Design and Realization of a Multi-Robot System for Real-Time Sensing and Monitoring

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Abstract— **The main objective of this research is to design and realize a multi-robot system for real-time sensing and monitoring suitable for hazardous and/or unreachable environment. The proposed system has three mobile robots; main, rover and eye. Each mobile robot has its own embedded microcontroller and set of sensors. Wireless communications between local site and these mobile robots are achieved by WiFi, ZigBee and Bluetooth techniques, and can be accessed through the internet. Wireless teleoperation of these mobile robots is a challenging task that requires an efficient interface and a reliable real-time control algorithm to avoid obstacles. The proposed system enables the authorized operator to send commands to the mobile robots, and receive scanned data and images from the environment through the internet. The mechanical part of the remote station has been built after careful selection of the design parameters using CAD/CAM tools. While, the system hardware and software parts of the embedded controllers were implemented using PROTEUS development tool to obtain the suitable design parameters. Then, real experiments have been achieved to demonstrate the system performance including the wireless teleoperation of the three mobile robots, their navigation to avoid obstacles, and real-time sensing and monitoring.**

Keywords- mobile robot; multi-robot system; remote sensing and monitoring; wireless sensor networks; obstacles avoidance.

I. INTRODUCTION

Recently, there has been a strong impact of computer and communication technologies in our life. This is mainly due to availability of inexpensive microcontrollers, smart sensors and actuators together with wireless communication technology. Therefore, there is a great challenge to apply these technologies for sophisticated applications to get better results with less effort. Many attempts have been adopted to replace humans by robots in performing repetitive, dangerous, and dirty tasks which humans are unable to do[1]. Robots have been already used in many applications performing simple and complex tasks with acceptable accuracy, high reliability and even more cheaply than humans[2]. In fact, there is a need to use concepts of robotics and wireless communication technology for real-time applications, such as monitoring and control.

Wireless Sensor Network (WSN) technology together with mobile robots can be used to detect several variables in unreachable and hazardous environment, where human involvement is limited or impossible. Each mobile robot can be considered as individual node in the network which can monitor its local region and communicate through a wireless channel with other nodes to collaboratively produce a high-level representation of the environment's states. By using such a network, large areas can be monitored with low cost. Mobile robots are essential tools in modern manufacturing systems, they can be programmed to achieve the same tasks done by human workers. Mobile robots when equipped with sensors are becoming widely used, especially in hazardous environments[3].

Mobile robot navigation is an essential issue in robotics, especially when it is wireless controlled. Usually, an embedded microcontroller and onboard sensors are used for robot navigation and obstacle avoidance. The robot should be capable of sensing its working area to obtain its location and then planning a real-time trajectory to reach the target position. There are several conventional methods used for online navigation, some of them [4,5] combine a graph searching technique with obstacle avoidance to generate robot trajectory. Others [6,7] consider the robot motion control for robot path planning by assuming that each obstacle exerts a repulsive force on the mobile robot, and the target exerts an attractive force. These two types of forces are combined at each step to determine the next step of robot movement. These methods require large data and complex computations that making them unsuitable for real-time applications. Neural network-based methods [8,9] were applied to generate the next movement step of a mobile robot from a neural dynamics mechanism which selects a movement direction from a set of possible directions. Fuzzy-based navigation algorithms [10,11,12] were developed for a mobile robot systems. Fuzzy logic offers a suitable framework for representing imprecise and uncertain knowledge in dealing with real-time navigation of mobile robots based on human knowledge.

In fact, teleoperation of mobile robots are so important in environments where it is difficult or impossible for humans to be there. Real-time navigation of mobile robots in such environments is not easy task without using sensors and obstacle avoidance algorithm. Without such avoidance scheme, it would be difficult to guarantee safe navigation.

Multiple robots teleoperation can be achieved by a single operator to provide enhanced capacity and efficiency on accomplishing complicated tasks. The communication between the operator and the multi-robot system and the communication among the multiple robots are both subject to communication constraints like time delays and packet losses [13]. Suzuki et al [14] proposed a localization method using shared information for teleoperation of multiple robots. The robot can perform the initial self-localization more efficiently by sharing the map information and each self-position. Farkhatdinov & Ryu [15] described two types of multiple teleoperation systems, in which all objects were controlled by human without any autonomous systems. They demonstrated that switching of control signals can make human-robot interface easier and more intuitive.

In recent years, internet-based tele-robotics has become more important in our lives. There are many scholars dedicated to this research field, especially the cooperation problems in operator with operator, robot with robot and operator with robot in multi-operator multi-robot teleoperation system. Fu and Ouyang [16] had given the solution of the items handover in the cooperative teleoperation system, designed the teleoperation robot system, given the specific experiment process and verified the feasibility of the scheme through the remote cooperation handover experiment.

II. Research Contributions

This paper presents the second stage of a project developed at Philadelphia University-Jordan. The main objective of the project is to design and implement a multi-robot system for real-time sensing and monitoring of environment `in unreachable area. Three mobile robots equipped with selected sensors and IP camera to perform real-time scanning, monitoring and control tasks. Each mobile robot is provided with an embedded microcontroller for real-time control and navigation algorithm to avoid obstacles.

In this research three main challenges will be discussed, these are;

- Design and implementation of a remote monitoring station with three mobile robots to perform real-time sensing and monitoring tasks in remote hazardous or unreachable environments.
- Adopt reliable wireless communication channels to guide mobile robots in the working area. In this case, each mobile robot is considered as node in the wireless network.
- Apply an intelligent real-time control algorithm to guide each robot and to avoid obstacles in the working area.

III. Research Contributions

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IV. System Overview

Multi-robot teleoperation system is required to allow human operators to execute several monitoring and control tasks in remote environments[17]. Such a system is composed of three parts, the local site, the remote site, and the communication channel. A human operator can generate manual commands from a local unit to control remote site which has three mobile robots. For multi-robot network design, it is very important to study the balance between the simplicity of the robot node, communication between nodes, and the control techniques required to manage robots operation within the network. The general layout of the proposed system is given in Fig.1, where three mobile robots are used to sense and monitor selected variables in the working area. The main robot holds both rover and eye robots, as shown in Fig.2. Each robot is considered as a node in the wireless network and it has its own embedded microcontroller, sensors and communication channels with other mobile robots. The operator can remotely monitor measured variables and also sends control signals to the selected mobile robot.

A. Mobile Robots Design

In this project the attention is focused on land-based track robots in which a continuous band of treads is driven by two wheels. Each mobile robot has two DC motors used for driving and steering, as shown in Fig.3. The right and left DC motors are controlled by the embedded microcontroller of the mobile robot via a differential box. The implemented prototype of each mobile robot provides support to the batteries, electronic board, and all elements related to the proposed design.

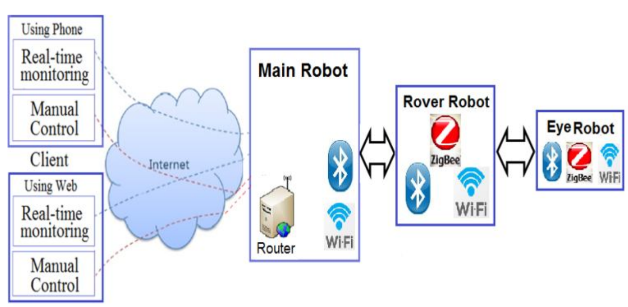

Figure 1. Wireless sensor network for group of mobile robots.

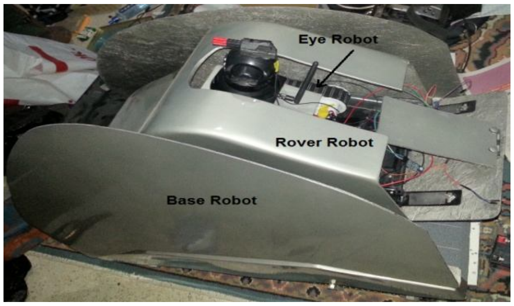

Figure 2. The main robot holds both rover and eye robots.

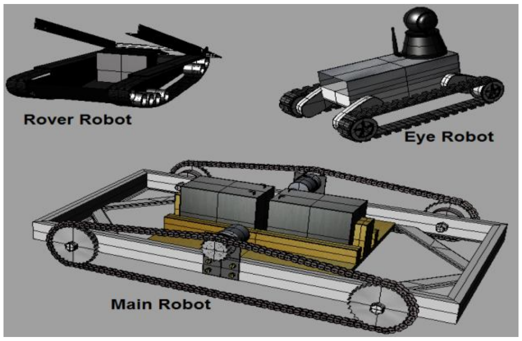

Figure 3. CAD/CAM design of the three robots.

B. Communication Channels

For the implemented system, the wireless communication between mobile robots and base station can be achieved using Bluetooth, Zigbee and WiFi technologies. The operator can access the main robot either through the internet or through the Zigbee and Bluetooth adapters. In one hand the main robot has WiFi router and Bluetooth adapter for communication with both rover and eye robots, while the rover robot has WiFi router to access internet via main robot router, and has Zigbee adapter for communication with eye robot and base station. The rover robot has also two Bluetooth units for communication with base station, eye robot and main robot. On the other hand the eye robot has Bluetooth adapter for communication with base station, rover robot and main robot, and it has Zigbee adapter for communication with base station and rover robot.

C. Embedded Microcontrollers

Each mobile robot has its own microcontroller, sensors and actuators. The microcontroller scans the sensors and communicates with other robots and base station through wireless communication channels. The microcontroller is used to generate the required control signals to each motor. An electronic drive circuit is designed to provide the DC motors with required current. Each microcontroller is connected to an SD card storage unit of 8 GB connected to the microcontroller. Figure 4 shows the general layout of the embedded system of the main robot where the microcontroller ATMEGA2560 is used.

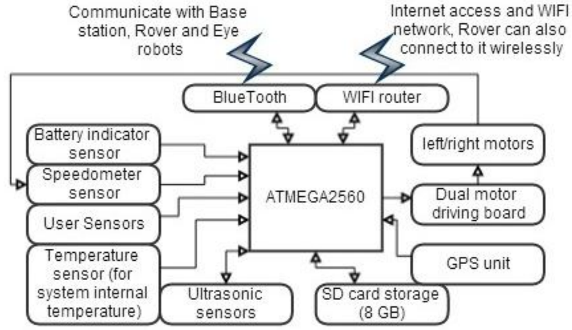

Figure 4. Embedded microcontroller of the main robot.

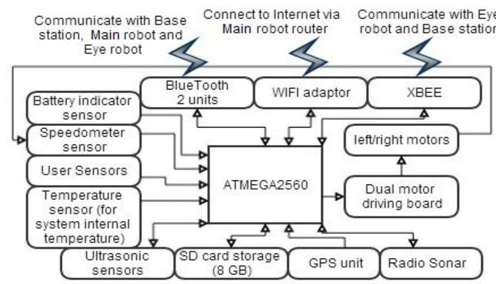

Figure 5. Embedded microcontroller of the rover robot.

The design of the rover robot embedded system is based on ATMEGA2560 microcontroller, as illustrated in Fig.5. As for the eye robot, the microcontroller ATMEGA328P is used, as shown in Fig.6. An IP camera controlled through the internet is used to view live video of the monitored area. Also, radio solar unit is connected to the microcontroller for tracking purposes.

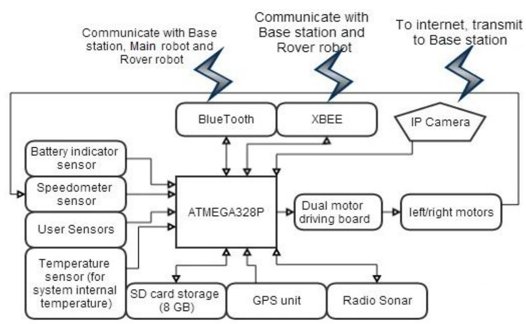

Figure 6. Embedded microcontroller of the eye robot.

D. Obstacle Avoidance Technique

As given in Fig.7, the rover robot has eight built in ultrasonic sensors (type HC-SR04) to detect the route and avoid any obstacle in the working environment. The output signals of these sensors are used by the rule-based intelligent controller to generate the required control signals to the two DC motors of the robot, as illustrated in Table 1.

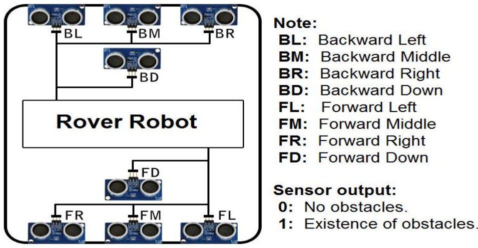

Figure 7. Ultrasonic sensors of the rover robot.

TABLE I. RULES FOR OBSTACLE AVOIDANCE.

Sensors Feedback Signals								Robot Commands		
FD	FL	FM	FR	BD	BL	BM	BR	Action	Motor1	Motor2
0	X	X	X	0	X	X	X	Stop	0	0
0	X	X	X	1	X	0	X	Back	-1	-1
0	X	X	X	1	X	1	0	Back Right	-1	0
0	X	X	X	1	0	1	1	Back Left	0	-1
0	X	X	X	1	1	1	1	Stop	0	0
1	X	0	X	X	X	X	X	Forward	1	1
1	X	1	0	X	X	X	X	Forward Right	1	0
1	0	1	1	X	X	X	X	Forward Left	0	1
1	1	1	1	X	X	X	X	Stop	0	0

V. GRAPHICAL USER INTERFACE

The control of mobile robots through teleoperation requires a flexible and efficient user interface. Successful navigation of the mobile robot depends mainly on how accurate information from the robot is presented to the embedded microcontroller during automatic mode, and to the human operator during manual control. This part of the system design is a graphical user interface (GUI) provides the operator with commands and real-time information about the remote site, as illustrated in Fig.8. The first section of the GUI has three main displays;

- monitoring and technical information (upper left),
- GPS locations of the three robots (down left), and
- live camera video from eye robot camera (right side).

The second section of the GUI represents the command section (right side of the screen) which consists of;

- four control buttons for each robot,
- refresh button to update sensors readings,
- fire button to fire up missiles from eye robot, and
- three sliders for speed control purposes.

The third section of the GUI contains set of special purpose buttons used by the operator to;

- connect robots,
- synchronize brain signals (for mind control),
- synchronize voice for voice control,
- synchronize touch pad control,
- update page setting,
- open maps via local secured program, and more others.

VI. TELEOPERATION OF MULTI-ROBOT

The problem of multi-robot teleoperation is an important issue for real-time control of the proposed system. An embedded controller for each robot performs real-time obstacle avoidance using ultrasonic sensors for both main and rover robots, and an IP camera for the eye mobile robot.

Figure 8. Graphical user interface of the multi-robot system.

A. *Forward Teleoperation*

There are two main modes to guide mobile robots from source point to destination, as shown in Fig.9, these are;

1). Automatic mode: when a command such as (spy or discovery) is assigned and the main robot is provided with GPS location (longitude and latitude), then it will automatically move to the desired location. Eye robot camera will detect and analyze the way. If the robot reaches to a point where there are too much obstacles or a place where climbing is needed, then the main robot gate opens to drop the rover robot. Obstacle avoidance can be achieved using eight ultrasonic sensors beside image processing. As illustrated in Fig.10, if command assigned is "Spy", then the rover robot releases the eye robot and will go silently to the working area to capture images and data from the environment. If the command is "discovery", then the eye robot will not be released unless the working area entrance is very small for the rover robot or if the rover robot battery is low.

2). Manual mode: robots will be manually controlled from the base station to the destination using live camera. The operator can read signals from sensors in live mode and view live video/audio.

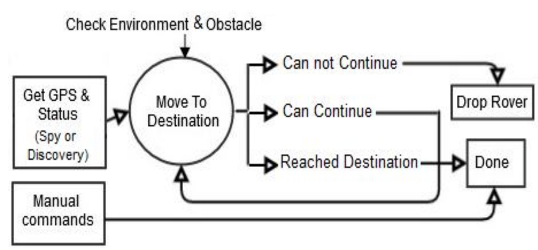

Figure 9. State diagram of the multi-robot teleoperation.

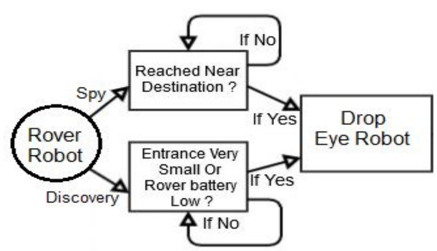

Figure 10. State diagram of the eye robot guidance.

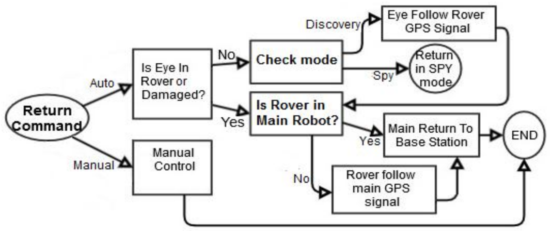

Figure 11. Multi-robot returning guidance.

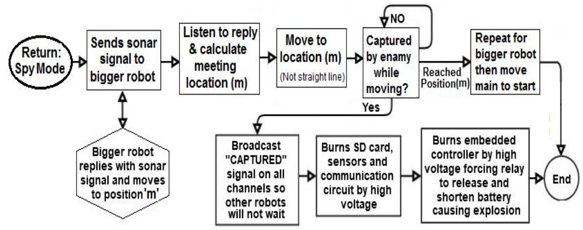

Figure 12. Return state diagram for spy command.

B. Backward Teleoperation

The mobile station can be directed to return back to the starting point using either manual mode or automatic mode, as given in Fig.11. During the manual mode, the operator can control the three mobile robots manually, while for automatic mode it is important to check if the eye robot is loaded by the rover robot or damaged, otherwise, the mode is to be checked;

1). Discovery mode; the eye robot follows the rover GPS signal. If the rover robot is still in the working area, it will follow GPS signal to be loaded by the main robot. Then, the main robot returns to the starting point according to the commands generated by the teleoperation algorithm.

2). Spy mode; the eye robot will return back silently to the rover robot, as explained in Fig.13. In this case, it is not safe to connect to the GPS, internet or even through any wireless signal. Also, robot drop point may not be the same as its return point since the bigger robot may move to another location to cover area, or it may move to "Not be discovered" state. In this case, the following procedures are used by the teleoperation algorithm;

- A sonar signal is generated by the eye robot (if not damaged) to notify the rover robot to forward a location to follow.
- The rover robot will broadcast a corresponding sonar signal for handshaking with eye robot.
- The meeting location (m) is a real-time calculation of the location given by the rover robot plus a constant number (k) generated by the teleoperation algorithm.
- Both eye and rover robots will move to the meeting location, then the eye robot will be loaded by the rover robot.
- The above steps will be repeated for rover and main robots.
- The main robot will return back to the starting point which is known by the main robot.

It is very important to mention that if a robot gets discovered (by enemy for example), it immediately broadcasts wireless signal on all channels saying "DISCOVERED". Then, other robots will escape away or continue mission but not try to contact the discovered robot. In this case, the discovered robot will destroy all data in its SD card and gives high voltage to all sensors, SD card, and communication circuits to burn them out. Then, it gives high voltage to the embedded controller causing its permanent damage. This damage will release a relay on output port that will shorten battery voltage causing an explosion inside. Off course, these steps of self destruction are used for safety to avoid enemy from having any piece of information that may lead them to know how robots work or how to find other robots.

VII. System Evaluation and Challenges

The mechanical part of the proposed system has been built after careful selection of the design parameters using CAD/CAM tools. While, the electronic part of each mobile robot has been designed and verified using PROTEUS workspace. The overall system has been tested under different conditions to check its ability and security. This implemented system has a hierarchical and distributed structure to guarantee the following features;

- If any robot gets technical problem, other robots can still respond.
- If a robot gets destroyed, one does not lose everything and still has backup.
- Keep batteries of smaller robots always full without making a lot of load on motors or consuming a lot of energy.
- If enemy can detect internet connection, the main robot will be in away area receiving orders and sending them to other robots via ZigBee on a range of 1.2 km, this will prevent discovery.
- Since each robot can be in a place, while the smaller robot will go deeper, at this time robot who stops will sense area for enemies signals to warn smaller robot and give it enough time to either go back or enter silent mode where it disconnects all wireless signals and stores data in SD card, this prevents discovery.
- If a robot battery is dead because of enemy electromagnetic fields for example, bigger robot can still bring it back safely, so one does not lose his spying nodes.
- If enemy discovers a robot in the working area, they will search for other robots in area, but will not search for robots outside the area, this gives an advantage that robots moves are known and gives enough information to put a backup plan without losing all robots in enemy area.
- If it is a danger situation, a robot can send radar signal that enemy will discover, while other robot is spying on area from other location, enemy will send strikes or units to destroy robot that sent signal without knowing that another robot discovered their units positions.
- Communication between robots make them work as one unit when in safe mode, and they can disconnect connections destroy their data when it is in danger mode.
- Battery charge for smaller robot will be 100% when it reaches enemy area, giving it more work time.
- If robot gets stuck or fail moving, or even is hit, other robots can continue from there leaving that robot as station reference for them in that area.

VIII. Conclusion

This paper describes the second stage of a project developed at Philadelphia University-Jordan. A multi-robot system has been designed and tested for real-time sensing and monitoring. The implemented system has three mobile robots; main, rover and eye. Each mobile robot has its own embedded microcontroller and set of sensors. Wireless communications between local site and these mobile robots are achieved by WiFi, ZigBee and Bluetooth techniques. Wireless teleoperation of these mobile robots has been achieved by an efficient interface and a rule-based real-time control algorithm to avoid obstacles.

Real experiments have been achieved under different conditions to demonstrate the system performance and to check its ability and security. Such a reliable system can be used for real-time scanning and monitoring in hazardous and/or unreachable environment where human involvement is limited or dangerous.

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