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A Robot for Real Time Detection of Nuclear Radiation Levels

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Abstract— In Jordan, the government is taking initial steps towards building the first nuclear reactor for peaceful purposes. Although this reactor is supposed to attain several significant benefits for local community, it raises voices against expected potential harmful consequences. In general, one of the major risks of nuclear power is the impact of nuclear radiation on human health. In this work, a robotic-based system is proposed to avoid nuclear risks by automatically alarming the level of radiation when it noticeably increases in predefined-radius areas. Though the proposed system used a single robot, it could be easily expanded to employ several robots that are spread out at different locations to detect the radiation and alarm the unusual harmful levels in huge constructions like nuclear reactors and plants. Experiments show the robot's great capability to reach places characterized as unsafe for humans. In addition, the robot is equipped with a camera to facilitate its dynamic and self-driven movement, and a set of electronic sensors to detect the radiation level and leak amount of rays from nuclear reactors. The radiation is measured by detecting the levels of Alpha (α), Beta (β), and Gamma (γ) in the air. Testing and evaluation experiments that are carried out exhibit the capability of the proposed system to detect radiation leaking, alarm harmful levels and ensure the realization of some behavioral properties like utility and robustness against such operational obstacles as natural barriers and weather conditions.

Keywords— Local society safety, nuclear reactor radiation, robotic systems.

I. INTRODUCTION

Recently, robotic systems have been developed to serve many applications such as exploration, drilling, anchoring, etc. [1]. In addition, the mobile robot plays an important role in these applications because of its rapid movement and adaptive functions [2]. For public safety, the robot replaces human beings in hazardous environments.

Nuclear environment, the target of this project, is considered one of the most dangerous environments on human beings [3]. Because the safety of nuclear power plants is very important, the inspection and maintenance of their components and monitoring nuclear radiation levels should be achieved simultaneously [4]. In case the level of nuclear radiation increases, an alarm should be raised for the safety of employees and the whole nuclear power plant. In specific, engineers have to pay more attention to protect life, property and safety of people [5].

Noticeably, investments in the nuclear domain are promising. As a sustainable energy source, the benefits of nuclear power ultimately alleviate the associated expenses and waste of efforts resulted from using other resources to generate the needed energy. With the global population growth and the high cost of traditional energy resources, the need for nuclear power becomes more persistent. Currently, 29 countries around the globe employ nuclear power and consider expanding its use [6]. Another 65 countries are planning to follow the same trend [6]. Fortunately, Jordan is among these countries which are stepping forward in this direction.

In spite of the wide benefits of nuclear power, the production of this kind of energy is always surrounded by a set of serious problems. One of the major risks that act as a real barrier in the way of expansion in this area is the human body exposure to dangerous nuclear radiation.

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To clarify, the radiation consists of sub-atomic particles that travel at a high speed; the speed approaches the velocity of light which is 186000 miles per second. The fast-travelling particles are very likely to penetrate the human body [7]. This causes significant damages to biological cells and initiates cancer and genetic diseases in progeny [7]. Although this risk constitutes a significant concern for governments, a careful monitoring of radiation levels can help save lives and gain economic advantages of the sustainable resource. Managing radiation levels and alarming the danger when it is about to occur are critical to maintain a sustainable resource in use. To realize this, radiation levels need to be monitored without the exposure of human body to radiations. Another issue is to automatically and periodically alarm the risk once unusual levels of radiation are detected.

This paper proposes RoboJO (abbreviation of "Robot of Jordan"), a robotic-based system. The main goal of RoboJO is to propose a system that measures radiation levels of nuclear establishments like reactors and laboratories, and reports the unusual levels classified as harmful. The system monitors radiation in a predefined radius in the reactor location. The RoboJO system has the capabilities of mobile robots that are utilized for accomplishing the aforementioned tasks instead of humans. In this way, humans will not be exposed to harmful radiations inside the reactor area. In addition, the performance of the reactor is monitored automatically; and unusual circumstances are reported periodically.

The system keeps data about the reactor. Thus, experts can make use of this data in one way or the other by taking further procedures and making precise decisions. The proposed system reduces the fears and concerns the local people of Jordan have about the establishment of the nuclear reactor in the country by reporting critical data needed for maintaining safety.

Governmental agencies can get benefit of the system to measure and monitor the radiological consequences of surrounding environment. In addition, scientific laboratories (*e.g.* chemical laboratory) or the industrial sector can use RoboJO to detect chemical leakage of dangerous materials like gases and control its effects.

The paper is organized as follows: Section 2 discusses the state of the art and presents some related works. The structure of RoboJO and its main components, along with an explanation of components intercommunication, are presented in section 3. The mechanism of RoboJO is described in section 4. In section 5, the results of experimental testing and operational evaluation are discussed. In addition, other applications of RoboJO are presented. Finally, the conclusions are given in section 6.

II. State of the Art

In the last years, rescue robots have been deployed for using them in disasters [8]. Many designs have been introduced based on factors like environment, challenge, type of disasters, etc. [8]. The nuclear power plant is introduced as a challenge for public safety. When Fukushima nuclear power plant explosion occurred, many researches on robotics were presented to monitor the nuclear station [5]. One of the developed designs of robotics uses a mobile robot. This design offers the rapid movement and adaptive functionality of robot with rough environments [2], [9]. In this research, the mobile robot is adopted and used as a prototype of the proposed system. Authors in [1] have presented the design and experimental validation of a mobile robot for planetary exploration.

Recently, many system-based robots have been deployed in context of nuclear radiation. In [10], the authors have introduced a novel design for a climbing robot system in order to inspect tubes inside a steam generator. The main part of that robot is a vehicle carrying a PT arm and four cameras. Concerning the climbing task in nuclear power plants, the authors in

[11] developed a wall-climbing robotic system. It was designed as a bipedal robot with five degrees of freedom. Its small size not only offers flexible motion, but also the reliability of use.
Due to the need for accessing complex underwater structures and performing non-destructive evaluations, In [12], the authors developed a compact, maneuverable, and underwater robot for direct inspection of nuclear power piping systems. Another underwater robot was also developed in [4]. In this work, the proposed design of system-based robot is constructed based on a mobile robot. Moreover, the proposed design is required to satisfy the reliability and robustness given by climbing and underwater robots.

III. RoboJO Structure and System Description

In this work, a robot-based system is developed for achieving the objectives introduced for public safety regarding nuclear power plants. The RoboJO system is divided into five main units as follows:

1. Movement Unit (MU): it is responsible for moving the robot in the four directions. This unit includes motor and 4 motor drives attached to a plastic wheel (as shown in Fig. 1 (a)). This unit enables RoboJO to move forward and backward, turn left and right, and rotate in 360^o.
2. Control Unit (CU): it is the main electronic board that glues other components. It is fixed inside the robot body-box. The proposed system uses Arduino microcontroller board UNO R3 (see Fig. 1 (b)). This unit facilitates internal-communication between different units of RoboJO.
3. Sensing Unit (SU): this unit includes mainly the radiation sensor (Fig. 1 (c)) which is used to detect and measure the current radiation level at the robot location. Geiger counter is used (Fig. 1 (d)) to measure the radiation level digitally. A small LCD-screen is attached to the staff to display these measurements (see Fig. 1 (e)).
4. Wireless Communication Unit (WCU): this unit serves communications between RoboJO and the controlling environment. The controlling environment which includes the software from which RoboJO is controlled and monitored will be discussed in details in the next sections. The centric part in this unit is a wireless switch (TP-Link 4-LAN ports/1-WAN port is used (see Fig. 1 (f)) which is fastened to RoboJO body. The CU is connected with this switch via Ethernet UTP cable to enable the wireless remote connection with the server. This unit includes a GPS controller which is used to determine the current location (its geographical coordinates, latitude and longitude) of the robot once a radiation-leaking situation occurs. The GSM controller (Fig. 1 (g)) is provided with a SIM card to send suitable SMS messages to the operator in case of alarms.
5. Vision Unit (VU): the RoboJO system is provided with an IP-Camera that acts as the eyes of the robot operator. It is attached to the WCU via Ethernet UTP cable and fixed on top of RoboJO (see Fig. 1 (a)). It works in both day and night modes so that barriers encountered by RoboJO during its movement can be overlapped.

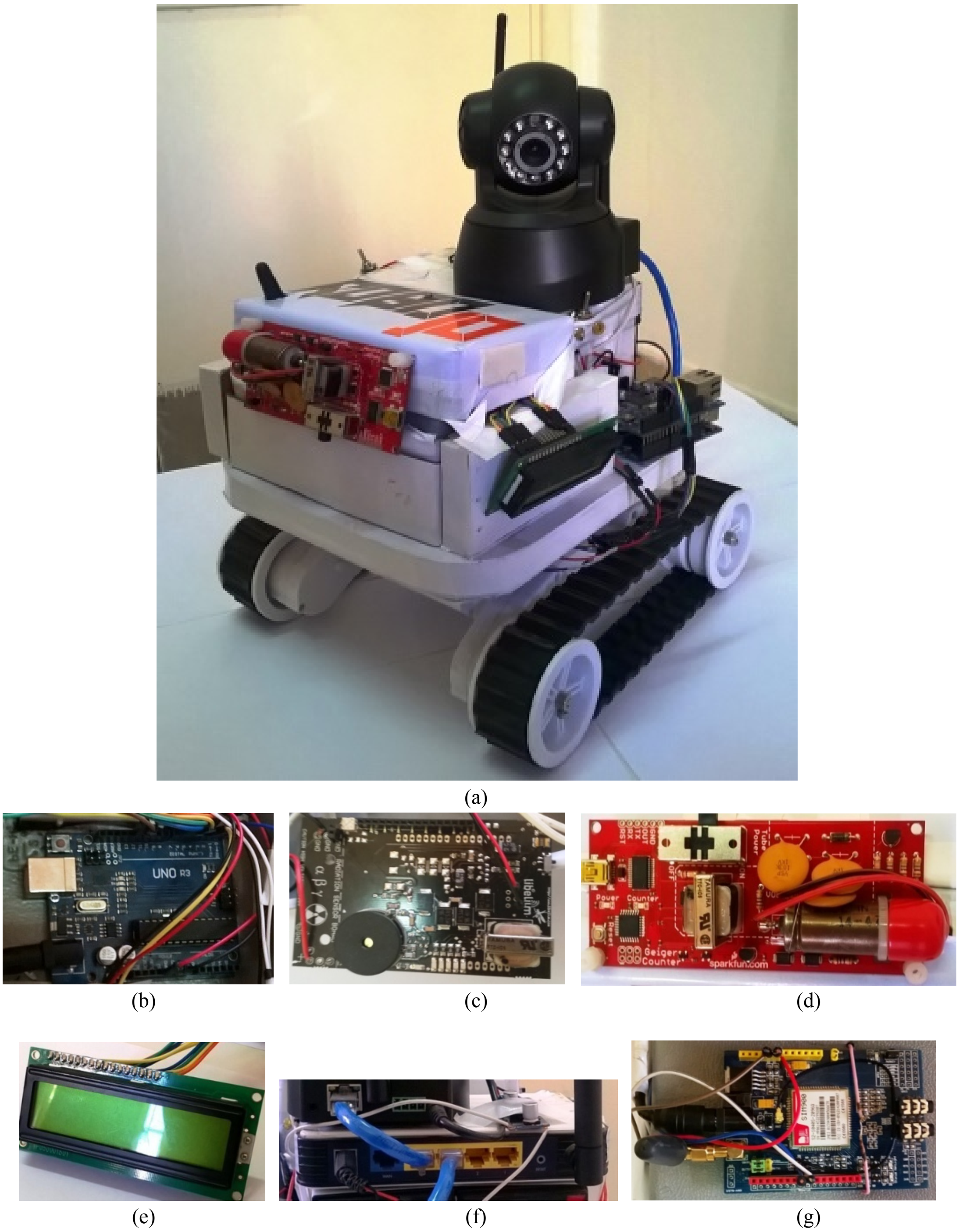


Fig. 1. Components of RoboJO: (a) RoboJO as a whole, (b) Control unit, (c) Radiation sensor, (d) Geiger counter, (e) LCD screen, (f) Wireless switch, (g) GSM & GPS controllers

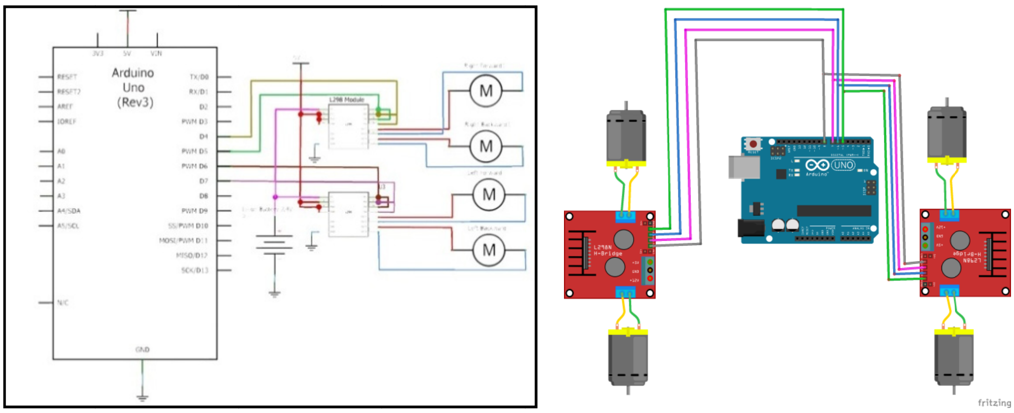
RoboJO is designed so that high flexible mobility, high degree of precision, and robustness are achieved. For example, the robot movement, rotation, and power consumption levels have to be in harmony for rapid movement and adaptive functions. In this way, precise results could be achieved with low cost effects.

Three considerable characteristics should be taken into account in the design of RoboJO system:

1. Smooth Movement and Robot Speed: the speed and movement of robot are important features to realize smooth execution and accurate performance. In some environments

like sandy or rocky lands, the robot needs to overlap conditions of skidding and sticking of wheels. In addition, weather conditions like rain, snow, storms, and strong wind act as negative factors in the performance of RoboJO. For this purpose, RoboJO is equipped with high power motors and flexible chassis made of intensified plastic in order to avoid the aforementioned obstacles and work accurately in the above environments. The ground and voltage gates are handled to move the basic robot vehicle forward and backward. The robot vehicle moves in the factory default speed which ranges from 100 PWM (Pulse Width Modulation) to 255 PWM. The board of motor drive is connected with a DC-Motor; which is programmed to avoid obstacles by automatically and gradually increasing the vehicle speed whenever obstacles are encountered.

2. Response Speed of Remote Control Signals for Rotation and Movement: the stability over ground has to be guaranteed while RoboJO is moving. Thus, the four wheels have to be always in touch with the ground. In case RoboJO moves forward or backward, each motor associated to a wheel has to run simultaneously with all other motors. At turning right and left processes, two of these motors will be turned off automatically. As a result, the speed of response increases at a curve, and the overall performance improves. Fig. 2 illustrates how the DC-motor and Motor drives are connected with each other. The DC-motor is connected with the CU (as shown in Fig. 2 (a)). The plan of DC-motor connection with motor board and CU along with power In/Out lines is illustrated in Fig. 2 (b). This design serves and eases the control of the vehicle movement during rotation. In addition, it enables the robot to move in circular motion paths as shown in Fig. 3.



(a) (b)

Fig. 2. (a) Connecting diagram of the DC-motor and the motor board. (b) Connections between the DC-motor, CU, and the motor board

3. Drive Motors and Power Requirements: RoboJO system is designed to execute other supportive and complementary functions like monitoring and data transmission. Therefore, power consumption is an issue; RoboJO needs to consume as minimum power as possible while performing all its duties accurately. Power requirements typically lead to high-torque, low-speed systems, with normal roving speeds close to 2km/h. RoboJO is designed to adapt low and high speeds. In case the operator of RoboJO intends to increase the speed, the voltage of motor drive is increased by 3V. The maximum voltage of motor drive is 12V, and the minimum is 6V according to Fig. 4. As for the distribution of the battery energy, Fig. 5 shows how the energy of batteries is distributed to other components (*i.e*. IP-Camera, CU, and WCU).

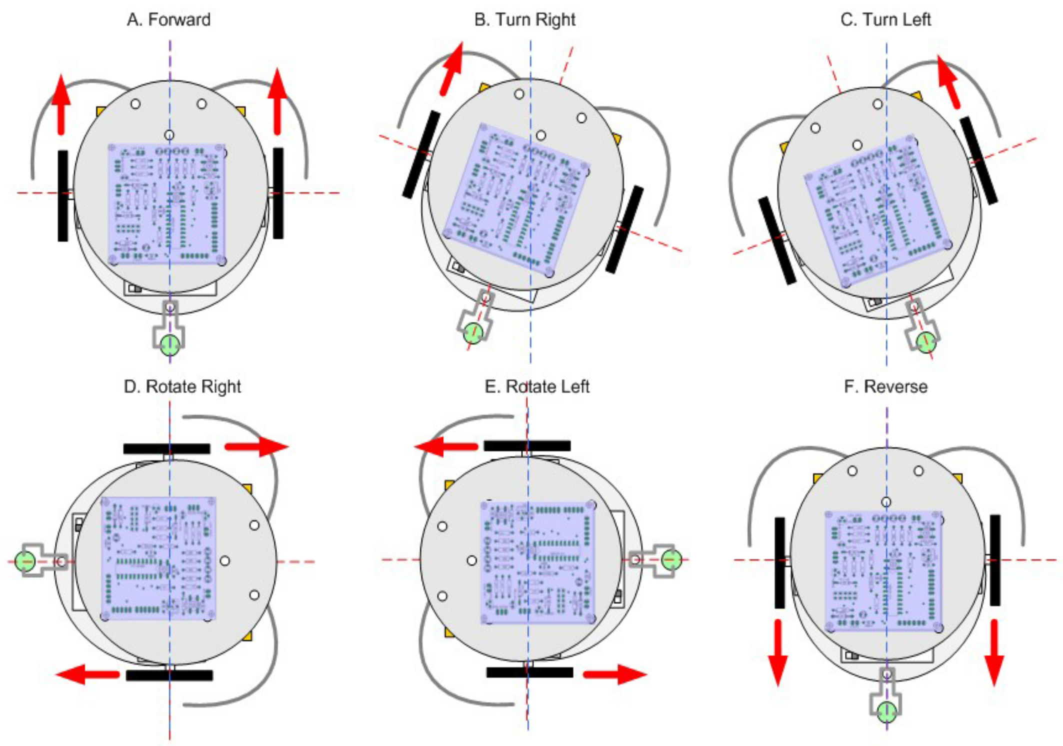


Fig. 3. A Diagram for the designed rotation motion of RoboJO

IV. ROBOJO MECHANISM AND IMPLEMENTATION

The RoboJO system, as a robotic composition, is constructed on a wood plate with dimensions of 20cm in length, 22cm in width, and 2.5cm in thickness. 4-wheel drives (DC-motors) of 3cm width and 5cm height are fixed at the bottom of that plate along with their plastic chassis. The other components are located on top of that plate (see Fig. 1 (a)).

To start running RoboJO, the operator turns on the system and sends command signals from the management software to the robot through the wireless channel in the WCU. The management software is implemented using Java® programming language. Once the command arrives to RoboJO via WCU, a connection port is opened using Telnet protocol on port number 23. The Telnet protocol is responsible for transferring the operator commands from the software server (in our experiments we use a PC) to the CU via TCP/IP protocol, as shown in Fig. 6.

The command set used to control RoboJO movement is restricted to: forward, backward, and rotate. Moreover, a connection to the IP-Camera is established to send live video stream to the screen of the operator control. Fig. 7 depicts the architecture of the control system. A client application (tablet PC) is connected to the control board via wireless network. A serial port communication is utilized to transmit data between the executor of the robot and the PC.

As for sensors, RoboJO is provided with two types of sensors as illustrated in Fig. 8. The first sensor is called radiation sensor, and the second is Geiger counter. The former discovers nuclear radiation levels (*i.e.* Alpha (α), Beta (β) and Gamma (γ)), see Fig. 9. The later sends the value of nuclear radiation level to the CU.

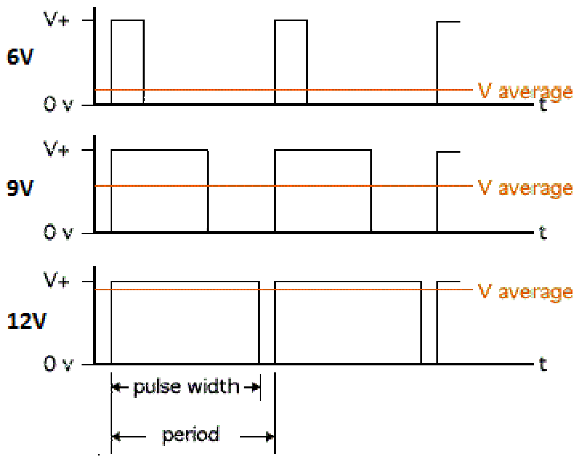


Fig. 4. PWM: voltage values adapted according to RoboJO speed

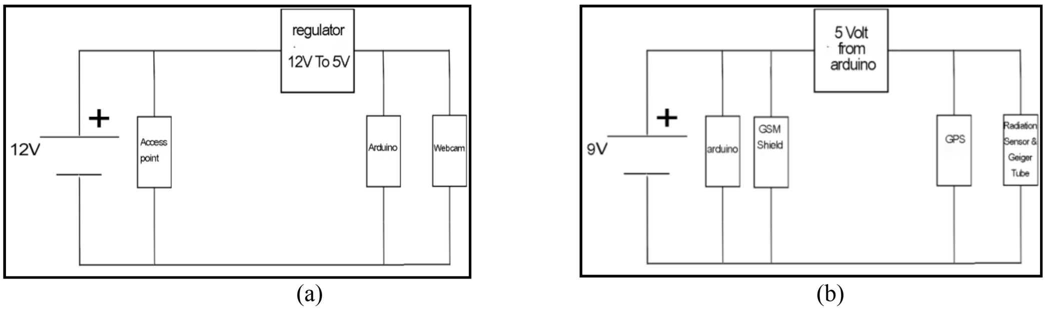


Fig. 5. Circuit of the energy distribution between battery and other components. (a) CU, SU and WCU connections. (b) CU, VU, and WCU connections

Once RoboJO starts working, and in case a detected radiation value is found to be larger than the allowable standard value (80 Count per Minute (CPM) on Geiger counter), the GPS service is activated to determine the location of radiation leakage and the current location of the robot. The location is geographically described by latitude and longitude coordinate values. In addition, the board of GSM is activated to extract Google Map™ of the determined location and send an SMS message to a predefined emergency phone number. Fig. 10 shows a simulation snapshot to RoboJO in case a message is sent to the operator. However, the value read by Geiger counter may exceed the threshold value mentioned above to larger values (classified as harmful to human) depending on the distance between RoboJO and the source of radiation leaking.

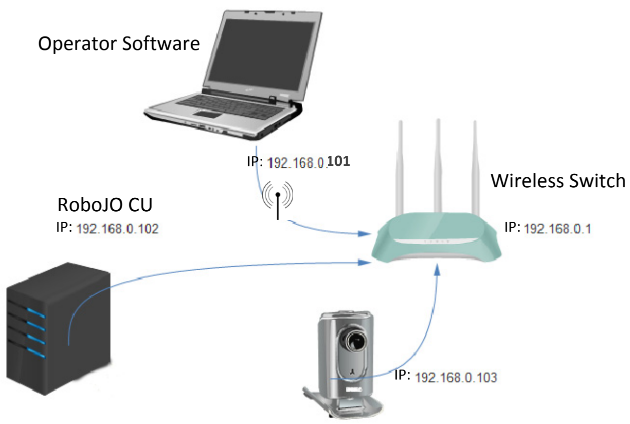


Fig. 6. A Diagram of the wireless connection between PC, WCU and IP-camera

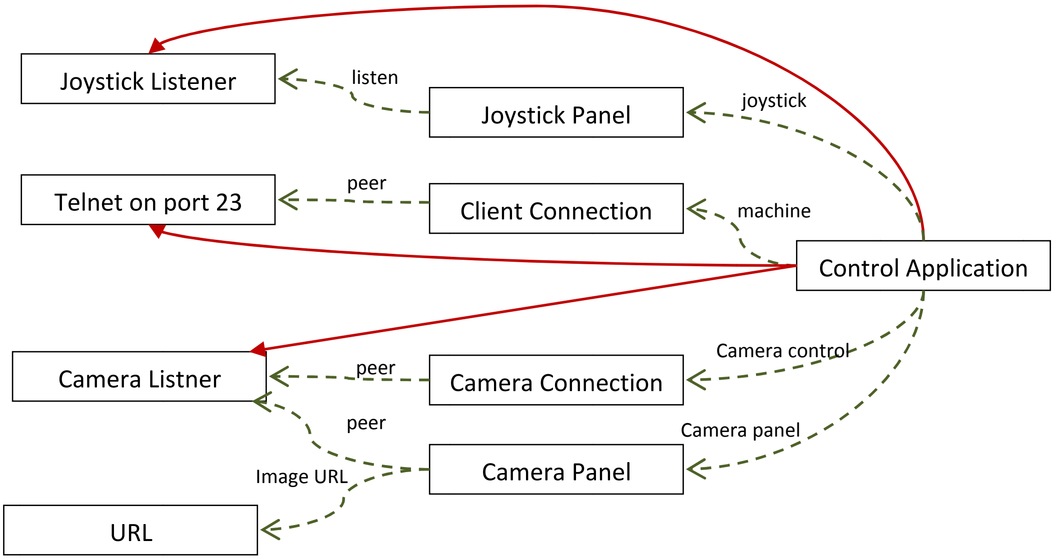


Fig. 7. Diagram for the data flow between PC, network switch and IP-camera

V. Experiments and Applications

Once RoboJO has been composed according to the description mentioned in the previous section, a testing phase is conducted. For this purpose, an intensive evaluation process is carried out to determine if the RoboJO system (as a whole) satisfies its functional and non-functional requirements.

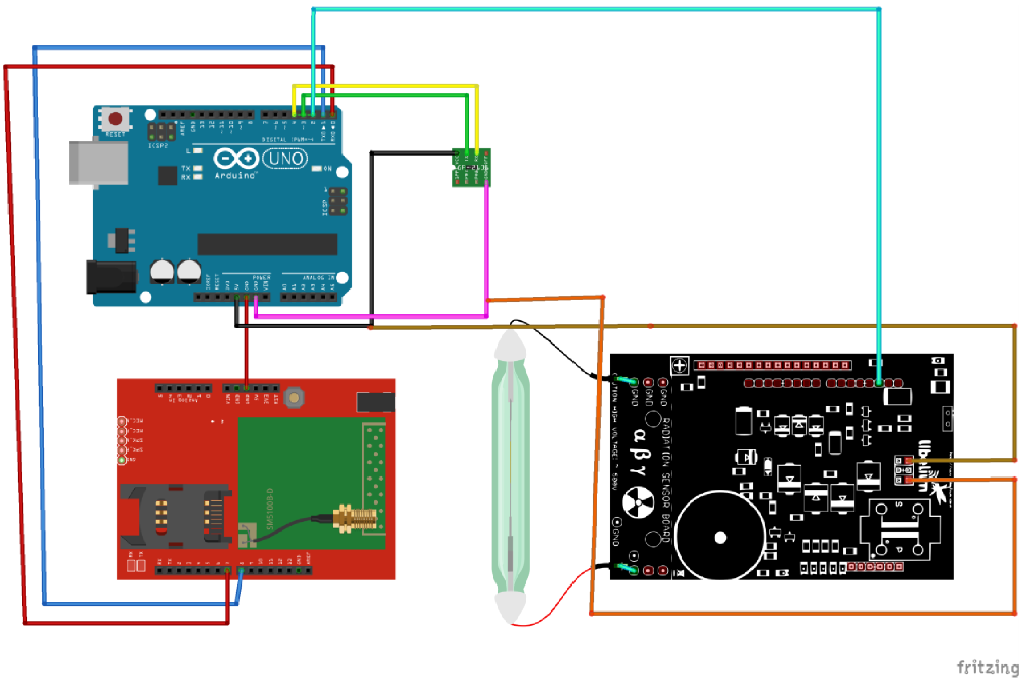


Fig. 8. Sketch for the connection between sensors and GPS, GSM and Arduino board

During the testing phase, RoboJO was run to ensure high quality of performance and high accuracy with respect to the expected results. The term "quality" is used to define to which extent RoboJO satisfies its specifications and meets system requirements.

Two types of evaluation have been carried out: Execution-based Testing (ET) and Non-Execution-based Testing (NET). In the NET process, a review of the obtained results is given (concerning RoboJO as a tool) in terms of its behavioral properties (*i.e.* robustness, performance and reliability). In contrast, the ET focuses on running RoboJO to make sure that the design and implementation are well-integrated and able it to overcome problems and achieve objectives.

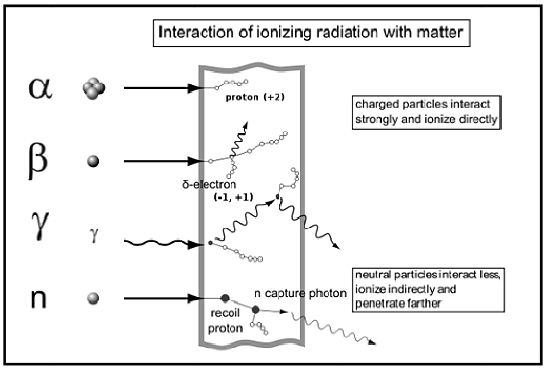


Fig. 9. Interaction of ionizing radiation with matter

The following subsections describe the software application of RoboJO and discuss in details the ET and NET testing strategies depending on the inference formulated from the behavioral properties of the robot in progress.

A. The Software Application of RoboJO

An application has been developed for RoboJO based on Java Programming language. The application consists of five main parts.

Fig. 10. Simulation for RoboJO including message sending task

Fig. 11 illustrates the interface of the developed application at which the main parts are arrowed. These parts are:

- *Client Connection*

The first part is client connection which is divided into two sections: (client connection for Arduino and client connection for IP-camera). Its main task is to initiate the connection by providing the required IP-Address and the Port number. In case the connection is unable to be established, an alert message is displayed on the operator. Otherwise, the connection is created between RoboJO and the application server. Then, the application is connected to Arduino Board and the IP-Camera.

- *Gear Box (Joystick)*

The second part is Gear Box (Joystick) which is used to direct and move RoboJO to Forward (F), Backward (B), Right (R), Left (L), Turn Left (TL) and Turn Right (TR). If the operator drags the gearbox (Blue Circle) in direction of the Character F (as shown in Fig. 11), RoboJO is moved forward. If the operator drags the gearbox in direction of the Character B, RoboJO is moved backward. Dragging the gearbox toward character R, RoboJO is moved to the Right. If the operator drags the gearbox in direction of the Character L, RoboJO is moved to the Left. If the operator drags the gearbox in direction of the Character TR, RoboJO is turned to the Right. Finally, if the operator drags the gearbox in direction of the Character TL, RoboJO is turned to the Left.

- *IP-Camera*

The third part is the IP-camera unit. It consists of two main parts. The first one is the IP-Camera control which is responsible for directing the camera to the four directions (*i.e.* up, down, left, right). The second part displays online the video stream recoded by the camera.

- *LED-Light button*

The vehicle is provided with a light which is turned off or on by a LED-light button. The color of the button is changed to orange color if the light of the vehicle is on. In contrast, the color of the button is changed to red if the light of the vehicle is off.

- *History Commands*

The last part is the command prompt, which enables the operator to type commands and save these commands as a history list.

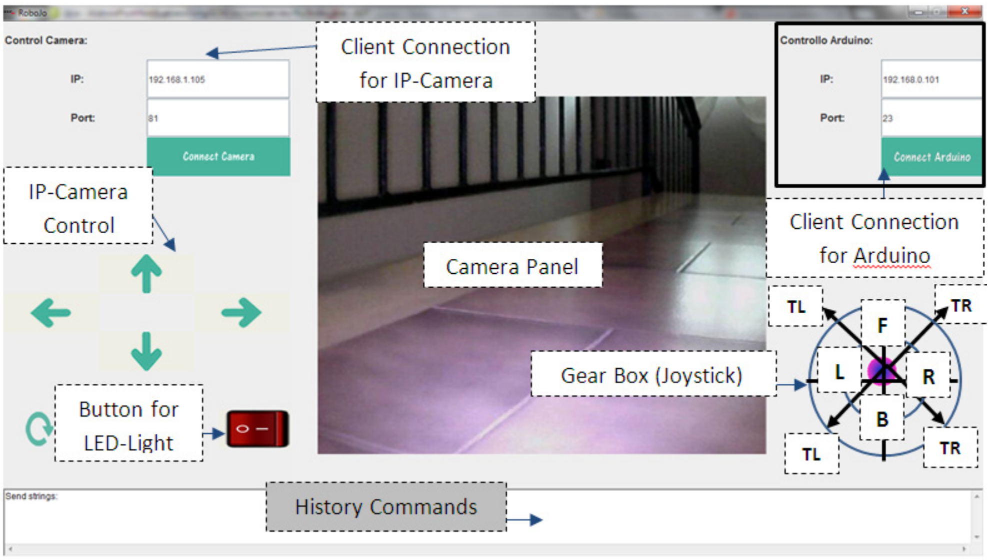


Fig. 11. The interface of the developed application for RoboJO

B. Evaluation Based on the ET Testing

To run the system of RoboJO, several scenarios have been carried out in context of functional requirements of the robot system. The first scenario is to avoid and climb obstacles. A box is positioned at the front of RoboJO. The box is 5.5cm height and 9.5cm width. RoboJO is able to climb the box easily. A Video stream is recorded; and snapshots are shown in Fig. 14.

In addition, a book is handed in front of RoboJO as shown in Fig. 15. The experiment has shown that RoboJO is able to smoothly increase the velocity to climb the book which has a height of 3.7 cm.

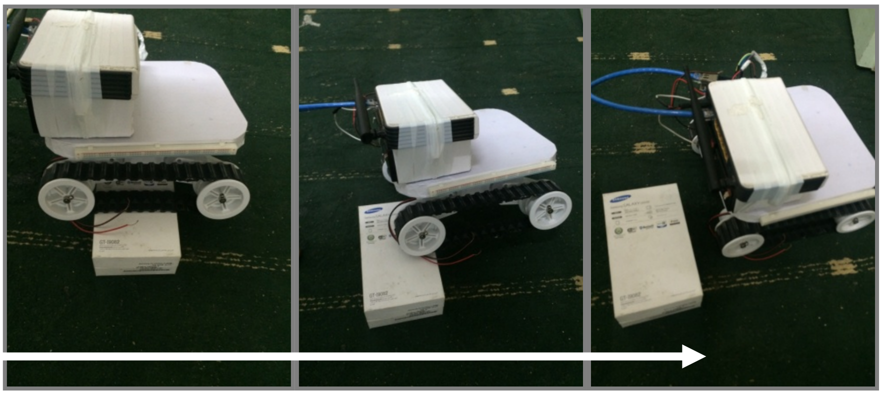


Fig. 12. Snapshots for avoiding and climbing a box while RoboJO is moving

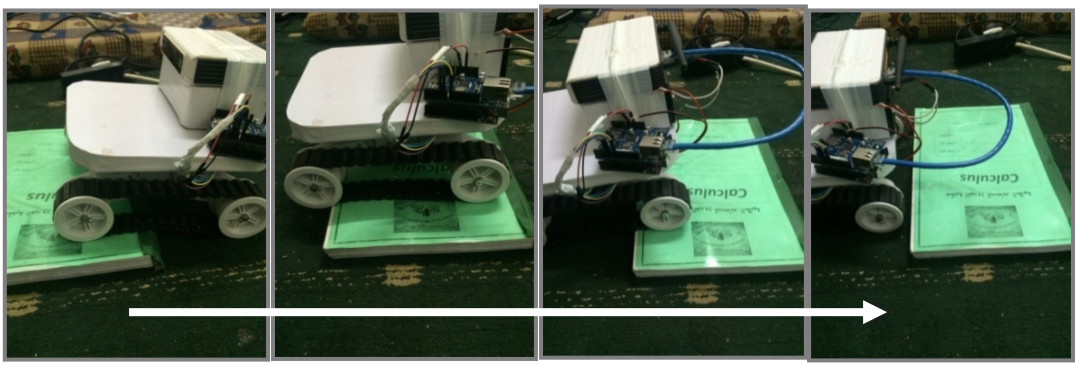


Fig. 13. Snapshots for avoiding and climbing a book while RoboJO is moving

The second scenario is to make RoboJO move in a circular motion. Fig. 16 shows several snapshots for RoboJO while it is rotating on the ground in a circular motion.

Fig. 14. Snapshots for circular motion

In the third scenario, RoboJO is tested for discovering the location of a radiation leakage and determining the nuclear radiation level. Samples of Vaseline Glass have been used in the experiment as shown in Fig. 17. These samples include Uranium with a percentage of 0.2%.

Fig. 15. Samples of Vaseline glass

The experiment has shown that RoboJO located the position of these samples. The discovering process is carried out by increasing the number of the micro Sievert (a unit used to measure radiation levels). Whenever RoboJO moves towards the samples, the counter printed on the LCD screen increases as shown in burst pictures of Fig. 18.

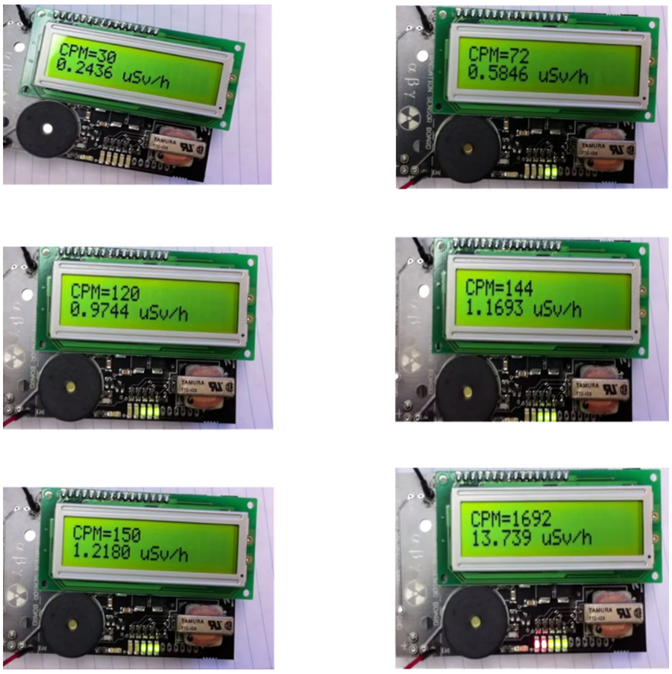


Fig. 16. A comparison between normal values of the nuclear radiation level (left column) and abnormal values (right column) as read by the radiation sensor

Moreover, a message is sent to the emergency contact, in which details of the location of radiation leakage are recorded. Once RoboJO records high radiation leakage, a message is sent to the operator. If the message is successfully delivered (*i.e.* an action is taken by the operator), RoboJO terminates the sending procedure. Otherwise, sending is repeated in a rate of about 20 Message/minute. The transmitting distance is not a matter because messages are sent via the mobile operator of the SIM-card.

Fig. 19 shows the template of a sent message which includes a link of Google map to the current location of RoboJO. Moreover, an alert beep is triggered whenever RoboJO moves toward the uranium samples.

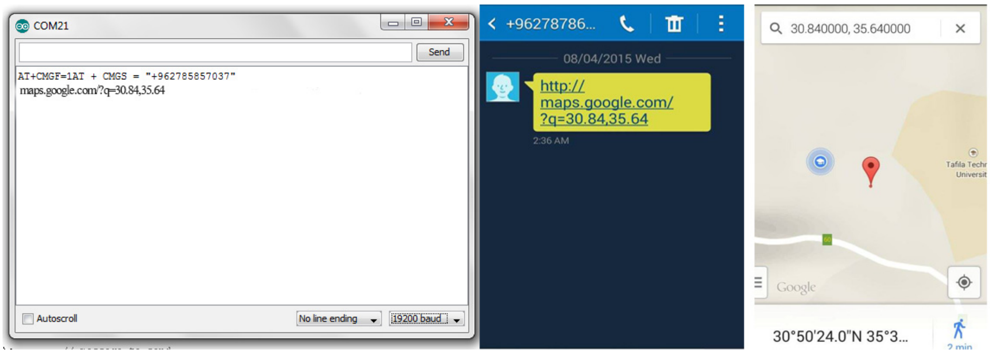


Fig. 17. An example of a message sent to the operator by RoboJO using the emergency contact of WCU

The IP- Camera, in turn, has captured a video stream. The video stream is transferred through the wireless connection to the control screen which is monitored by the operator. In Fig. 11, the control screen shows the place of the video. In case the light is turned off due to environmental effects, the control system turns on automatically and the infrared light captures the location in darkness as shown in Fig. 18.

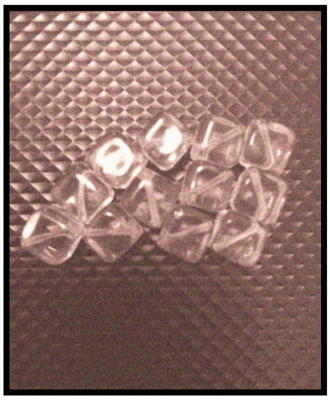


Fig. 18. Samples of Vaseline glass captured in the darkness mode of the IP-camera

C. *Evaluation Based on the NET testing*

After successfully running RoboJO, a non-execution-based testing is carried out to confirm the high quality of the developed robotic system. For this purpose, two behavioral properties are inspected: utility and robustness. For the utility property, the objectives introduced for RoboJO have to meet its outputs. As for the robustness property, RoboJO needs to be robust against the environmental effects; which may be generated based on unexpected effects (*e.g*. a shadow or darkness). In addition, the second property inspects RoboJO stability against failures caused by communication network interruptions.

Both behavioral properties were discussed based on the results achieved in the previous section. Since there is no nuclear reactor available in Jordan, results have been obtained by establishing the experiments in the nuclear physics laboratory at Tafila Technical University. Therefore, and as a future work, RoboJO system must be tested in actual environments like nuclear reactors of Jordan's friend countries.

- *The utility property*

To explain how RoboJO affirms its specifications and requirements, the achieved results have to be discussed in terms of its objectives. Therefore, the property utility here is presented to confirm that RoboJO meets its objectives.

According to the objectives of RoboJO introduced previously, the key idea of RoboJO is to enable the operator in nuclear power plants to be more efficient in monitoring and discovering the radiation leakage. The performance of the nuclear reactor is monitored automatically; and any unusual circumstances are reported timely. Moreover, the public safety is guaranteed and fears of local people are mitigated.

The utility property is discussed here in context of the usability and functionality of RoboJO. The usability refers to RoboJO's ability to read the nuclear radiation level precisely through advanced sensors. Concerning functionality, RoboJO can automatically alert the system operator in case a radiation leakage occurs. Moreover, RoboJO realizes the capability to make emergency calls and determine an accurate location of the radiation leakage.

- *The robustness property*

It is essential to figure out to which extent the operator relies on the developed design of RoboJO. Therefore, the robustness of RoboJO must be tested. RoboJO must be robust against unacceptable results with valid input assured. The developed system must not crash when a failure is recognized. In the developed RoboJO, two types of failures could occur: the first is yielded due to environmental effects while the second results from the failure of connection to the Board of Arduino Server or network communication.

With respect to the first type, environmental effects (like shadow and darkness) over the location of radiation leakage can prevent the appearance of surrounding objects, the ground surface, or in-path obstacles. This kind of effect increases the possibility of failure because the operator cannot guide RoboJO into a safe area or overlap obstacles. The IP-camera is able to automatically turn on an internal light to overcome the failure due to environmental effects. Thus, RoboJO is able to handle this kind of failure and alert the user if the application of RoboJO does not handle the failure.

Connection to communication network is not always available due to logistic problems (*e.g.* coverage area of WCU or mobile network operator). Since the connection is necessarily needed to control RoboJO successfully, the developed software application monitors the network connection. In case the connection is disconnected while RoboJO is running, an alert is raised at the operator side to indicate that the connection to RoboJO is lost. Moreover, the data sent between RoboJO and the operator travels in the communication network. Therefore, software application can monitor the data and confirm successful sending.

VI. CONCLUSIONS

In this paper, a robotic-based system called RoboJO is presented. RoboJO is designed, developed and tested in the field of public safety against nuclear power plants radiation leaking. The experiments carried out to discover and locate the nuclear radiation leakage demonstrate its capabilities. A software application is developed to enable the operator of the nuclear power plants to control RoboJO easily. With the friendly interface designed for the application, RoboJO can realize the human-machine interaction through an IP-Camera and Advanced sensors. RoboJO has shown its capability to avoid and climb obstacles while it is moving. Once RoboJO discovers the nuclear leakage, an alert sound and alert message are activated. The latter includes information about the leakage position and the position on Google maps. RoboJO has satisfied two behavioral properties: utility and robustness. RoboJO, as a mobile sensor and a single mobile robot, brings the advantage (against fixed sensors) of exploring different locations. In addition, the operator is able to move the sensor closely toward the radiation leakage.

For work, an algorithm should be proposed to enable RoboJO to automatically detect and recognize obstacles. A mobile application needs to be developed to control RoboJO from outside the environment on far distances.

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