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Exploration Robots for Harsh Environments and Safety

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Abstract: In this paper the development and demonstration of various robotic systems for safety applications and harsh environments are presented. These robotic systems assist human to monitor and explore various types of spaces and measure physical parameters of these spaces. Each individual robot can be equipped with 3D ceramic-packaged multi-purpose sensors/actuators, smart navigation systems, and reconfigurable high-speed wireless communication networking. The targeted applications are real-time monitoring/rescuing in various kinds of harmful environments e.g. deep mines, pipe and tube systems, dramatically reducing risk of life and economic damage.

Keywords: Robotic exploration, harsh environments, safety and security, co-operative robot.

1. INTRODUCTION

This paper presents the design and demonstration of three novel compact robotic systems, which can be integrated with 3D ceramic-packaged, multi-purpose micro-sensors and high-speed ad-hoc wireless communication systems. The targeted application is for real-time monitoring and exploring folded spaces under possible harmful conditions e.g. chemical leakages, pressure level, temperature and gas concentration in harsh environments as well as for security and archaeological applications; decreasing the risk of life and economic damage.

2. DJEDI ROBOT: A PYRAMID EXPLORATION ROVER

The Great Pyramid of Giza is the last remaining wonder of the ancient world. The pyramid contains three chambers, including the king's and queen's chamber. Airshafts have been discovered in both chambers, however the queen's shaft has no obvious purpose nor does it breach the outer face of the pyramid structure, unlike the king's chamber. Exploration of the northern and southern airshafts to answer the mysteries of its purpose and construction required the use of specialised mobile robotic tools, such as the Djedi Pyramid Explorer Robot (Figure 1) which in May 2010 performed a video survey successfully, by climbing the full length of the southern air shaft.

Produced from soft limestone of varying surface roughness, the air shafts are approximately 210 mm x 210 mm and spans through different configurations for the northern and southern shaft. The southern shaft begins running horizontally for approximately 2 m before rising at an incline of 40° from the horizontal, spanning approximately a further 62 m in length from the chamber entrance. Additional obstacles exist within the shafts such as a lateral step at about 30 m or the 40 mm vertical step at 59 m and at the top of the shaft are the main objectives, which consists of two limestone blocking stones of 60 mm approximate thickness for the first stone and an unknown thickness for the second; each spaced approximately 200 mm apart.

The specifications for the Djedi robot required the robot to climb the air shafts with minimal or no damage to the pyramid walls, yet retain the capacity to obtain sufficient tractive force to safely navigate the steep inclines, smooth surfaces and counter the resultant forces from the on-board drill. Building upon the testing of three prototypes using different variations of an inch worm mechanism, the latest design of the Djedi robot had two independently driven pinion carriages on the same rack, with one carriage for driving the robot through the shafts and the other for driving the on-board drill.

To brace against the shaft walls and provide the necessary traction to climb and provide stability during drilling, custom linear actuators were created with a silicon rubber brace pad mounted at the end. The points of contact between the brace actuators and the wall from each inchworm step during the shaft ascent does not move (Figure 2), also the applied force is perpendicular to the wall surface. These features combined with the soft silicon pads resulted in a large reduction to the risk of damaging the air shaft walls. The four wheels were left unpowered and served only to allow Djedi to climb the vertical step and to prevent dragging on the shaft floor.

The use of 3D printing technology was used almost exclusively for the manufacture of the carriages. Enabling rapid productions of chassis parts with complex features, which allowed for increasingly compact carriages to be reduced in weight and size and therefore increase step and drill length of the robot.

Embedded into the carriage chassis are eleven composite cameras with an additional snake arm camera attachment to replace the drill. Each camera is strategically positioned to provide a full field of view for all sides of the air shafts and vital components of the Djedi robot for visual monitoring. The findings from the climb revealed red ochre markings or hieratic characters previously unseen for thousands of years (Richardson, R 2013).

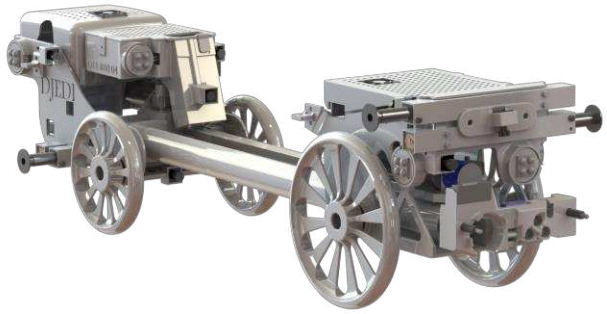


Fig. 1. Djedi Southern Shaft Rover.

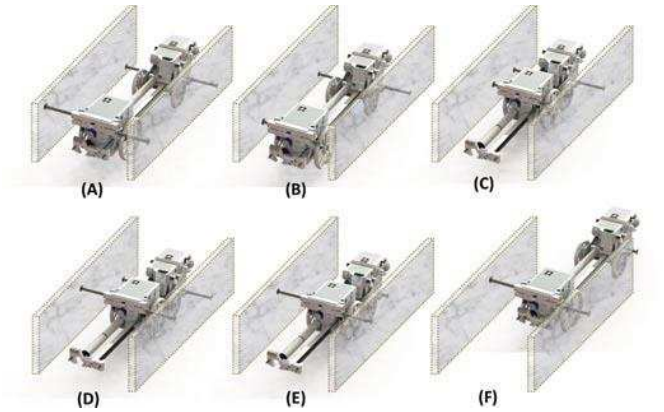


Fig. 2. Rendered images of the Djedi rover during different stages of the inchworm locomotion.

3. MINEBOT: A DUAL-TRACK RECONFIGURABLE ROBOT

The subterranean environments such as mines and tunnels are remote, inaccessible, and dangerous for human entry. Inherent dangers in environments motivate the use of robotic technology for addressing such challenges (Morris, A 2006). In order to inspect subterranean environment, it is common to drill small boreholes from the surface into what is expected to be the exploration area. The idea is to insert a small robot through the borehole, lower the robot into the subterranean space, and explore the area. However, there are still many challenges in terms of limited diameter of borehole and lack of illumination posed by boreholes exploration.

In response to these challenges, a dual-tracked reconfigurable robot with on-board camera and Cree LED light, named Minebot, was developed at the University of Leeds. The Minebot is an imaging mobile system that can be lowered down through narrow passages, such as boreholes, for subterranean exploration. It can establish a remote, subterranean presence without unnecessary risk to humans. The Minebot is capable of reconfiguring to move inside the tunnel, using dual-tracked mobility system to move in parallel (as shown in Figure 3).

When the situation requires the robot to be inserted into boreholes or navigate obstacles, it can transform into a snake-like configuration (as shown in Figure 4). The Minebot is designed to be deployable and retrievable through a 9.1m long, 41 mm diameter borehole into tunnels and to operate at long ranges in tunnels of approximately 200m long on a slight incline over rough terrain.

Table 1. Minebot measurements

Weight	2.7 kg
Fully deployed size	33 x 335 x 455 mm
Snake-like size	33 x 1199.5 x 31 mm
Maximum speed	11.4 mm/s

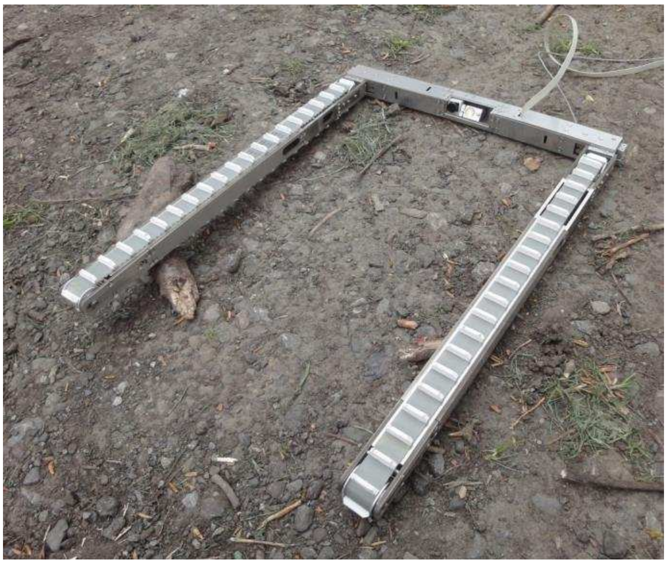


Fig. 3. Fully deployed configuration of the Minebot.

Fig. 4. Snake-like configuration of the Minebot.

Provided with some approximate environmental specifications, the locomotion and deployment systems of the Minebot were developed. The diameter of the borehole was a fixed variable supplied from a portable borehole drilling device used to gain entry into the mine. Considering the small diameter of the borehole and its length, a limit of 35mm diameter for the entire Minebot during the deployment phase was agreed upon. This allowed for a value of torque to be calculated to compensate for the robots mass on an incline and frictional drag forces from the tether. Without the ability to replicate the Djedi robots ability to brace on two sections of wall, the Minebot replies on the weight to produce the required traction to travel the long distances.

Extraction of the Minebot was also considered as essential for the mission brief. This resulted in the need for a high torque reversible joint capable of changing between the fully deployed state and the snake-like configuration with no assistance.

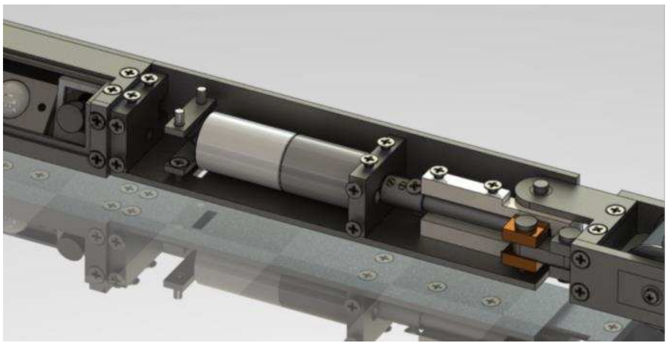


Fig. 5. Gearbox housing within track section.

Fig. 6. High torque with slender profile joint.

4. LETTERBOT: A FOLDED BUILDING EXPLORATION ROBOT

The Police and other authorities often have to search buildings without prior knowledge of what hazards may be present. Large robots currently in use require a door or window to be broken before it can enter the building. LetterBot was designed to enable quick deployment into any building without requiring tools or damage.

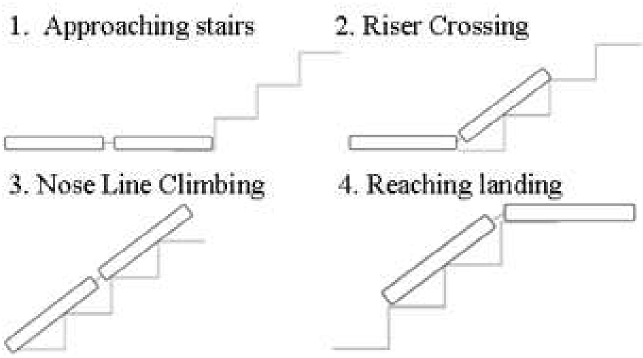
In the majority of locked properties the only damage free way to insert a robot is through the letterbox. The standard BS EN 13724:2002 (BSI 2002) gives the minimum dimensions of the slot to be 230x30mm. This gives a very tight height constraint requiring careful actuator selection. For the robot to provide information beyond that of a pole camera it is important that it can overcome stairs as reported by Nguyen et al. (Nguyen 2000).

To ensure the robot is capable of ascending all regular stairs, UK building regulations (HM Government 2013) were reviewed. Giving the requirement that the robot length is ≥443mm to span two steps, it will have to overcome step heights of over 7 times its height, and produce enough torque to climb up stairs angled up to 42°.

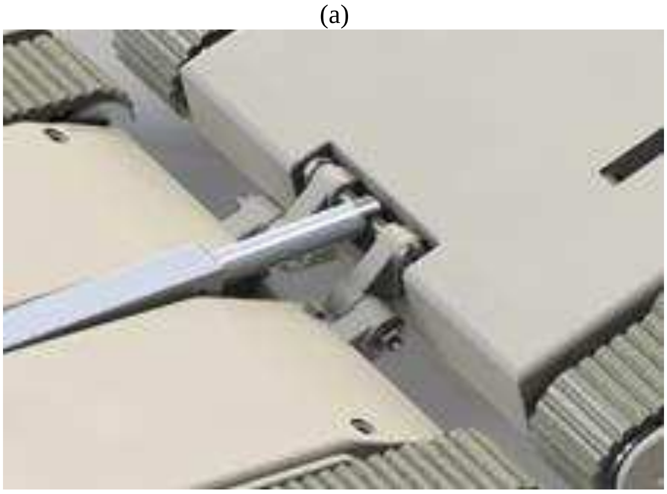
A variety of robotic methods have been developed for stair climbing, such as a rack and pinion arm to lift itself up each step (Wende, G 2004), a tri-wheeled design that interlocks with the stairs (Hirose, S 2001), a multilink mechanism with six driven wheels (Michaud, S 2002) or various humanoid designs. While these have all been shown to climb stairs they all rely on the robot being larger than an individual step.

A tracked design with two separate sections and an actuated link joint was developed. Liu et al. (2005) analysed fundamental kinematics and dynamics for a tracked robot to climb stairs. The process is split into Riser Climbing, Riser Crossing, and Nose Line Climbing. A tall angled front is often used to aid riser climbing (Tao, Ou and Feng et al. 2012) but cannot be used in this case due to the height restriction.

The two sections allow the robot to ascend the stairs without the Riser Climbing stage (Figure 5).



(a)



(b)

Fig. 5: (a) Sequence for a two sectioned robot to climb stairs. (b) Version 1 mechanism.

Two versions of LetterBot have now been created. The mechanism used in the first was designed to be simple and robust. A very short lever arm and a 200N linear actuator make the front section lift around a one degree of freedom revolute joint as shown in Figure 5. The second version uses an adaptation of a "little-known" gear slider mechanism, Figure 6, (Chironis et al. 1996). To aid weight optimisation and complex geometries 3D printing was used for the first design.

Version 2 used a steel base plate as a thin rigid base, with aluminium modules building up the rest of the chassis.

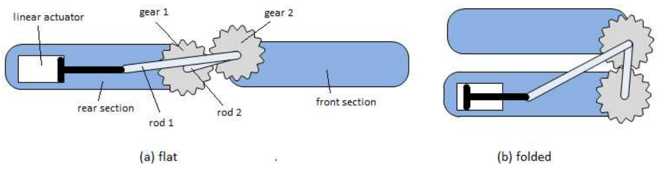


Fig. 6. Modified gear slider mechanism.

Continuous tracks were chosen as they can be used with a smaller diameter driving wheel than sectioned tracks. The tracks were custom designed to enable the robot to grip the noses of steps while climbing and reduce the friction when turning. When climbing the angle reduces the friction force, the contact area is also much smaller. Therefore welded on profiles were designed to mesh with the steps like teeth of a gear. They also help keep the robot perpendicular to the stairs. Using analysis by Rastan et al. (2011) the pitch was found to be optimal at 20mm. As the robot uses a differential drive system to steer, large sideways frictional forces are generated during turning which can remove the tracks. The angled profiles reduce this drag as does hinging the robot in the middle to shorten the track length in contact.

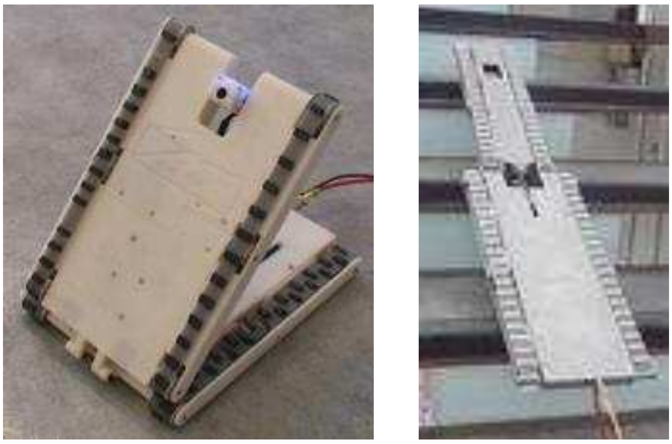


Fig. 7. Left, LetterBot v1 folded up and looking around. Right, v2 climbing stairs.

5. CLIMBING IDEAL INCLINES

For a compact exploration robot to climb an incline of angle θ_a, a robot of mass M_r must generate sufficient pulling force F_p to overcome gravitational force F_g, frictional drag forces F_d, and the forces required to drag the tether F_c. The gravitational force can be resolved into a two components of force, one parallel to the ground and the other perpendicular to the ground.

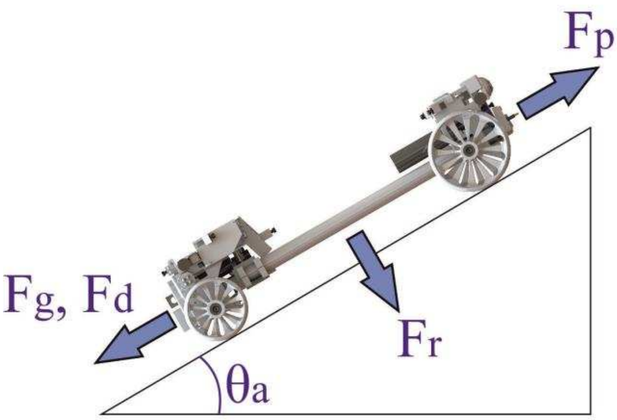


Fig. 8. Free body diagram of robot on an incline.

These equations are valid for the free body diagram:

$$F_r = M_r.g.\sin(\theta_a), \quad (1)$$

$$F_g = M_r.g.\cos(\theta_a). \quad (2)$$

The pulling force F_p exerted by the robot is limited by the frictional coefficient between the robot and the floor surface (μ_n) and the normal force (F_r),

$$F_p \leq F_r.\mu_n. \quad (3)$$

In order to overcome the frictional drag from the tether (F_c), the sum of the forces due to the cable need to be considered. If the friction coefficient between the cable and floor is (μ_c), the cable weight is C_m and x_c is the length of the tether in meters. The force required to overcome the cable frictional drag is then calculated as:

$$F_c = C_m.x_c.g.\sin(\theta_a) + \mu_c.C_m.x_c.g.\cos(\theta_a). \quad (4)$$

Therefore, in order to climb the incline, the required pulling force is:

$$F_p = M_r.g.\sin(\theta_a) + C_m.x_c.g.[\sin(\theta_a) + \mu_c.\cos(\theta_a)]. \quad (5)$$

The most straightforward method to increase the robots capability to climb steep inclines is to increase the friction coefficient between the robot and floor (μ_n) and decrease the friction coefficient between tether and floor (μ_c).

In the case of the Djedi robot, the tether was custom made with a thin, low friction, sheath. As a result of the inch-worm mechanism the weight of the robot was designed for minimal weight (M_r) as the four linear actuators can exert the required normal force (F_r) to overcome the opposing forces. On the other hand, the Minebot and Letterbot with the tracked configurations will rely on the mass of the robot to provide the necessary force for sufficient traction.

6. CONCLUSIONS

The Djedi robot operated as intended and reached the top of the southern shaft. The findings from the video survey provided valuable evidence towards the purpose and construction of the pyramid. The locomotion system was successful in protecting the pyramid from damage, as no surface marks in the shaft walls were observed after repeated climbs.

The use of rapid prototyped bodywork proved to have sufficient strength to endure the forces experienced during manoeuvring in the shaft. A noticeable drawback to the inch worm locomotion was the robots low climbing speed. Taking up to four hours to ascend the shafts, this time was acceptable when just one or two ascents are planned, but if future surveys require the use of multiple tools, then the ascent time would be a serious issue.

Deployment of the Minebot through a 3m long tube of 40mm diameter has been demonstrated successfully. Further testing in lab spaces has shown the Minebot to be capable of changing its deployments states with no assistance and also able to drive effortlessly in the dual track configuration on a wooden floor.

However to achieve the operational distance of 200m to fully survey the proposed mine tunnel, the Minebot will require a large increase in weight to 6kg in order to supply the necessary traction. The current weight of 2.7kg allows the Minebot to survey up to a theoretical distance of 92m. A consequence of increasing the weight to 6kg is the robots un-deployed length must also be increased which will affect either the deployed length or width. This could possibly affect the robots ability to navigate and this trade-off will require further study.

LetterBot has successfully been deployed through a letter box and has climbed sets of stairs while returning HD video. The mechanism is robust, simple to maintain and has proven reliable over many test deployments. Version 2's mechanism (Figure 6) gives a greater mechanical advantage and allows the front section to be both longer and heavier, so larger steps can be negotiated. However due to its added complexity there is a trade off in reliability.

7. FUTURE WORK

Whilst the Minebot has been successfully tested in lab environments, future work will involve field testing in more realistic real world environments to find its capabilities to overcome rough terrain with debris and also its effective range in the mine environment. The inclusion of debris could allow for a larger coefficient of friction between robot and floor which would result in a greater range without the increase in robot mass however the low ground clearance may play a significant role in limiting range.

Building upon the experiences and techniques used in the Minebot for condensing the electronics and mechanisms into smaller spaces, these techniques can be applied to further improve the next iteration of LetterBot. At which point the LetterBot will be improved for easier deployments through higher and/or vertically orientated letterboxes with the capacity for additional sensor packages.

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