Magnetic–type Climbing Wheeled Mobile Robot for Engineering Education

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Abstract
The tendency of developing wheeled mobile robots in different applications is growing every day. During the past decades, the need for robots capable for climbing vertical wall has been increased. As a result of that, this paper presents a light and low cost wall climbing robot WCR of wheeled locomotion and adopted neodymium magnets to provide adhesion force. This climbing system is intended to be used for educational and research purposes. The mechanical and electrical constructions are presented. The proposed design has the ability to achieve ground-wall transitioning. In order to provide sufficient information about robot mass properties, novel mechanisms to determine the coordinates of the center of mass COM and moment of inertia MOI of the proposed climbing robot have been introduced. In addition, the vision system was suggested to provide feedback signal of robot pose (position and orienting). Finally, to evaluate the performance of the robot design, a prototype was built and tested in the laboratory environment.

Keywords: Wall climbing robot, educational purpose, magnetic Adhesion mechanism, center of mass, moment of inertia

I. Introduction
Along many years, there have been tireless efforts to involve robotics at the different educational stages. Robotics is widely used in teaching engineering concepts such: programming, math, physics, design and even art and music to students at undergraduate and postgraduate level. Recently, educational robots have penetrated the world markets and these robots have gone along fundamental changes. Using platforms and kits in research and edutainment are constantly rising, and keep up with that evolution is a growing number of robotics courses introduced at universities, also dissertation projects in this field[1][2].

Educational platforms are usually not expensive, exist in great numbers, and they are broadly used in schools and by amateurs. Fig. (1-a) shows the most popular robots which currently in use. Recent, in addition to ground educational robotics, new aerial and underwater robots are appeared, as shown in Fig. (1-b,c). Introducing these robots in the market in a sufficiently low cost manner helps for large range educational use[3].
It can be realized that there are many educational robots in different areas, but in climbing field, unfortunately they are virtually non-existent. Where the most of the wall climbing robots WCRs research available in literature are specialized in certain applications such: inspection, testing, civil construction, cleaning, Transporting and Security, all of them are away from educational field[4]. Even the markets are till now empty from WCRs, this a strong signal indicates that WCRs have not been widely studied to date. What available in markets now (until the date of preparing this paper) are just for entertainment purposes for child, and a type of modified drone to hover close to wall, shown in Fig. (2).

The first attempt in this area was by Berns et.al[5], they presented a practical course in building a climbing robot. Their work was also include introducing of a prototype design of wall climbing robot proposed by the students at the end of the course, as shown in Fig. (3). As this course was geared towards computer science master students, it can be realized from robot construction that attention has been devoted to the software more than the hardware aspects.

The design of the entire robot system from scratch is very difficult because of the limited available time during university term or research stage of master and PhD students. Also, this operation is an interdisciplinary topic and requires multi-engineering skills like mechanical, electrical, and computer science engineering as well as the development of control structure[2]. Therefore, it is aspired through this article to introduce an educational robot helps to provide enough time for students and researchers. We called this robot UOTWCR, it is the first WCR developed in our labs.

This article is constructed as follows. Section II will introduce the overall structure of the climbing robot and discuss in detail the magnetic adhesion mechanism. While, section III shows the suggested practical methods to determine the robot center of mass (COM) and moment of inertia (MOI), also a source of feedback signal is proposed. To verify robot performance, some experimental tests are achieved in Section IV. Finally, in Section V, the main conclusions and future work are outlined.

II. UOTWCR Design

A number of necessary requirements must bearing in mind in building a wall-climbing robot. To meet the need of low power consumption, the robot should be light-weight as possible. Furthermore, it must have ability to generate sufficient attraction force to keep contact with wall without slipping. In addition to the requirements of the fact that the robot has the ability to climb vertical surfaces, the educational field imposes to be safe, inexpensive, has a flexible architecture and providing sufficient information about its design. The remaining part of this section will discuss in detail the design of the proposed robotic system.

A. Adhesive mechanism

Based on a comprehensive study to the main characteristics of the common adhesive principles, magnetic adhesion mechanism was the most appropriate for educational application. Although, the use of this mechanism is restricted to ferromagnetic surfaces because of the nature of magnets, but it is able to provide high adhesion forces on a very small space. Also, it is noiseless, safer, less complexity and more reliable than other principles such propellers type, spine and dry adhesion [6]. The exclusion of electromagnets and adoption the permanent magnets makes the robot more meeting the requirements, since the adhesive mechanism does not need to energize externally, the system will not loss contact with the wall because of power failure.

B. Locomotion principle

According to characteristics of the robot working area, as well as the general requirements which are stated previously, it can determine the design features of the robot. Since the robot is intended for educational purpose, it can assume that the vertical surface is a ferromagnetic flat plate of sufficient thickness in laboratory environment. So, for this even terrain, wheels looks to be the most applicable.
The main advantage of wheeled system is the continuous and fast movement and the simpler control elements and mechanical structure [7].

C. Kinematic of UOTWCR

Once the adhesion and locomotion principles have been chosen, it kinematic configuration and the magnetic adhesion mechanism are necessary to be designed. As is well-known, there are many type of drive of mobile robot. The simplicity and the nature of target surface for climbing are the main selection criteria to choose the more convenient type. First of all, to get high maneuverability, all mechanisms which can’t provide zero-radius turning will neglect. In spite of, Synchronous-Drive can achieve omnidirectional motion but it has complicated mechanical structure[8]. Therefore, differential–drive approach based on two active wheels and a passive ball caster wheel in the rear was adopted. Although the Skid-steer maneuverability is relatively close to the differential drive system, it was discarded to their increased weight and power consumption, also due to wheels (or tracks) slippage related for steering.

In the magnetic climbing robots, the adhesion and locomotion elements are decoupled in many cases [9] and combined in the other [10]. Also there are robots which adopted the both principles[11]. Each of these designs has its pros and cons. The combining between the adhesion unit (magnets) and the locomotion system (wheels) has mainly two shortcomings[12]:

1. The generated adhesion force will be obtained from only a limited number of magnets which are close enough to the surface.
2. As the magnets are fixed around the wheel perimeter, therefore the amount of the adhesion force is highly influenced by the wheel dimensions. This means, increasing the attraction force (increase the number or size of magnets) requires bigger wheel.

On the other hand, the separation between the magnets and the wheel (installing the magnets on the body) has the following drawbacks:

1. The system design will pass through the loop shown in Fig. (4), which often at the end, producing a heavy robot with several kilos.
2. Decreasing the deriving parts (motors, adapters, bearings) life as the adhesive force will pass through these parts to the surface.
3. Increasing power consumption by raising the load applied on motors.
4. Making the robot more sensitive to magnetization of the surface, in other words, the magnetic force between the robot and surface should not exceed the design safety limit, to achieve that, electromagnets are used.
5. Needing to keep constant close distance between the robot and surface.
6. Making the transition mechanism more complicated than magnetic wheel.
7. Needing extra area on robot platform to distribute the magnets and preventing the effect of the magnetic field on electronic circuit.

According to the previous discussion, magnetic wheels look to be closer to meet the requirements and to be the optimal solution. The magnetic wheels allow exploiting all platform area to carry the robot component. This approach can reduce robot height and present more compact robot. Also, the fact that the body frees from magnets helps to get rigid system without using heavy material. Therefore, the whole structure can be made from light material such transparent plexiglass sheet of 4mm thickness. Plexiglass has outstanding stiffness, strength, lightweight relatively and high impact resistance. Acrylic sheet is easy to bonds well with solvents and adhesives. In addition, it is cheap and available in local markets.

The robot components were distributed in way to reduce the effect of wheel size as possible, where the motors are installed on the sheet upper surface to reduce the robot height. While the battery on the lower face to keep the center of mass COM at the closest point to the wall.
To cover the electronic parts and wires, a simple frame with a sheet of paper was implemented. To make it easy to reach the internal component, the roof was installed to platform depending on the fitness or by using little hot silicon glue if necessary.

It is also important to note that the maximum number of magnets that can be utilized on the robot with the current design is limited by wheel diameter, and vice-versa. To reduces the weight of wheels as possible and to keep smooth and continuous motion, a 29 cylindrical neodymium magnets of d=10mm and L= 3 mm along the perimeter the wheel of d=100 mm are used. Fig. (5) shows the magnetic distribution on wheel. A rubber tire is used in order to increase the friction and to protect the surface from scratching due to direct contact with the magnets.

Although the structure based on differential drive has advantage in simplicity and the ability to achieve zero radius turning, it is suffering from wheel reaction torque. This torque generated as a result to rotate drive wheel actuators and it may result in flipping the whole robot body. This effect is worse in wall climbing robots more than ground robots, where the climbing robot can lose the adhesion with surface and fall. To eliminate the effect of this issue, it is usually to attach the drive wheels in the front of the robot and the passive one in the rear, or in other word, avoiding the rear drive state. But that solution is at the expense of the robot maneuverability.

In addition to the foregoing, the robot will be under the influence of a moment due to gravity force centered on the contact point when the robot ascends or descends on the vertical wall[13]. This moment can be supported by the caster wheel when the robot climbing the wall, as shown in Fig. (6-a). While, if the robot moves down, the moment will work to detach the rear wheels from the wall surface which leading to fall down the robot from the wall, as shown in Fig. (6-b). To overcome these problems, a magnetic attraction force can be applied to balance the robot and prevent rotating. Two cylindrical magnets of d= 15mm and L= 5mm were attached to the robot body. These magnets are preferred to be installed close to the caster wheel to reduce the deformation in the robot structure and to increase the value of the generated moment which guaranteed that the caster wheel will not separate from the wall.

It is worth mentioning that the robot whole weight is 520 g, and the weight of the utilized magnets is about 100g, which occupied less than 20% of the system overall weight. Fig. (7) shows a CAD design to illustrate the main parts location and the dimensions.

**D. Transition mechanism**

One of the important features in WCR is to be able to transit between perpendicular planes. This ability gives the robot more flexibility to achieve tasks. The proposed design with adopt magmatic wheels will support a smooth transition especially if the front wheels extend in front of the robot. But the rear ball caster wheel has limitation though the operation, where in the last stage of transition, the caster wheel body rubs against the ground, as shown in the Fig. (8). To overcome this problem, two light wheels have been added to prevent the undesirable contact, as shown in the Fig. (9). Also these wheels provide more stability to transition (two supporting points). These addition constructions can be easily installed and removed from robot body.

**E. Electronic system**

Two 6V continuous servo motor type SM-s4315r are used as driving motor. The major advantages of the servo motors are space saving design and low weight considering their performance. The robot is energized by two cells Li-ion onboard battery. The servos are power supplied through voltage regulator. UOTWCR is equipped with ATmega328P microcontroller which is quite familiar with many types of sensors commonly available in market. The robot have two communication facilities: six channels radio receiver is integrated to the system in order to manually control the robot, and Hc-05 Bluetooth module to easy connection with PC. The electronics system diagram of is shown in Fig. (10).

**F. Feedback signal**
It is clearly the need of accurate control of mobile robot is very necessary. Therefore, the close loop controller based on sensor is dispensable. Because of the nonholonomic constraints of the wheeled mobile robot and the hardware configuration of standard encoder (such, the optical encoder which fixed on the motors), the cartesian position of WMR can’t be obtained accurately [14].

To overcome the problem position measurement, an interesting approach based on vision system can be adopted to directly supplied the controller by the information of the cartesian position. Where the camera is assumed to be fixed in front of the working area of the robot such that the plane of image is parallel to the robot trajectory plane. Also the camera can take images over the entire workspace of the robot. The vision system can feedback robot pose (position and orienting) to controller by tracking two physical characteristic at least. These characteristics can be a light of two emitting diode (LED) or two colored spot of different color or size marked on the robot, as shown in Fig. (11). The benefits of using camera to provide the robot orientation are twofold: the camera reading is less affected by vibration than IMU sensor data, and the camera is already used to track robot position so it’s preferred to get information from the same source.

III. Mass properties and magnetic force measurement

As it is known that introducing an uncomplicated design with low cost is not the end, especially if it is intended to be used for educational purpose. This section includes an experimental way to help the user to determine the mass properties (center of gravity and moment of inertia). These properties will let the educator to have deep understood to the constriction of the robot, also no dynamic model is indispensable for knowing this information. Providing these methods to the researcher allows him the opportunity to study the effect of changing the components of the robot such as motors, wheels and others as well as the location of these components.

First, it is important to know that we are dealing with three-dimensional, irregular and non-homogenous body. The most common methods to find the center of mass of bodies are:

1. Using specialist devices, such as Space Electronics products.
2. Using 3D CAM software, like SOLIDWORKS.

The first method can be used to find the mass properties of compound bodies accurately, but these apparatus are not available in all laboratories and they are very expensive. While, using software is not the optimal method, because, in order to get a good results, it is needed to:

1. Precise representation of all internal body component and all surface details.
2. Good knowledge of mass distribution (density) of all components.

So, it does not meet the simplicity requirement. The following proposed methods try to meet certain criteria: accuracy, low cost and simplicity.

A. Center of mass

The suggested mechanism is simply relied on a principle of treating the body as one piece of regular exterior (appearance). Fig. (12) illustrates the proposed mechanism, which consist of transparent box (made from Plexiglass) freely swing with ruler on metallic shift supported in both its side.

Two simple steps must be achieved to find the COM of the robot:

1. Determine the COM of box only (empty box) by marking a line on (one side of) the box with help of ruler. The box COM is at the point of intersection of the two lines which resulting from changing box hinging point in the same plane, as shown in Fig. (13-a), by change the plane of hinging, it can obtain the box center along three axes, as shown in Fig. (13-b). This step is not necessary if the box is Symmetrical, while if it was not, it requires to be done just once.
2. Repeat the same procedure in the first step after fixing the robot inside the box to get COM of the box and robot together, as shown in Fig. (14).
Then, the moment principle can be used to determine the center of the gravity of the robot only[15]. It is important to mention, there are different ways to fix the robot inside the box: matching between the robot dimensions and the internal dimension of the box or by using zip ties if it is possible, as shown in Fig. (15), its preferred to adopt fit box way as it more accurate (because the weight of the box will be as small as possible relative to the robot weight) also the author will use this method in figure illustration.

One of the common ways to determine COM is the Multiple Point Weighing Method[16], where each robot wheel is supported to scale to find the reaction force on each wheel. But this approach determines the location of COM in one plane (X,Y) and does not inform along the height of the robot, which is considered crucial issue in WCR world.

B. Moment of inertia

The experimental methods to measure the moment of inertia can be divided into two categories: acceleration methods and oscillation methods. Methods based on oscillatory motion can be considered more accurate than the acceleration methods, and the torsional pendulum from all oscillatory methods is the more accurate [17]. This method is more appropriate to the robot shape. The torsional pendulum devise, as shown in Fig. (16), is very common in the laboratories, also it is inexpensive and easy to manufacture. Torsional spring is the main part and can be gotten from wall watches. This devise have two problems: how to fix the robot on the platform surface to prevent any movement during the test and how to ensure the robot is installed at a certain point on the center of the disc. It can overcome be these problems by using the same box that used in finding COM. Where the box can protect the robot form direct contact with adhesive material (glue). The transparent wall of the box helps for precise installation at certain point, as shown in Fig (17-a). Also, the test consists of two steps; First, calculate inertia of box only. This step is not need to be repeated, where the parallel axis theorem can be used instead of that. Second, the box with robot together, as shown in Fig(17-b). The test procedure can be reviewed in[18].

C. Magnetic force measurement

The robot structure contains magnets in two places with different contact case with the wall:
1. On the wheel circumference with full contact to wall (rubber tire in between them).
2. At the free end of anti-flip rod, there is air gap between the magnet and wall.

A simple structure can help to determine the magnet force experimentally. Fig. (18) depicted the device which consist of portable weight scale attached from top to wooden frame though screw to control tightness of tendon that attached to the other end of the scale. The tendon hold a plastic piece, which have millimeter length scale, the magnet can be glue to the other side.

The attraction force of the magnets which are installed in the rear of the robot should be selected carefully. The selected value must not only prevent the robot from losing contact with the wall but also to keep the friction in the caster wheel at minimal. The generated magnetic force can be mainly set by controlling the two parameters; either the size and type of magnet or the air gap between the magnet and the wall. This device can be used to draw the relationship of the magnetic force against the increasing in the distance of magnet from the wall.

IV. Performance test

The proposed magnetic climber robot has been prototyped and tested in the laboratory environment to validate the effectiveness of the mechanism. The robot was tested to move on a metallic sheet of 1.2 mm thickness in both directions: parallel and perpendicular to gravity. In these tests, the signal of the desired trajectory was send from PC to the robot through Bluetooth and the camera was used to track the robot position. The experimental tests conducted on the prototype demonstrate that the robot successfully climbed the wall without losing adhesion and tracking the desire path accurately. Finally, the robot mechanism of ground-wall transitioning was manually examined using a remote controller. The robot average speed through the performance test was about 0.1m/s. Video files
of UOTWCR performance test are uploaded at the below link\textsuperscript{1}. Fig. (19) shows the prototype of UOTWCR attracting to a ferromagnetic wall in our lab. To provide sufficient description about UOTWCR design. Fig. (20) illustrates the assembly drawing of robot part.

V. Conclusion
This paper introduced UOTWCR, the first wall climbing robot developed in our labs for educational purpose. The suggested design is adopted the magnetic force to provide the required adhesion and used wheels for locomotion. This work includes introducing experimental methods to determine mass properties of robot. These methods can be also invested as laboratory apparatuses to illustrate the related concepts such as parallel axis theorem and principle of moments. UOTWCR has been checked in laboratory circumstances to confirm its ability to transition between orthogonal surfaces and move over a ferromagnetic wall in various directions.

In the next research, Robot dynamics are focused and explained. Also addition of an onboard cheap camera to perform image processing will be considered.

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![Figure (1): (a) ground educational robots (b) Underwater robots from kits/instructions by MBARI (c) the AR drone Wifi controlled quad rotor[3].](image1)

![Figure (2): (a) GECKOBOT (b) RC wall climbing car (c) Drone with wheels](image2)

![Figure (3): Educational WCR introduced by[5].](image3)
Figure (4): design procedure of magnetic WCR with permanent magnets on the robot body

Figure (5): Distribution of magnets on the wheel.
Figure (6) The gravity influence on differential drive wheeled climbing robot. (a) Robot moving up; (b) robot descending on the wall.

Figure (7): Main part location and dimensions of UOT-B1. a. back view b. top view c. side view. 1. wheel, 2. Cover, 3. Motors, 4. Battery, 5. cater wheel, 6. rear magnet.

Figure (8): Limitation throughout transition with ball caster wheel.
**Figure (9):** a. Robot top view with the additional wheels, b. Transitioning sequence

**Figure (10):** Hardware architecture of wall-climbing platform. Red and blue lines represent power and control system respectively.

**Figure (11):** Using colored spots to detect robot position and orientation.
Figure (12): The proposed mechanism to find COM of the robot

Figure (13): Determine the COM location of box in a. x-y plane, b. x-z plane.

Figure (14): Determine the COM location of box and robot together in a. x-y plane, b. x-z plane.
Figure (15): Installing the robot inside the box with zip ties through holes.

Figure (16): Torsional pendulum device.

Figure (17): a. Installing the box at a specific point. b. calculate the inertia of both robot and box.
Figure (18): Simple mechanism to measure magnet force.

Figure (19): UOTWCR on wall.
Figure (20): Subassembly of the proposed robot.