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Design of a Modular Robotic System for Archaeological Exploration

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Abstract— **This paper presents the design and field tests of an intelligent robotic system for archaeological exploration. The system is designed for recording the internal environment of the underground ancient tombs. The recorded data is used for the preservation of antiques inside the ancient tombs as well as for providing the valuable references to the archaeological research. The whole system is modular and minimized in size that can be adapted for two different archaeological situations during the exploration of the ancient tombs. The robotic system can enter the covered ancient tombs through the digging holes prepared by the regular archaeological exploration. One size of the vertical digging hole is less than 12 centimeter in diameter, and the other is 50 centimeter in diameter. The archaeologists can operate on the remote station to control the robotic system with wired communication. The field test results are finally presented for validation of this archaeological robotic system design.**

Index Terms: Robot, Modular system, Archaeological exploration, Field tests.

I. Introduction

As we know, Chinese civilization is one of the oldest and lots of historical relics are buried in the ancient tombs. There are thousands of ancient burial sites all over the country. The traditional exploration techniques in archaeology are destructive. Many antiques such as ancient wall paintings could not be restored to the original look any more once the ancient tombs are uncovered. Therefore the new techniques need to be developed to facilitate the preservation of the antiques buried underground as well as to explore the internal environment and valuable antiques of these ancient tombs. Hence this paper presents a modular robotic system for more preservative archaeological exploration, and the project is collaborative with the National Museum of China.

In 2002, the robotic exploration of the Great Pyramid of Khufu was reported [1-5]. That was the first robotic system applied in the field of archaeological exploration. That archaeological robot so-called Pyramid Rover is fit for monitoring of the narrow channels. The robot Pyramid Rover was 12cm wide, 30cm long and had a height varied from 11cm to 28cm. During the exploration the robot was connected to a main computer by a fiber-optic cable that carried video signals and controlled all aspects of the robot's movement. However, the robotics system designed in this paper is different from the Pyramid Rover because the field situations and requirements are totally different. The main difference of this design is to obtain the chemical components inside the underground tombs in order to further protect the relics once they are uncovered.

In this paper, the robotic system is designed for exploring the underground ancient tombs. A professional tool called LuoYang Shovel is traditionally used to check whether there is a tomb underground that be able to dig 12cm-diameter vertical holes, Fig.1 (a). The robot is thus required to be minimized in size to fit into and go through any of these holes to collect data in this case. Another situation is to open a 50cm-diameter hole in the entry of the ancient tomb, Fig.1 (b). The robot is also required to enter in this way and move along the corridors of the tombs. Therefore, the whole robotic system design is modular such that the same individual parts can be reassembled to satisfy these two different situations.

The main contribution of this paper is the development of the first practical robotic system for the exploration of the underground ancient tombs in the world and the successful deployment at the real archaeological sites. The system is composed of two main parts, the robot and the remote station. Section II presents the detailed design of the modular robot and the illustration of the remote station. The results of the field tests are presented in Section III to show the successful application of this system. The conclusions and the future work are discussed in Section IV.

(a) (b)

Fig. 1. The two situations of the fields

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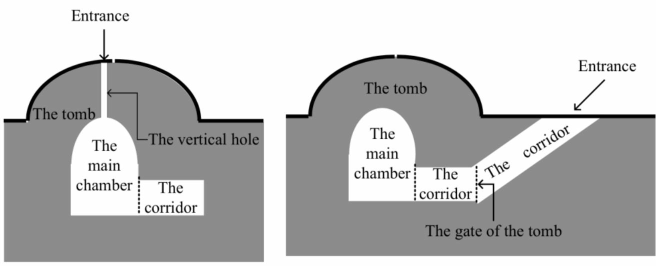


(a) Case 1 (b) Case 2

Fig. 2. The field situations

II. DESIGN OF THE ROBOTIC SYSTEM

A. Overall Requirements

The goal of the intelligent system is to get the images and some environmental parameters of the underground tombs with the minimal destruction. A camera and the sensors for detecting temperature, humidity, oxygen, carbon dioxide, methane and hydrogen sulfide are the basic elements on the robot. The robot should be designed to provide 2-D turnings for the camera for searching around and transmitting the videos and all the sensor data to the remote station in real time. The remote station should be at least 100-meter away from the robot. The communication should be able to work in the situation that the remote station is located on the ground and the robot is underground.

As we mentioned in the last section, there are two types of the exploration requirements asked by the archaeologists. For the first case, the robot has to pass through a vertical hole that dug by a special tool called Luoyang Shovel (12cm diameter). The robot only needs to move up and down for the detection purpose in this case. A protecting cover should be designed to prevent the falling mud from accumulating on the robot. The Fig. 2(a) shows the field situation for Case 1.

For the second case, the diameter of the entry to the corridor of the tomb is about 50cm, Fig. 2(b). The robot should be able to move around inside the underground tomb. The floor of the tomb is most uneven and tilted somewhere, so it is desirable for the mobile robot to be able to move on rugged surfaces during the exploration. Moreover, the center of the gravity should be designed as low as possible that allows the robot to climb at maximum 45° without roll-over. In this case the real-time attitude angles of the mobile robot also need to be collected to help rebuild the internal structure of the tomb. The whole system should be designed to satisfy the above two cases with minimal reassembling because they could happen at the same cluster of the ancient tombs.

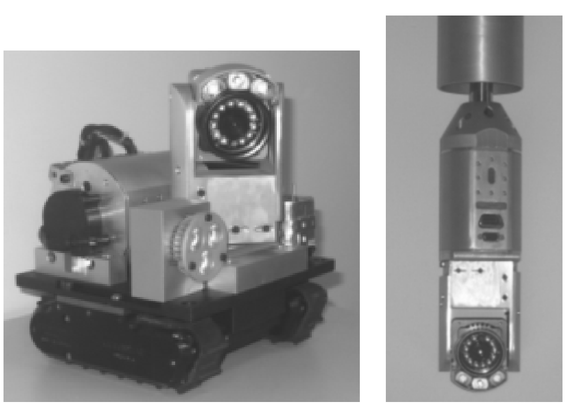


Fig. 3. The photos of the designed robot in two forms

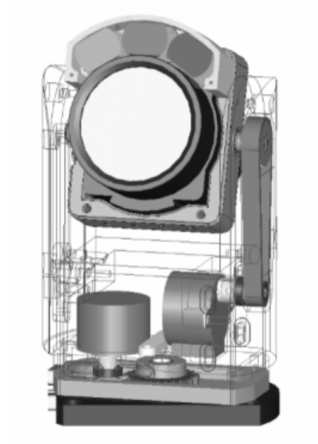


Fig. 4. The structure of the camera module

B. Mechanical Design

A modular robot is designed for this system that can be assembled as a mobile robot with the track base, or as a drum-robot, Fig. 3.

The diameter of the 12cm-diameter digging hole limits the size of all the parts while the requirement of the gravity center for the mobile status limits the heights of every part. To make the reassembling easy for the archaeologists, the robot is designed in four main modules such as the camera module, the sensor-and-control module, the mobile base, the accessories including the protecting cover and the elongated bars.

The camera module includes the far-infrared camera, the pan/tilt mechanism and the headlight as shown in Fig.4. The working environment of the robot is totally dark. Three LED lights are designed as the headlight to help capture colorful images within 20 meters from the position of the camera. The camera with the infrared lights is used in the case that the external headlights are not bright enough.

The pan/tilt mechanism is designed in two degree-of –freedom (DOF) to make the camera have wider vision. Due to the limited size of the digging holes, the tilt angle is designed between 0° to 270° while the horizontal pan angle can be varied from 0°to 330°. Two small stepper motors are used as the actuators for both directions of turning. The requirement of the torque is calculated according to Fig.5.

The diameter of the camera ϕ_C is given as 70mm and the length of the camera l_c is 90mm. The mass of the camera m_C is 500g and the distance between the centre of the gravity and the axis of the rotation L is 3mm. The torque requirement is derived as,

$$N = I\ddot{\theta} + GL, \tag{1}$$

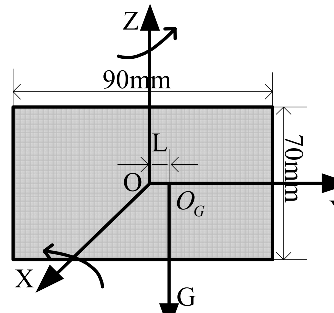


Fig. 5. The torque analysis of the motor

$$I = \frac{1}{4}mr^2 + \frac{1}{12}ml_c^{\ 2}, \tag{2}$$

where N is the rotational torque. I is the rotational inertia. G is the graviton. r is the radius of the camera. Set $\ddot{\theta} = \pi / 2(rad / s^2)$ as the maximum acceleration for the purpose of observation, we get 15.2mNm for the rotation around X-axis and 0.60mNm for the rotation around Z-axis. Thus two step motors are chosen here with the maximum torque 45mNm as Fig.4. This whole camera module is of 90mm in diameter and 130mm long.

The sensor-and-control module includes the main control board of the robot and all the sensors except the Inertial Measurement Unit (IMU), Fig.6. The four gas sensors and the control board are arranged carefully to keep every piece inside the 96mm-diameter shell as well as to make all the sensor probes in the open air. To avoid the probes from the accumulating falling mud, thin breathable covers made of fibers are used to protect the probes from the dust. The diameter of this module is also 90mm as the camera module, and the length is 138mm.

The two modules introduced above can be assembled in a drum form or the mobile status as Fig. 3. The mobile base includes two small tracks, the base and the IMU. IMU is only used to measure the tilt and orientation angles for the mobile robot to prevent the roll-over and help map the internal structure of the tombs. The tracks are controlled independently from other modules. The accessories including the protecting cover and elongated bars are designed only for the drum robot. The protecting cover is of 96mm x 300mm to help the robot pass the vertical holes without impactions. Each elongated bar is 150cm long and the number of the bars depends on the depth of the digging holes that is unknown before the exploration.

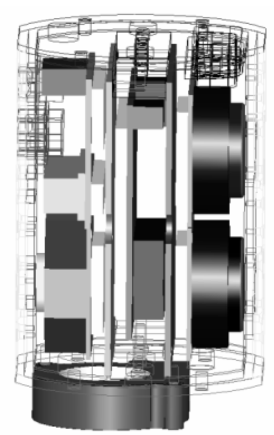


Fig. 6. The structure of the sensor-and-control module

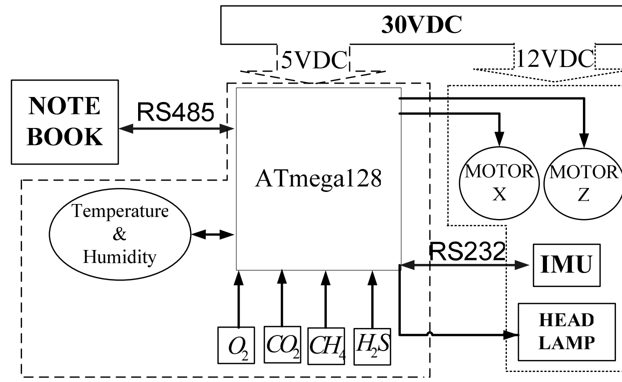


Fig. 7. The block diagram of the circuit board

The mechanical design above makes the robot fit the overall size and functional requirements. The size of the mobile robot is 220mm×200mm×230mm while the diameter of the drum-robot is 96mm.

C. Board Design

The board design is shown in Fig. 7 to illustrate how the different functions are achieved. The main control board is composed of five units: the micro control unit (MCU), the power unit, the multichannel data acquisition unit, the pan/tilt mechanism, motion and luminosity control unit, and the communication unit. Considering the interfaces to the gas sensors, the servos and the communication, ATmega128 is chosen to be the microcontroller of this robot [6-8].

A power unit is used to supply the power for all the devices on the robot [9]. The 30V DC input is provided by the remote station through the cable because of the limited size of the robot and the power consumption of all components. The input voltage is then regulated to 12V DC and 5V DC by LM2596.

Six sensors are used here for monitoring the internal environment parameters such as CO_2, O_2, H_2S, CH_4, the temperature and the humidity. Table 1 shows the specifications of these sensors used in this system where the

Table 1. Major parameters of the sensors.

Name	Accuracy	Range	Output	Size(mm)
CO_2 sensor	±40ppm+3 %read (25°)	0~2000ppm	0~4VDC	57.4 x 51.2 x 18.6
O_2 sensor	±0.1%vol	0~25%vol	4~20mA	45.2 x 45.7 x 30.3
H_2S sensor	±3ppm	0~200ppm	4~20mA	45.2 x 44.9 x 31.6
CH_4 sensor	±0.2%LEL	0~100%LE L	4~20mA	45.1 x 45.2 x 31.9
SHT1 1	±0.5°, ±4.5%RH	-20~80°, 0~100%RH	dual-wire serial interface	$\phi 11.2 \times 4.6$

temperature and humidity detections are integrated in one chip and the outputs of the above gas sensors are all analogues.

The two stepper motors are designed to be driven with L297 and controlled by the ATmega128 while the pulse width modulation (PWM) signals are used for the luminosity control. The reflection spots of the lights are expected to be eliminated through the luminosity control. RS485 is used for the communication between the main board to the remote station, and RS232 is used to communicate the main board to the IMU.

D. Remote Station

In order to make this system portable, a notebook computer is chosen as the remote station of this system. A operator interface software is designed and running in the notebook[10]. The operator interface diagram is shown inside the dotting box of Fig. 8 that includes the video, the field information, the environmental parameters, the control of the pan/tilt mechanism and the light control.

The images and videos captured by the camera on the robot can be previewed and recorded in the interface [11]. The archaeologists can justify if the explored tomb is valuable in archaeology and can roughly tell the period of the ancient tomb according to these videos. The field information part is available to type into the background of the current field explored by the robotic system. The environmental parameter part displays the data of all the sensors both in numbers and the histograms. The data are refreshed every second. All the data of the sensors are auto-saved.

The posture of the camera can be controlled by adjusting the turning angles of two motors on the interface. The target angle can be typed onto or be adjusted by the keyboard. The lighting control can also be achieved by a virtual slider on the interface.

III. Field Tests

The field tests were taken in three ancient tombs near the city of Xi'an in China. This city is the focus of many archaeologists because it was the capital of the country for thousand years. The first field test is located at the ZhangHuai Prince's Tomb that was built about 1,300 years ago and has

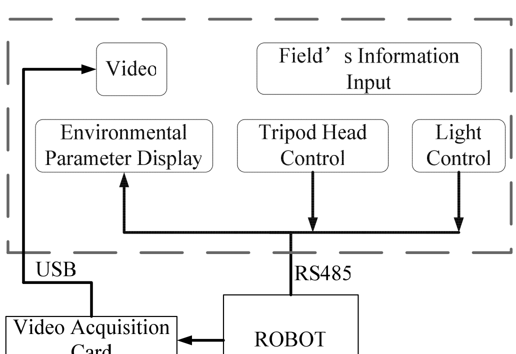


Fig. 8. The block diagram of the remote station

been explored by several archaeologists. The robot was expected to enter this tomb through its long and tilted corridor. Thus the mobile robot was used in this situation.

Fig. 9 is one of the images captured in the tomb by the robotic system, where the internal structure of the corridor is clearly shown. Especially the gate of the room in the tomb is indicted in Fig. 9 because this is one of the most valuable points the archeologists care about. The Fig. 10 shows the obvious changes of the temperature and the carbon dioxide during the movement of the robot in this experiment. Since the data of the other gas-sensors are similar to the data of the outside and only changing in a small range as the tomb has been open, they are not present in this paper. It is clearly seen from Fig. 10 (a) that during the period of A, the temperature fell sharply when the mobile robot was running into the corridor and increased when the robot moved out of the tomb. The temperature is relative stable in the period of B when the robot is moving inside the main chamber. Fig. 10 (b) shows that the content of carbon dioxide kept increasing as the robot moved to the deeper inside and decreased as the robot is closer to the ground.

The tilt and heading angles from the IMU are shown in Fig.11. It is concluded the slope angle of the corridor is about 15° because the pitch angle is around -15° at first and 15° at last in Fig. 11 (a). The rest of the tomb keeps horizontal since

Fig. 9. An image captured in the ZhangHuai Prince's Tomb

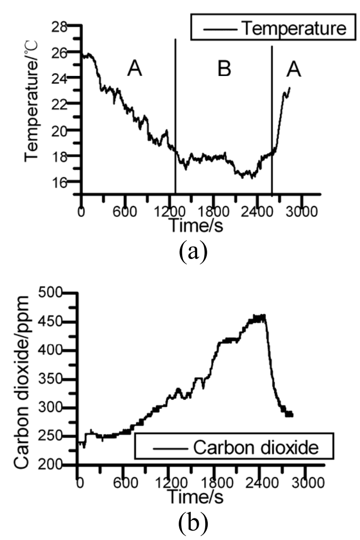
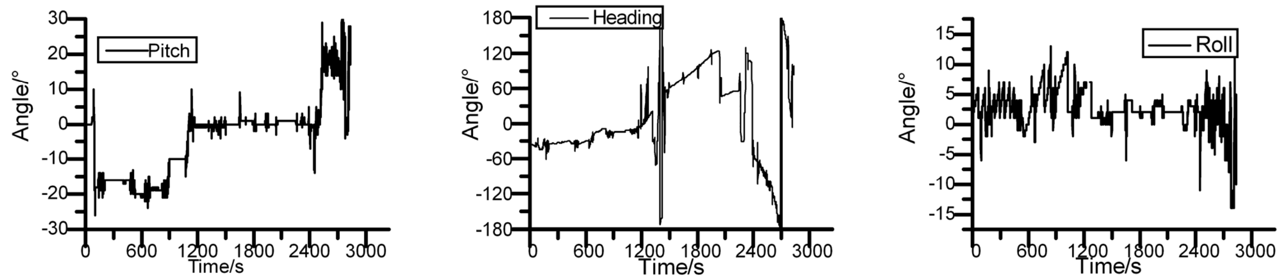


Fig. 10. The data collected in the ZhangHuai Prince's Tomb



(a) (b) (c)

Fig. 11. The IMU data collected in the ZhangHuai Prince’s Tomb

the pitch angle stays around 0° for the rest. The data in Fig.11 (b) shows the heading angle of the robot. It is predicted that the orientation of the whole corridor is facing to the North that verifies the expectation of the archaeologist. The Fig. 11(c) shows that the robot is stable in the range of -15° to 13°of the roll angles and the robot was no danger for roll-over in this experiment. All these data obtained in Fig.11 together with the odometry data of the mobile base can be used to reconstruct the terrain and orientation of the unknown tombs which is the near future work of this paper.

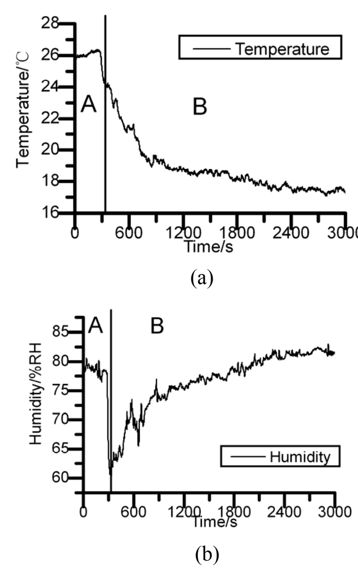
The second field test was done in the Pangliu Tomb that had not been explored by any archaeologist before. Fig.12 shows a piece of wall painting captured by the robot about the daily life of the ancient people. These captured paintings made the accompanying archaeologists very excited in the field because they are invaluable in the view of archaeology. In Fig.13, the period of A in both Fig. 13 (a) and (b) shows the data when the robot was still on the ground and not sent to the entry of the tomb yet. The period of B shows the data when the robot was sent to the tomb. From Fig. 13 (a) we can see that the temperature in the tomb was about 18° while the Fig. 13 (b) shows the tomb is with high content of humidity because this tomb was blocked for years.

The last field test was carried out in the tomb just discovered in a building site called Yanlian. This tomb was also the first time to be explored where only 12cm-diameter vertical digging holes are available. So the drum robot is chosen to be used here. The depth of these holes is 70cm. The robot was pushed through one hole in the way mentioned in Section II. Fig.14 shows the data of the temperature, the humidity and the oxygen in this test. As shown in Fig. 14 (a)-(c) the temperature and the content of oxygen fell and the humidity grew as the robot entered the tomb.

IV. Conclusions

This paper proposes the development of a modular robotic system for archaeological exploration of the underground ancient tombs in China. The robot has the modular and portable structure such that it can be simply assembled as a mobile robot or a drum-robot in the fields. The drum-robot can do the exploration through the vertical holes within 12cm diameter while the mobile robot can move in and out of some ancient tombs through the entry with 50cm diameter. This robotic system can help the archaeologists preserve the antiques more efficiently once the visual and parameter information is obtained inside the tombs. Several field tests were carried out and lots of valuable information is obtained in the fields to show the validation of the whole design. The future work will focus on the reconstruction of the internal structure of the unexplored tombs. Another future work will be the development of the distance measurement algorithm based on the vision of the robot such that the positions of the antiques and the volume size of the covered tomb can be

Fig. 12. An image captured in the Pangliu Tomb



(a)

(b)

Fig. 13. The data collected in the Pangliu Tomb

estimated without the additional hardware.

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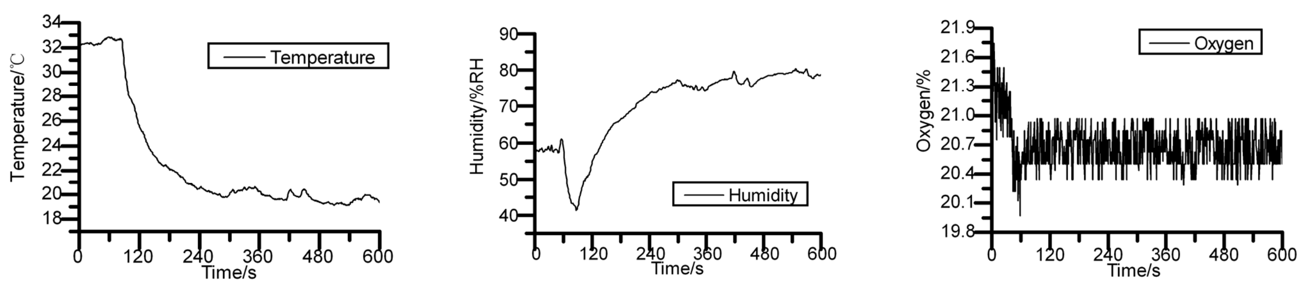

(a) (b) (c)

Fig. 14. The data collected in the Yanlian Tomb