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A Novel Mechanism Design Technique To Develop A Vertical Climbing Robot With High Mobility For Flat And Spherical Surfaces

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***Abstract*—The following paper represents a new and improved wall climbing mechanism that can climb on flat and spherical surfaces. The design methodology of the robot was solely directed towards heavy lifting purposes; as the robot uses a redesigned mechanism to endure an enhanced workload. The robot was specially designed to climb any given vertical surface with the help of the Reverse Propulsion technology; which provides backward thrust as a convenient heavy-duty suction mechanism. The robot was built keeping overall body weight at a minimum and consisted an array of powerful brushless motors for the suction and navigation. The robot can be put to multiple use based on its operation such as surveillance, inspection, cleaning etc.**

Keywords—Wall Climbing Robot, Vertical Structure, Reverse Propulsion, RF Wireless Communication, Electric Ducted Fan.

I. Introduction

The modern era consists the use of robots in various fields of work. The use of wall climbing robots have become a unique and essential necessity in the area of robotics. Various wall climbing robots are being developed for inspection of sea vessels, surveillance, space activities. The wall climbing robots are beneficial as such to reduce human labor, in turn diminishing the risk of human injuries. Over years, many developments are being done to make the robots light weighted and efficient. These wall climbing robots can be made using different type of topologies. The most recent uses are those with legged mechanism and wheeled mechanism [1]. This paper makes use of the wheeled climbing mechanism with the additional use of Electronic Ducted Fans (EDF) to provide greater adhesion due to the additional weight. The additional weight accounts for the multidisciplinary heavy-duty components with the addition of the outcome-based mechanisms built in. The robot was designed to climb any high raised buildings to perform multidisciplinary tasks. The reverse propulsion system was designed using two pairs of EDF Brushless motors and two brushless motor propellers. A simple RF configuration was set up in order to control the various movements required for efficient climbing. The body of the robot was designed using Aluminum and 3D printed materials to ensure structural integrity as well as a decrease in overall weight.

II. Literature Review

During the 19th century, different generation of robots were developed. The most advanced technology of that era were the third-generation robots which were developed in the 1990s and these machines were stationary or mobile, autonomous or insect type, with complex programming, speech recognition or synthesis, and other advanced features. The research and development of the fourth generation of robotics in the early 20th century involves human comprehension, self-replication and assembly.

Industrial Manufacturing Robots distinguishes from other advanced robots due to a distinct number of capabilities that enable them to be used in industrial environments. These robotic activities included industrial welding, product assembling, industrial soldering and many more. . The most commonly used robot configurations for industrial automation, included Cartesian robots, Gantry robots, SCARA robots, articulated arm robots and Human-assist robots [2].

Fig. 1. Yamaha Large type SCARA Robot [3]

In the world of robotics, the capability to ascend walls with mobile movements had long been a problem. Climbing robots had their own special designs to support them ascend [4]. In the past 10-15 years, many climbing robots were built. Climbing robots stick to flat or smoothly curved surfaces using devices like suction cups or magnets or ducted fans. These were therefore restricted to glass, metal or other smooth surface environments. Bio-inspired robot feet have recently been designed to manufacture robots which can ascend floors, tiles or other flat surfaces.

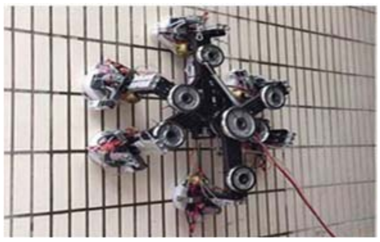

Fig. 2. Wall Climbing Structured Robots [5]

Currently, the only comparable wall climbing robot is the Vertigo [6] which uses two propellers coupled with motors to help it mobilize. It is very light weight as the overall main body and wheels are 3D printed. While this robot is only made to climb any walls or surfaces, it can however not carry much additional load due to its much compact size. The robot in the paper is larger in comparison to vertigo as it requires to carry much additional weight to carry out its task. The main body frame is larger than the Vertigo and weight is increased due to the use of four EDFs, each of which weighs around 178g. The weight is also increased as aluminum sheets have been used for the main body frame as compared to 3D printed one of Vertigo to increase the integrity of the robot's body.

In the following paper, the robot used the EDF to provide maximum reverse thrust and the propellers were responsible for the navigation of the robot. Furthermore the navigation system also comprised of several servo motors mechanically paired and designed with utmost simplicity. All the motors of the robot was controllable using a Pulse Width Modulation (PWM) signal from a Radio Frequency (RF) receiver. The RF receiver channels were reinforced using the Raspberry Pie 4 (model B). In order to control the overall weight addition, a metal aluminum unibody was chosen considering its low density and structural integrity. The unibody was cut making many compartments to house the motors; this further reduced the weight of the body. The design was further optimized by adding 3D printed plastic wheels and clamps to reduce the weight. The 3D printed ABS plastic components were built to retain maximum stress applied to them.

III. Mechanical Design Analysis

The mechanical design of the robot was done in the software SolidWorks. The aluminum unibody design was chosen to ensure less weight of the body. Some cutouts were made in the body to fit various components. Many peripheral components were attached to the metal body using simple means of welding.

Fig. 3. Designed prototype of the Wall Climbing Robot

A. Structural Design

The main aluminum body frame was designed using CNC cutting from a thickness of 2.5mm aluminum sheet. The two bigger round shape cuts were made to house the ABS propeller frame while the four smaller round shaped cuts were made to house the EDFs.

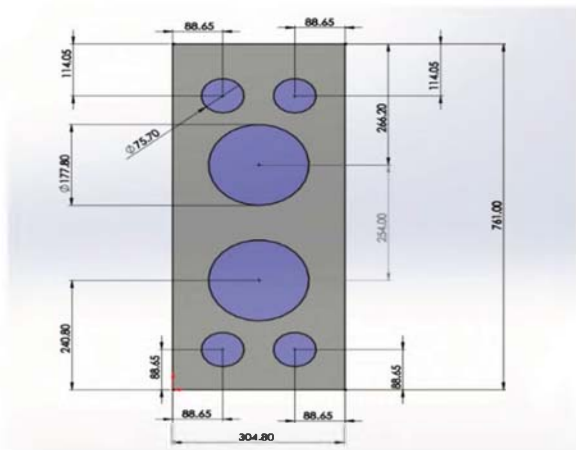

Fig. 4. Aluminum Body Frame with Dimension (in mm)

In the following robot, three specific ball bearing sizes were chosen to perfectly fit their purpose. The 608 Z ball bearing was used in the turning mechanism of the two front wheels. The multidirectional propellers were equipped with 695 ZZ ball bearings each to aid the connected servo motor in the motion of the propeller. Two of these ball bearings were an appropriate choice as the propellers needed a smaller alternative as the 695 ZZ. The robot uses a 12mm inner diameter CSK 12 PP bearing, which is unidirectional which serves as a natural braking system for the robot as it rises against gravity.

The wheels were complemented by the bearing to facilitate in one directional movement. ABS plastic was chosen as the best material for the wheels of the robot. The choice of the material was to ensure lightweight and structural integrity due to the web-shaped design.

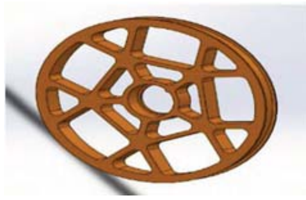

Fig. 5. ABS Plastic Wheel

The wheels of the robot were connected to the shaft using multidisciplinary clamps specially designed to increase structural integrity. The clamps were designed using small chunks of aluminum to reduce the overall weight of the robot.

Fig. 6. Wheel Movement Shaft with Dimensions (in inch)

The Square Shaped fixed clamps were used to hold the rear wheels at a fixed position with the shafts. The clamp was joined to the body through welding. The T-Shaped clamp adjoins the L-Shaped to the body of the robot. These clamps do a combined operation of rotating the front wheels using a sophisticated turning mechanism. In order to connect the wheels to the bearing and the body of the robot, aluminum-built shafts were used.

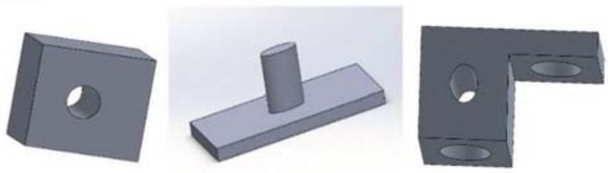

Fig. 7. Aluminum Wheel Clamps

B. Navigation System Design

The navigation system was designed using a series of rotary shafts. The shafts connect the wheels to the main body of the robot, as well as they serve as the key component for the differential turning mechanism attached to the body of the robot. Apart for the turning mechanism, the robots forward navigation consists of a system of propellers that provide forward force for the robot's movement. The wheel movement shaft was designed specifically to inter-connect the necessary clamps of the two front wheels. The shafts deliver rotational movement throughout the two wheels equally. A small perforation was made to connect the servo motor to the shaft. The servo motor will serve as the controlling element which will ensure proper turning motion.

Fig. 8. Rotating ABS Propeller Frame with Dimensions (in inch)

The frame used to house the propellers were made as the same material as the wheels which is ABS plastic. The exterior shape was of round shaped to complement the propeller adjustment. In the interior, two parallel lines were built to ensure structural integrity and to house the holder of motors used to rotate the propellers. Two ABS built clamps were used to hold the frame in place. The circular shaped frame had small holes and was used to house the motors of the propellers. Two different ABS plastic clamps were used to hold the propeller frames in place. The U-shaped clamp was used to house the MG996R servo motor of 10kg.cm torque in each frame.

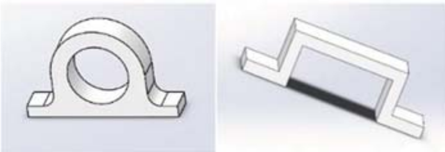

Fig. 9. Circular Shaped ABS Plastic Clamps

IV. Wireless RF Controlling

The Radio-Link controller and receiver were used to wirelessly control the robot. The channel connections were made maintaining user friendly interface. The interface was created using an array of rotary joysticks, two state levers and three state switches. The R9DS receiver uses a 5V power supply and is connected to the PWM terminal of the motors. The receiver provides a customized PWM signal that is supplied wirelessly using the controller. The wheel controlled comprised of the full turning operation of the robot. A servo motor coupled with gears and shafts provided total control of the two front wheels. The turning operation of the robot was dedicated to the channel-1 of the receiver. When the associated knob is turned to the left, the robot is turned left by the servo motors. The channel 1 responds with a positive signal from the controller during this operation.

Fig. 10. Left Turning Operation of the Robot

Fig. 11. Right Turning Operation of the Robot

When the knob of channel 1 is moved to the right, the robot is turned right by the servo motors. The channel 1 responds with a negative signal from the controller during this operation. The wheels of the robots respond to the signal as shown below. The propeller control was connected to the third channel of the receiver, which was in turn controlled by a bi-directional vertical knob. When the knob is faced upward, the propellers provide an inclined forward force to make the robot move forward. The servo motors associated with the propeller received a positive voltage signal from the receiver. During braking, the mechanism was designed such that the robot could stop its motion when required. For the braking, the knob of channel-3 was shifted downwards and the propellers exerted a backward force to the robot's free fall towards gravity. Servo motors controlling the propeller direction received a negative voltage signal from the receiver.

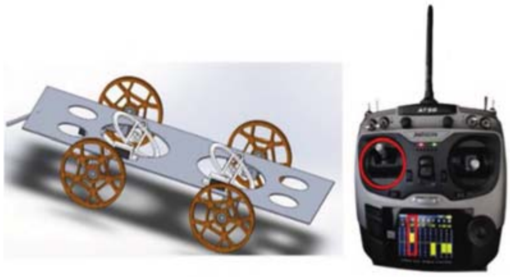

Fig. 12. Forward Movement Operation of the Robot

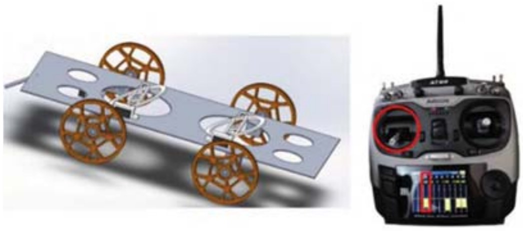

Fig. 13. Breaking Operation of the Robot

V. Design Topology

A. Electrical Workflow

The robotic system was tested in simulation tools that generated real-world theoretical outputs. For a wall-climbing robotic system, it was difficult to find a tool which contains all the component for the system. The operation of Electrical Ducted Fan, Servo motors, Brushless motors with the processor was observed in the simulation. The output result was satisfactory enough for motivating on building the real-world system. The response of the connected system in the simulation tool was observed properly to build the robotic system. The four Brushless DC Motor situated at the top and bottom of the robot provide a downward thrust which serve as the suction mechanism. The mechanism allows the robot to firmly grip itself to any given surface of high raised buildings. The EDF motors operate at a maximum current of 65 A, provided from the Li-Po batteries. The PWM of the DC motor is provided from the Servo Tester which allow users to control the thrust provided by the motors. All four EDF are connected to a ESC; motor driver, to control the amount of current entering the motors. The design consists of two more brushless DC motors in the form of propellers to provide forward and backward thrust, horizontally, to navigate the robot. The two brushless motor propellers were connected in the middle of the aluminum body to ensure maximum effect of the thrust. Similarly, to the EDFs, the propellers also consist of an ESC connected to them. These motor drivers were rated 30A each which was ideal to operate the propellers. The propellers were controlled via a RF Controller, wirelessly. The RF controller paired with the propellers provided an ideal system for proper navigation of the robot. The RF controller was powered using four pairs of AA batteries. The controller paired with the receiver provided eight multipurpose channels which were used to control various components of the robot. The receiver was a digital device of rated 5v, the rated voltage was controlled using some specific I/O ports of the Raspberry Pie 4 micro-controller. The micro-controller provided proper output voltage in order to efficiently run digital components like the RC receiver and servo motors. The Servo motors of the robot were connected and chosen for the most efficient navigation system possible. Two servo motors controlled the steering of the robot while the other two were responsible for rotating the propellers as per required. The servo motors were controlled using the controller and were connected in two different channels for the above-mentioned tasks. All the above-mentioned electrical components were operated using two 15V 5500 mAh Li-Po batteries. The batteries provided constant power to every given electrical component. The battery voltage was regulated in the case of digital components as they can only be operated for the rated 5V Dc power. In order to provide a shutdown feature from the controller, a RC Switch was connected to the batteries then to the receiver.

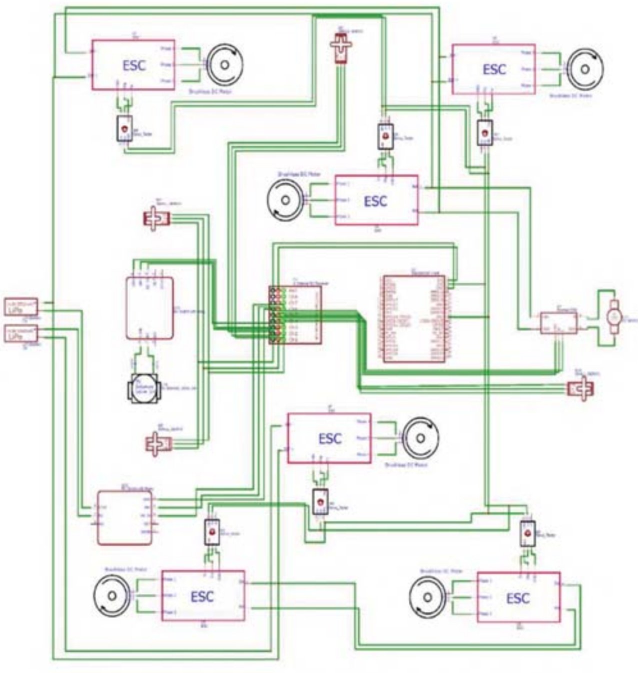

Fig. 14. Simulation of the Control Mechanism of the Robot

B. *Workflow Design*

In the given mechanism, the power supply system consisted of two 15 V 5500 mAh Li-Po batteries; which were connected to three servo motors, six ESCs, raspberry pie 4, the cleaning mechanism, two DC brushless motor propellers and lastly four Electronic Ducted Fans (EDFs). The batteries were used to power up all the above-mentioned electrical components. One pair of ESCs and one pair of servo motors were connected to two different brushless motors for controlling movements of propellers for the sole purpose of navigation. Each of these two ESCs were rated 30A and provided perfect motor control over the propellers for navigational purposes. Each of the two servo motors were of 10kg.cm torque. The brushless motors each were rated as 2300kV and provided thrust of approximately 1kg.cm. So, in the end, two 30A rated ESC and two servo motors of 10kg.cm torque were used along with two brushless motors to control the movements of two propellers to navigate the robot. Four ESCs were powered up using the batteries which were connected with four EDFs. This enabled the reverse propulsion technique to balance the robot while operating on the surface of high raised buildings for cleaning. Each EDF provided a thrust of approximately 2.3kgs. So overall, four of these EDFs provided around 9.2kgs thrust which balanced out the weight of the robot perfectly. Each of the EDFs had motors of 2300kV rating and was powerful enough to keep the robot balanced on wall or any surfaces necessary. One servo of 20 kg-cm torque, connected to the battery, was used for turning the two front wheels. Two of the front wheels were interconnected using the servo motor which helped for the movements of the robot. The Raspberry Pie 4 which was also powered by the batteries; was connected to the receiver of the controller. The receiver was used for directing the input commands that were programmed beforehand using the controller. The raspberry pie 4 was responsible for providing the 5V continuous DC power to the receiver.

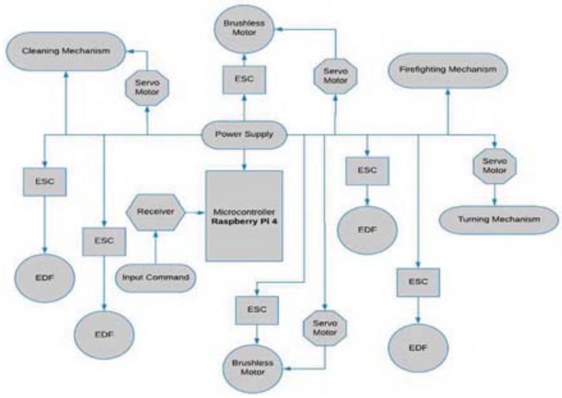

Fig. 15. Block Diagram of the Working Procedure of the Robot

VI. Experimental Analysis

A. *Body Weight Analysis*

The body of the robot was designed using careful considerations and critical design reviews. The body was initially designed using the SolidWorks simulating software. The software was chosen due to its designing capabilities if the software as the software could be used to deliberately calculate the various components associated with the design. The robot's design was made keeping a low weight distribution throughout. During modeling, the material of choice for the body was chosen to be Aluminum; as it had a very low density and had admirable structural integrity. The overall body weight of the robot was found to be approximately eight pounds; ignoring all the electrical components. The cumulative weight of the robot was identified to be approximately 15 pounds. The total surface area of the robot, as seen in the figure above, was over 1000 square inches. Other information are listed below, which were obtained from the simulation software.

Metal Body Weight - 8.05 pounds or 3.65 kg

Total Body weight - 15.4 pounds or 7 kg.

Total Surface Area - 1154.90 square inches

The Center of Gravity of the robot lies in:

X = 10.44 inches

Y = 15.41 inches

Z = 21.33 inches

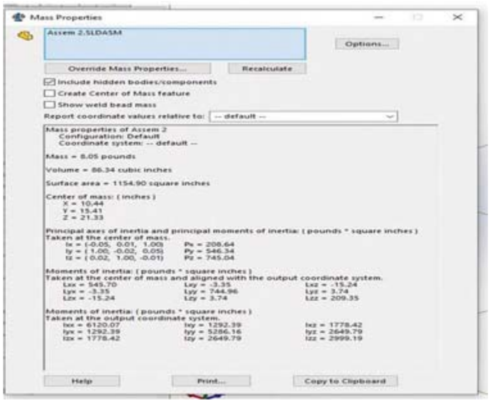

Fig. 16. Simulation of Body Weight Analysis

B. *Vertical Movement Analysis*

The vertical movement of the robot was calculated using some basic physics topologies. The vertical movement was divided into two parts: Vertical Holding and Vertical Movement. The vertical holding capabilities of the robot was calculated using Sir Isaac Newton's law of motion. The topology of the 3rd Law of motion was used to calculate the vertical holding. This law states that, every action has an equal but opposite reaction. So the greater thrust that was provided using the EDFs allowed the robot to stay in stationary position.

The EDFs provided a total force that well exceeded the total weight of the robot.

Force needed to hold the robot against gravity,

Force = Mass of the Robot x Acceleration due to gravity

Force = 7 kg x 9.81 m/s2

Force = 68.67 N

Thrust required = 7002.39 grams.

We have used 4 EDF each with a thrust of 2200g which in total gives a thrust of 8800g or 86N.

The vertical movement of the robot was determined by the two brushless motor propellers and four high powered EDFs. All six motors contributed against the forces of gravity as two brushless propellers provided a total force of 2000g or 20N. The total calculations of the forwards forces was calculated.

Resultant Force:

F_H = Forward Horizontal Force,

F_V = Forward Vertical Force

$$F_R = \sqrt{{F_H}^2 + {F_V}^2} \quad (1)$$

$F_R = \sqrt{20^2 + 86^2}$ = 88.3 N

Thrust Available = 9004.1 grams.

So, Thrust to Weight ratio is 1.25.

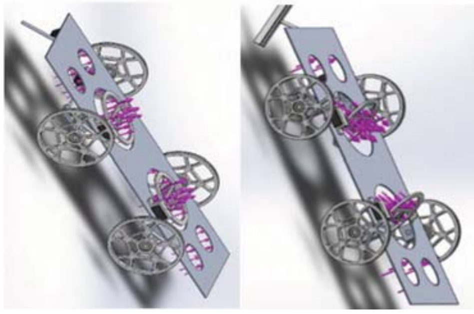

Fig. 17. Vertical movement of the robot using reverse propulsion method

VII. Conclusion & Future Work

In this paper, the unique method of using the EDFs and propellers to fabricate a wall-climbing robot for multipurpose use was presented. The aluminum body was chosen as such to reduce overall weight of the body. The use of several multidisciplinary components including propellers, EDFs and other motors provided an excellent mechanism for mobility and navigation of the robot over wall surfaces. Dynamic Simulation of the wall-climbing robot was carried out using SolidWorks software. The simulation was conducted thoroughly to ensure the overall efficiency of the robot would carry out its tasks properly. The controlling of the robot composes of a wireless RF controller. Overall, the controlling of the robot has also been made very user friendly.

Several changes can be brought upon the robot to develop it further. By utilizing proper image processing and using thermal cameras, we can use the robot to inspect areas where human entry is strenuous for inspection purpose or to extinguish fire or clean surfaces. With advanced technology, we can also make use of solar energy as a source of power to perform its tasks. Recyclable materials can also be used to construct the body frame of the robot, thus reducing costs. As we are using EDFs, we can also develop it to work as a drone in case of emergencies by rotating direction of the EDFs and providing positive thrust. This paper provides an exceptional and reliable mechanism design of a wall-climbing robot with heavy duty support and perform multiple tasks which reduce the risk of human life.

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