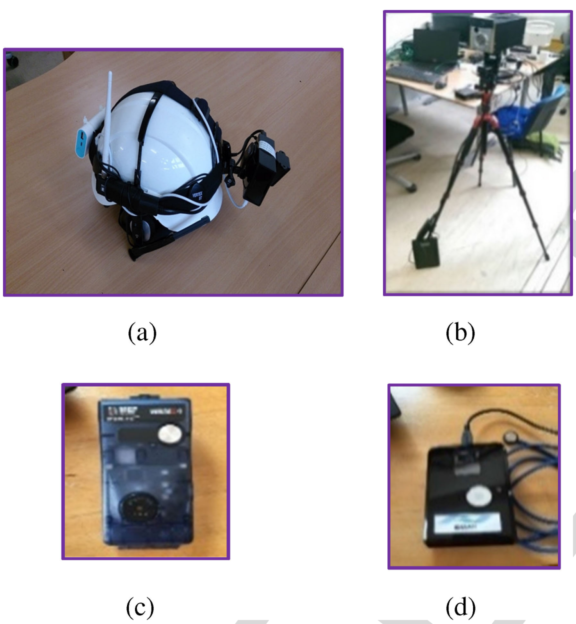

Fig. 5. DAQ system sources. (a) MPSS. (b) Gamma radiation camera. (c) Operational dosimeter (DMC) for real-time radiation data (d) sensor board (PTU).

(JSON) formatted messages from the DAQ Server. Additionally, the server of the CS controls the data inputs and generates alarms in case a measurement exceeds a certain threshold. The safety system was designed to accept various types of sensors for testing in the ATLAS environment; hence, the adaptation of this service-based application is also a crucial goal that is successfully fulfilled. This system can be adapted in various environments where supervision and safety are important factors. Such environments are mentioned in Section VII. The architecture of the proposed safety system is shown in Fig. 4.

The safety system provides the following services:

1) sensor DAQ;
2) video streams acquisition;
3) gamma camera DAQ;
4) data-base storage;

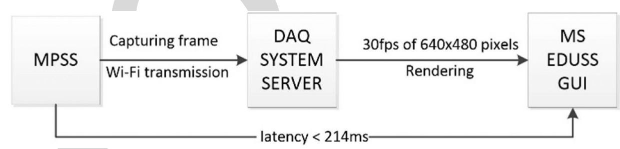

Fig. 6. MPSS data flow.

5) user interface development for remote supervision of workers in the ATLAS cavern for security purposes;
6) control automation that creates alert signals.

Once the JSON data are acquired from the DAQ Server, Hibernate [14], an object relational mapping tool, is used to map the java classes to the DB tables and the java datatypes to SQL datatypes. Hibernate persists the acquired data in an Oracle Database (DB). The developed system is based on the ATLAS Personnel Visualizer System (APVS) [15] of the WPSS [16] research project of CERN. The CS is a Google Web Toolkit (GWT) application that contains the Java-server and the web-client responsible for the GUI. This GUI, called EDUSAFE Supervision System (EDUSS) GUI, is the web client application of APVS, written in Java, and it connects to the java-server via Atmosphere [17], the Asynchronous Web Socket/Comet Framework. Through this interface the supervisors can monitor with video streaming the activities of the personnel in the ATLAS cavern and communicate with them in order to guide them when needed. The functionalities of this interface are described in the Section VI.

IV. DAQ System

The DAQ sub-system can acquire various types of data from the following subsystems:

1) the MPSS [see Fig. 7(a)] developed by Novocaptis [18], acquiring video, audio, and radiation data;
2) the gamma camera [see Fig. 7(b)], acquiring radiation hot spot localization images;
3) the operational dosimeter (DMC) [4] [see Fig. 7(c)], used for the measuring integrated dose in real time;

Fig. 7. PCB of the power module sensor board.

TABLE V
MPSS Data Flow Performance Characteristics

Data Flow Performance Characteristics	
Video transmission latency	Under 214ms
Frames per second (fps) transmitted	30fps of 640x480 pixels resolution
Network bandwidth usage	270-405KiB/s for transmission 12-15KiB/s for data reception

4) the PTU sensor board [see Fig. 7(d)], acquiring environmental, and biological parameters.

The MPSS is a wearable mobile safety device [see Fig. 7(a)], which combines several technologies and integrates them in the personnel safety system where data are received from different input sources (gamma camera, vision cameras, and sensors) interacting with multiple on-site users. A Raspberry Pi 2 single board computer and a dedicated camera were used for the implementation of the MPSS. It is used for wireless transmission of data through UDP, which permits a continuous packet stream for supervision purposes and it is mounted on the safety helmet that all the personnel use in the ATLAS cavern. The data transmitted from the MPSS are video, bidirectional audio and radiation sensor data received from the dosimeter. The MPSS wirelessly acquires video, audio and radiation data through IEEE 802.11n module and transmits to the DAQ Server in MJPEG format for the video and JSON formatted messages for the radiation values. The video transmission latency is achieved under 214 ms, transmitting 30 ft/s of 640 $\times$ 480 pixels resolution. In analogy, the average duration for a single blink of a human eye is 100–400 ms, according to the Harvard Database of Useful Biological Numbers [19].

The data flow performance characteristics of the video DAQ process is shown in Fig. 6 and Table V. The video transmission latency refers to the time required for the MPSS USB camera to capture the frame and transmit it through Wi-Fi to the DAQ Server added to the time required for the DAQ server to receive the video frame and render it on the GUI. Common power bank capacity is 2547.2 mAh for 4-h usage of the MPSS. The device acquires video from the USB camera, streams it to the DAQ Server and splits it in two paths, one is for storing the video and the second is for converting it in MJPG format. Finally, it streams the video data on a specified port for proper rendering in the EDUSS GUI. The SW that is used on the Linux server side for the Video Acquisition is GStreamer 1.2.4-1, v4l2loopback 0.8.0-1, OpenCV 2.4.9.

The Gamma camera [see Fig. 5(b)] that is used is developed from Canberra [20], and provides 3D Gamma images, Hot spot localization of the radiation and transmits wirelessly to the DAQ System.

For work in Controlled Radiation Areas (see Table I), where the radiological risk and the dose rate are above 50 μSv/h, the additional use of an operational dosimeter is required. CERN provides all staff who may work in Limited Stay Radiation Areas or high-radiation areas with a system for active dosimetry with an alarm, in the form of a dosimeter, model DMC-2000 from MPG instruments [see Fig. 5(c)] [4]. This dosimeter is used to acquire the personal dose for every user of our system.

The sensor board [see Fig. 5(d)] wirelessly transmits all the acquired environmental and biological data to the DAQ Server in JSON formatted messages as well. The DAQ from the sensor board is based on the MSP430F1611IPM Microcontroller from Texas Instruments, which enables the acquisition in different rates according to the type of the sensor source (sensor measurements fluctuate in different ways) [21]. It is an ultralow power processor with many analog and digital input and output options. The various sensors are connected to the microcontroller to either its analog or digital inputs.

The main responsibility of the Sensing uController is reading and sampling the measurements from the sensors and forwarding them to the main processing group through Universal Asynchronous Receiver-Transmitter (UART) hardware by the Modbus Protocol [22]. The device features a powerful 16-b RISC CPU, 16-b registers, and constant generators that attribute to maximum code efficiency. The power supply module is responsible for providing the power to the sensor board. The input voltage for sensor board and processor board is +5.0 V. The sensor board can also work with USB connection with approximately 0.5 Amps. The PTU board has an input voltage of +12.0 V, which works with 2.8 amps. In total, the system consumes approximately 30 watts. The charging circuit LTC 4008, which has 24-V input and will charge the Li-I battery with 12.6 V. The capacity of the battery is 6800 mAH by which system can run approximately from 5 to 6 h. The charging circuit provides the voltage to the converter circuit to reach different voltage levels for example +12.0, +5.0, and +3.3 V. The dimension of power PCB is 60 mm $\times$ 36 mm (see Fig. 7).

The DAQ Server receives through Wi-Fi the images that correspond to the radiation hot spots of the monitored area. Finally, the server wirelessly acquires the radiation dose measurements from the DMC through IEEE 802.15.4 standard. In Limited Stay Areas the limit for the radiation dose rate is 2 msv/h.

Once the DAQ Server has acquired through TCP/IP all the data from the various external HW sources numerous processes take place. First, the web server renders in real time the video and the sensor data in the developed Remote MS that will be described in Section VI. Through this GUI, the Supervisor can monitor the complex tasks through real-time video, provided from the camera that is placed in the MPSS helmet and monitor each user's health condition. Second, the CS uses filtering algorithms to send radiation data to the developed AR glasses display. Moreover, the server persists all the acquired data in the developed OD for offline analysis of the most important and critical data such as radiation measurements. All these processes are graphically depicted in Fig. 8.

Moreover, the audio communication between the supervisors and the personnel is accomplished through an Asterisk communication server [23]. This SW is used for real-time communication by handling all the low-level details of sending and receiving data and each MPSS device functions as an asterisk-client.

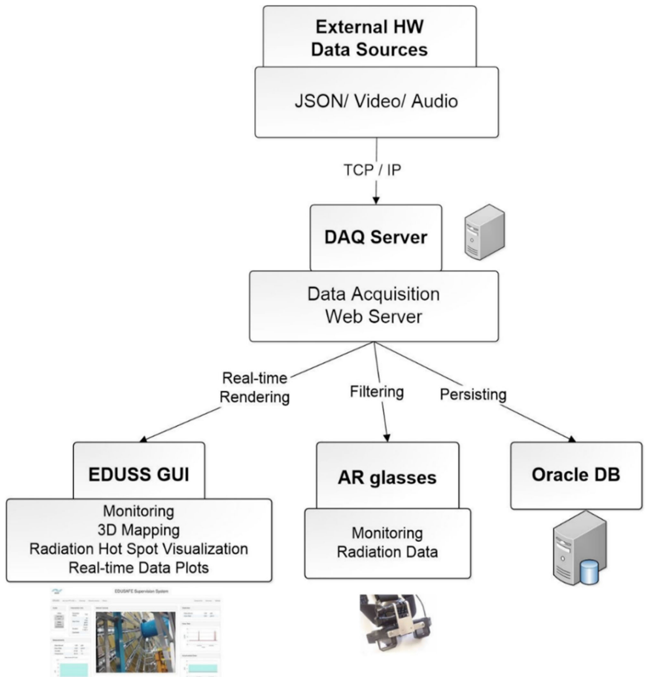

Fig. 8. DAQ System architecture.

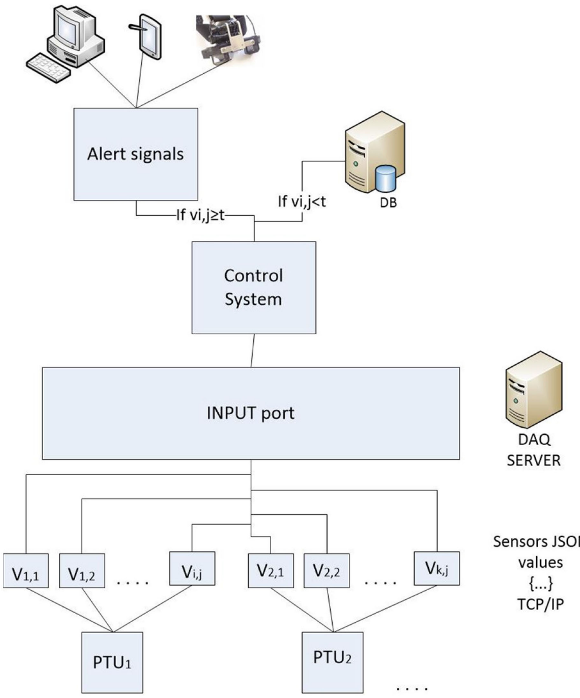

Fig. 9. Alert signals generation though the CS.

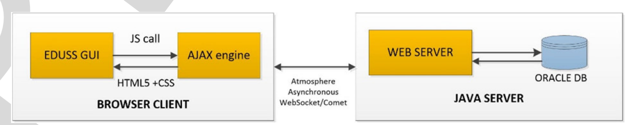

Fig. 10. Asynchronous communication between CS and MS. Q5

V. Control System

Rich Internet Application (RIA) technologies provide richer, faster and more interactive experiences by updating data without reloading the entire page. AJAX (Asynchronous JavaScript and XML) is one of the most popular RIA technologies [24]. The CS is written in Java programming language and uses the GWT framework, which is an open source Java Software Development framework, to develop and maintain the complex Web application (front-end development). GWT was chosen because it is a powerful tool that facilitates the development of our complex application, providing a mechanism that simplifies the communication from the web application to the web server. GWT takes a strong approach to OO (Object Oriented) architecture, hence proper software architecture (as applied in java, since GWT is Java-based) can be applied in GWT as well. This offers a lot of potential for maintaining and scaling up this application.

One of the most crucial functionalities of the developed Safety system is to create alert signals in case of emergency in the highly complex environment of the ATLAS cavern. As described, the PTUs, transmit through TCP/IP the values $v_{i,j}$, where i : the number of the PTU and j : the current sensor value, that are acquired from the environmental and the biological sensors to the DAQ Server. The CS checks the input port of the Server and in case a measurement exceeds a certain threshold, it automatically generates alert signals in all the available monitoring interfaces (the supervisor GUI, the tablet of the user and the AR glass). In case the measurements don't exceed the predefined thresholds, the system simply stores the data in the DB. The overview of this process is shown in Fig. 9.

A data mining algorithm is developed to filter the dose data that are acquired from the dosimeter device and send through a predefined filter-port the radiation measurements in the display of the Augmented Reality smart glasses. Through this process the user can see in his AR glasses screen, in real time, the current radiation dose that his body is receiving in mSv/h. The AR system is briefly described in this Section.

The radiation thresholds are customizable through configuration files of the CS and according to the ICRP. The ICRP recommends a limit for radiation workers of 20 mSv effective dose per year averaged over five years, with the provision that the dose should not exceed 50 mSv in any single year. The limit in the EU countries and Switzerland is 20 mSv per year and 50 mSv in United States [4]. Many physics laboratories in the US and elsewhere set lower limits while the dose limit for the general public is typically 1 mSv per year [4].

The CS is functioning also as a standalone software block to enhance the modularity of the safety system in case the dependent SW components crash. The CS can acquire the sensor data from the hardware sources of the system. A value filter algorithm is used to tackle the problem of persisting in the DB values that remain stable for a long period of time and overload the DB space. This algorithm compares every new measurement with the previous value and in case it is the same moves the timestamp one step ahead (see Fig. 11).

The AR system consists of a head band, which is used for fastening it on the user's head. A mount is attached on the forehead side of the band. On the mount an optical see-through HMD is attached from Vuzix, STAR 1200XL-D, which has a

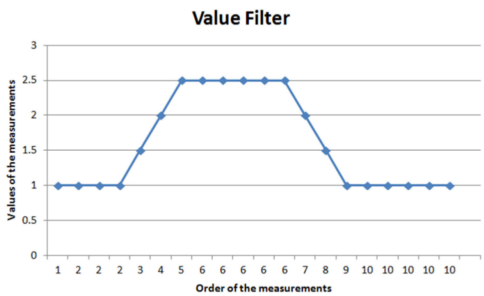

Fig. 11. Value filter algorithm of the CS.

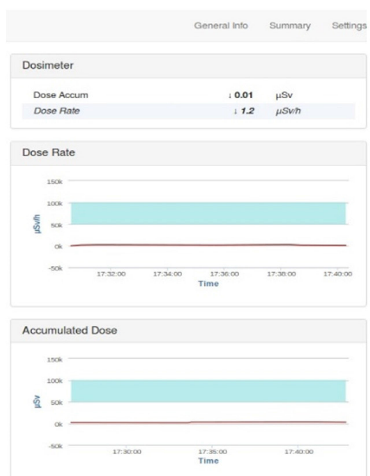

Fig. 12. The dose rate [mSv/h] and dose accumulation [mSv], displayed at the supervision interface.

1280 × 720 image resolution with a stereo support. Besides the display, the mount also holds a GoPro camera and an Inertial Measurement Unit (IMU) from Xsens. Apart from the head-mounted modules, the AR system also has a computer module fixed on a belt. The belt holds a portable battery pack to provide power to the PC unit, which is mounted the other side of the belt. The unit consists of an Intel NUC PC unit and a video converter box from the HMD. With the PC unit, stereoscopic images are rendered on the HMD so that a user can get depth perception. A voice-command control (microphone attached on the HMD) is also developed to enable user interaction.

VI. Remote MS

In this section we present the Remote MS that was developed, which will be referred as the EDUSS GUI. It is designed to monitor remotely the various worker sessions and guide the personnel if needed, through the wireless communication between supervisors that are located in the surface and the technicians that work underground in the ATLAS cavern. The EDUSS GUI enables the health monitoring of each worker by monitoring the various sensor data such as the gamma radiation measurements, which correspond to the dosimeter of a specific user.

Through the EDUSS GUI, the supervisor can mainly do the following.

1) Create multiple sessions with the workers in the ATLAS cavern.
2) Monitor every worker with real-time video streaming.
3) Communicate with audio connection.
4) Monitor the sensor values, such as gamma radiation measurements, which correspond each time to a unique dosimeter.
5) Access the graphical interface of the gamma camera that is set in the cavern.
6) Generate and save plots of the complete session for each sensor type resulting in faster offline analysis of the acquired data.
7) Dynamically generate plots using GWT highcharts [23].

The MS depends on the JAVA Server of the CS to send the incoming data to the Web Server and communicate asynchronously through Atmosphere WebSocket with the browser Client. The video data are acquired from the helmet camera of each worker and are streamed to the “Camera” interface of the EDUSS GUI. The dose rate and dose accumulation measurements (see Fig. 12) are acquired from the DAQ system in JSON format, are stored in the OD, and finally displayed in the EDUSS GUI. The rest of the sensor data are also acquired from the sensor board in JSON formatted messages and stored in the Oracle DB for offline use. The supervisor can dynamically generate plots using GWT Highcharts (see Fig. 13), which is a comprehensive API within the GWT application, offering interactive charts such as line, spline, area, and area spline charts. There is also a gamma camera user interface integrated in the EDUSS UI providing the current view of the gamma-ray measurements on the field.

The user interface is providing the supervisor with the following information among others:

1) sensor data from the sensor board (PTU): O2, CO2, barometric pressure, accumulation dose, dose rate, and temperature;
2) gamma-ray data acquired from the standalone gamma camera;
3) video streams from the worker’s view (helmet camera while he works at the ATLAS cavern, for supervision purposes);
4) plots of the measurements that are received from PTUs.

A. *Main Intervention Interface*

The main interface for supervising one individual user is shown in Fig. 14. Multiple users can be supervised simultaneously through additional interfaces, providing an overview of all the users and their health condition. The supervisor can choose to monitor one user individually or more than one user simultaneously in the same tab view of the MS. Once a personalized intervention is needed, a session is set up through the EDUSS platform. The interface shown in Fig. 14 represents the main “PTU-view” of the current intervention. It is divided in seven parts.

1) *Audio* [see Fig. 14(a)]: the audio communication between supervisors and the supervised person.
2) *Intervention info* [see Fig. 14(b)] provides information about the following:
   a) dosimeter status: the status of the DMC dosimeter that the current person uses;
   b) start time: the initialization of the intervention;
   c) duration: the total duration of each session;
   d) dosimeter: the type of the current dosimeter.
3) *Measurements* [see Fig. 14(c)]: this table is updated every 5 s or in the sending–receiving rate of the sensor data

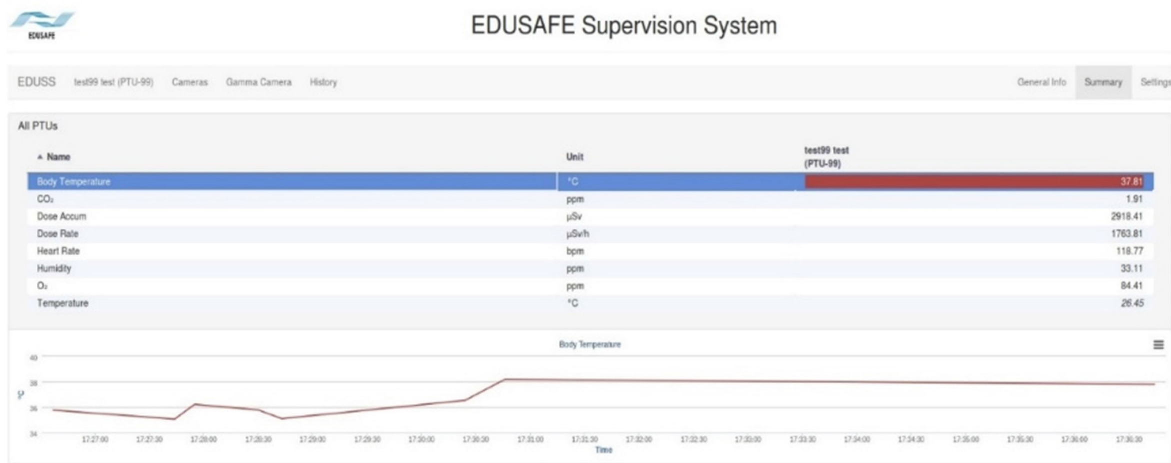

Fig. 13. Example of a plot generated for the humidity variable (these values were generated from a simulator for demonstration purposes and they do not represent actual measurements on the field of ATLAS).

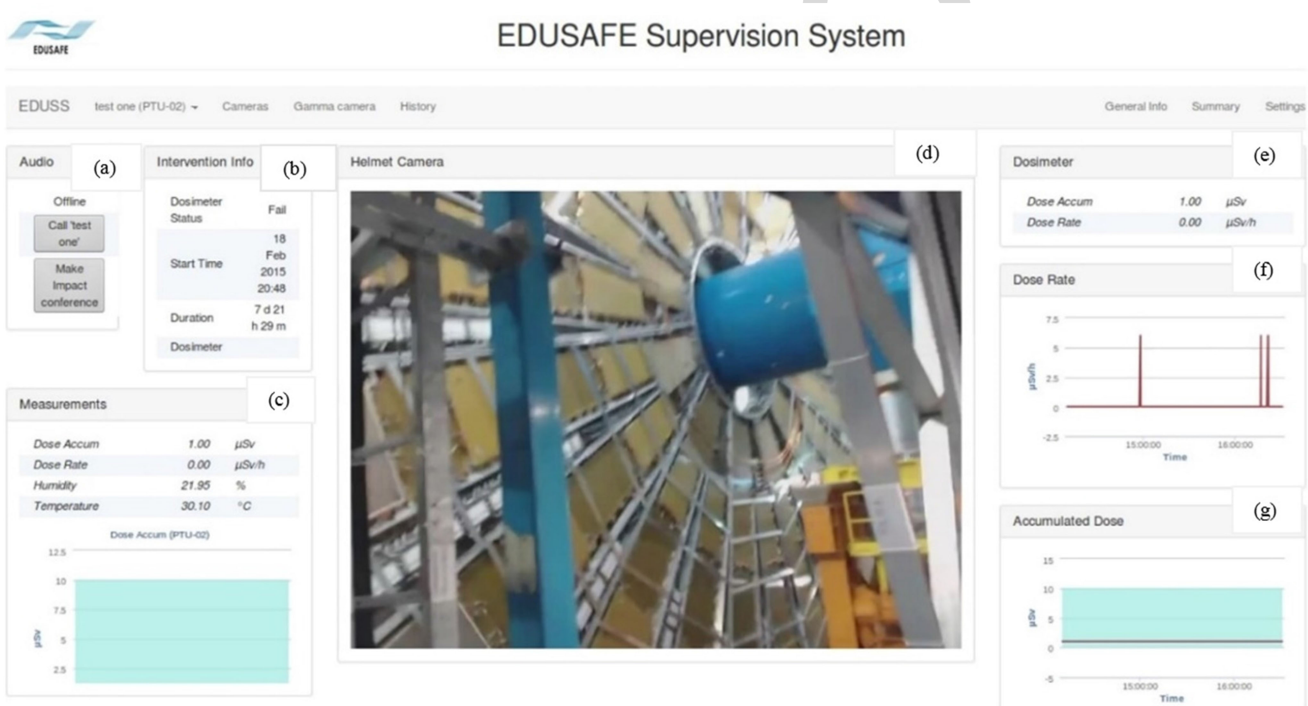

Fig. 14. Supervision user interface with measurements and video display for each user.

from the PTU. The DAQ rate can change according to the requirements of each session. There is an arrow decorator to indicate the increase, decrease, or stability of the value that is measured, to provide a visually faster overview of the worker status. There is an option of creating instantly a plot just by clicking the sensor type that the supervisor needs to check. These plots are created using highcharts SW, and they are dynamically formed according to the changes in the values from the start of the intervention initialization until the ending point.

4) *Helmet camera* [see Fig. 14(d)]: This is the central part of the page where the video acquisition from the camera of the MPSS is displayed. The video acquisition settings are available in the "Settings" tab.

5) *Dosimeter* [see Fig. 14(e)]: in this block, the values of the dose rate and dose accumulation are separately displayed. These two measurements are separately displayed due to their big importance, especially in extreme environmental conditions such as the ATLAS cavern where radiation is crucial.

6) *Dose rate plot* box over time provides an overview of the dose rate through time [see Fig. 14(f)].

7) *Accumulated dose plot* box over time provides an overview of the accumulated dose rate through time [see Fig. 14(g)].

VII. Conclusion

This paper presents the safety system that was developed, installed, and tested in the ATLAS experimental infrastructure to ensure human radiation protection, enhance the personnel's safety against anticipated hazards, and provide real-time monitoring and guidance. Radioprotection is crucial especially in areas where access is allowed even during beam operation, such as USA15. Three subsystems; the DAQ system, CS, and the remote MS, were developed and integrated to form the safety system. This system increases the personnel safety while working in extreme environmental conditions such as the ATLAS cavern. It provides a personalized real-time supervision of multiple users performing simultaneously various complex tasks in the cavern. The stress that workers experience can be decreased by reducing the intervention time and consequently their accumulated radiation dose. Real-time guidance is achieved through bidirectional optoacoustic communication between users and supervisors and through superimposed directions on the AR glasses. Radiation background monitoring of the infrastructure is also achieved through the gamma camera installed in the cavern.

So far, the personnel working in the underground experimental areas can monitor their personal exposure to radiation through their dosimeter devices. The Dosimetry Service of CERN organizes through a monthly dose reading, the legally required personal dosimetry monitoring of individuals occupationally exposed to ionizing radiation. The return on investment, in terms of radiation dose savings, is the proposed safety system provides a real-time monitoring and control of the dose accumulation for each worker resulting in direct radiation protection. Additionally, real-time monitoring of each worker's health status is succeeded by providing an overview of all the parameters that may affect his safety on a dedicated user interface (EDUSS). This safety system provides a personalized approach for each individual worker and creates alerts by analyzing the measurement data inputs. Future users of this system can also consult stored interventions for training purposes which can lead to the reduction of the intervention time and therefore limit the radiation exposure.

Finally, the system is adaptable and scalable in various extreme environmental conditions. Hence, it can be used as a safety system in various research environments and industrial nuclear facilities such as nuclear power plant emergent or planned maintenance, aircraft maintenance/build, aerospace maintenance activities while in operations, industrial subsea activities, ship maintenance, and mining among others.

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