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Windmill Climbing Robot

Khaldoun Hatoum
Mechanical and Mechatronics Engineering Department
Rafik Hairi University
Mechref- Chouf2010, Lebanon
hatoomkc@students.rhu.edu.lb

Rami Alkhatib
Mechanical and Mechatronics Engineering Department
Rafik Hairi University
Mechref- Chouf2010, Lebanon
khatibrh@hotmail.com

Nael Jaber
Mechanical and Mechatronics Engineering Department
Rafik Hairi University
Mechref- Chouf2010, Lebanon
jaberna@students.rhu.edu.lb

Maher Sabbah
Computer and Communication Engineering Department
Rafik Hariri University
Mechref- Chouf2010, Lebanon
sabbahmm@rhu.edu.lb

Mohammad O.Diab
Computer and Communication Engineering Department
Rafik Hariri University
Mechref- Chouf2010, Lebanon
diabmo@rhu.edu.lb

***Abstract*—Having the windmill main components at the top of its high tower made its maintenance a very risky job for workers, and with an increase of use of wind turbines, the risk of accidents occurring is proportionally increasing too. For this, engineers started working on climbing robots and mechanisms to replace risking human lives. This research works on adding to this research topic, by proposing a full study of a new mechanism enhanced with calculations and modeling for it to be applicable and reliable. The proposed robot mechanism can circumference the tower of the wind mill and climb upwards through means of rubber chains.**

Keywords— Windmill; Climbing Robot; Screw Motion

I. Introduction (*Heading 1*)

A Windmill is a combination of several complex parts synchronized while working, aiming to extract the maximum of passing wind currents. Having high towers and its main components such as the nacelle, blades, and gearbox located on the top, a mill's problem falls in its maintenance procedure where its tower is considered to be very slippery, thus climbing such structure tends to be a very hazardous job.

For solving this issue, engineers and researchers have been working over the years to find the optimum solution, coming up with several climbing mechanisms having many of them applied in the fields while others are still in research phase. One of the proposed solutions was a Wall-climbing robot which can work in severe conditions when deployed at high altitudes. So, the mechanism was set to be studied upon high design standards for it to hold large wind loads, high vibration rates, and surface contact instabilities. The paper introduced a new suction method to be applied into hook-like claws which tend to be of sharp edges. The proposed robot design was later translated into mechanical models then implemented into a prototype tested on an 8-foot concrete wall which produced very promising results having the robot performing with high stability, satisfying inspection requirements [1].

Another paper proposed what is called Tankbot. It represents a tank-like climbing robot utilized by adhesive treads of soft elastomer. Having the characteristics of a wheeled robot design gives Tankbot a strong attachment to both smooth and rough terrains with minimal vibrations. This tank-like structure design study was focused on the peeling force to have its normal component maximized with respect to the surface in order to maximize the climbing stability. These design standards make tankbot a super climbing robot on any terrain condition, and on any slope angle, vertically or laterally. Upon study and derivation of mechanical models, Tankbot was translated into prototypes of several dimensions and tested to reach the optimal and viable Tankbot design which reached the optimal tread tension range for maximum pealing force, having the best performance [2].

Tackling common research topics, a paper presented the design of a four-legged robot, each leg having four degrees of freedom. The design was a combination of two climbing techniques, one adapted from rock climbing with four limbs while the other from cats climbing with its claws. So, the actual design was having four legs with each leg utilized with a claw providing the robot to move in all directions while climbing up a wall. Moreover, a gripping device made of twelve hooks are installed at the end of each leg. The system is provided with a locomotion algorithm which makes the robot able to travel its predefined route autonomously taking into consideration the contact force with the surface and to review the grip status from the twelve-hook gripping device with every move to increase the stability and reliability of balancing its weight and attaching to the wall. After modeling, a prototype was built and tested showing high reliability on both, the gripping device and the running algorithm [3].

Addressing conical shapes and especially wind mills towers, a paper proposed the design of a robot dedicated to this task. The method introduced was the use of four magnetic units utilizing the robot for it to adapt to the conical surface. Upon their study, and with the aid of ANSYS, the results showed that the distance between the units and the surface in contact has a direct effect in the magnetic field. After completing calculations, comparisons and all means of analysis, mechanical models were set. The study reached the desired results after conducting simulations and experiments that showed the effectiveness of the installed magnetic units as modeled where the climbing robot was able to keep in contact with the slippery surface of the windmill tower (conical surface) [4].

Wind energy is recognized to be one of the greenest renewable energy sources. Windmills extracting this energy made for human a better life, with less pollution and relying on fossil fuels. This system, known as windmills or wind turbines seems perfect and of limited disadvantages, but in reality, and in return for this generous grant of power it has been taking several people lives. It's the dark side which media is still trying to cover although thousands of accidents have been documented and it's still it's considered a secret knowing the real number of tragedies occurring worldwide. For instance, in the United Kingdom alone, the Renewables UK which is industry trade association confessed that during the past five years, 1500 accidents have occurred resulting four deaths and 300 injuries [5]. When it comes to the total estimated numbers, until 2018, of all accidents occurring due to wind turbines, the Caithness Windfarm Information Forum based on its reliable sources put us in front of a huge number of 2231 accidents, 137 of them fatal [6].

Climbing robots have been, are still challenging. Engineers are discovering day by day much advanced and reliable techniques, and this research aims to provide one of these new techniques which deliver a new concept other than the recently known ones such as magnetic units or suction methods.

II. Methodology

A. Design

The robot needs to climb a tower with a diameter varying from mill to mill, and within the same mill there is also variation due to canonical shape. Based on such condition, the proposed design is to have one main chain to push the whole mechanism upward or downward. By examining the tower features, it has been noticed with two main features that hinders climbing: the hight and the surface friction. In order to achieve the needed grip (traction) for the drive chain, supporting mechanisms are essential. Thus two robotic arms connected through chains to circumference the tower. Fig.1 shows the proposed mechanism design.

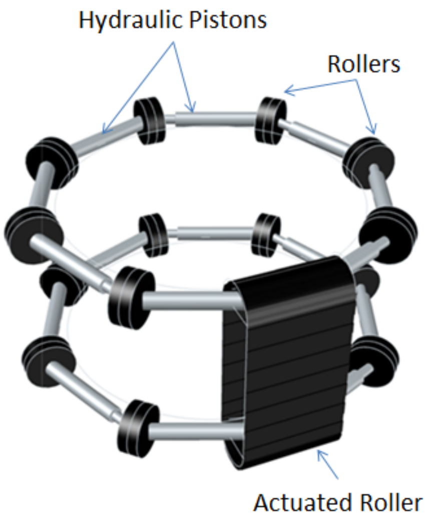

Fig. 1. Climbing Mechanisim

The average base diameter of the tower is 5 meters, and the top diameter is 3 meters. That change in diameter leads to a linear variation of 6.28 meters between top and bottom of the tower. Taking that variation in length and forces, the use of hydraulic pistons to hold the seven rollers on each arm of the robot is chosen.

The chain mechanism consists of a body (chassis), Sprocket, Guiding rollers, and the chain. Some constrains are to be considered on the outer chain shape and material. The outer face should be flexible to take the shape of the circular tower and made out of rubber (60 A belts) to maintain a good friction and prevent slipping. Rollers must be coated with the same rubber for same conditions. This has contributed to transferring rotation into linear motion. Fig.2 emphasizes the robot mechanism as it is on the tower:

Fig. 2. Robot Mechanisim climbing the tower

Pistons are used to connect the chain to rollers all around the tower, thus providing flexibility in changing diameter and in providing adequate force to grip around the tower. These pistons should have at least 77 centimetres of elongating shaft in order to suitable for the base and top diameter.

The rollers are of diameter 50cm and a width of 20cm. The purpose of putting these items in the design is providing mobile connection and clearance between the pistons and the tower. As mentioned before, the surface of the roller has to be coated with rubber (60 A belts) for friction. On each side of a roller we fix a 2 axis joint. One axis is central with the roller, and the other is perpendicular to the first axis, with one degree of freedom to allow rotation about this axis so that the piston is connected, and can rotate while moving from small diameter to big diameter.

B. Calculations

Fig.3 shows a top sketch of the robot at the most extended, and least extended position. As the figure indicates, there is eight contact points with the tower, one chain and seven rollers. The rollers and the chain sprocket have the same diameter, thus they will have the same rotational speed during motion. The estimated travelling distance of the robot is the average length of the robot which is 60 meters. The tower shape resembles a cone and thus an inclination angle is calculated to be arctan(3/60) = 2.86 degrees. Thus, from the top of tower it is clearly that the axis of the tower is a perpendicular straight line, and the path followed by each of the chain and the roller is a straight line planar to the axis and inclined by an angle of 2.86 degrees. For small displacements, the motion can be considered linear.

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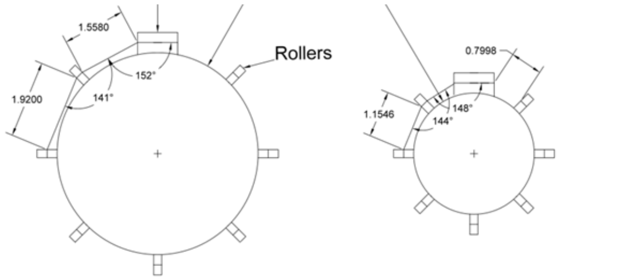

Fig. 3. Top view

The two positions of the robot mechanism are illustrated in Fig.4.

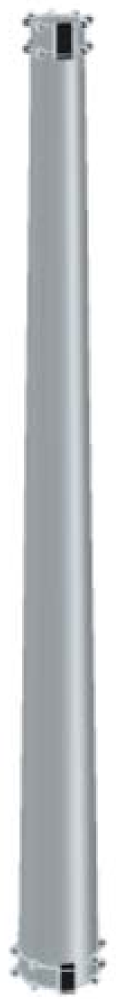

Fig. 4. The Robot at two different positions on the tower

Now it is important to consider force calculations to determine good traction (friction) between rollers, chain, and tower. In this design, the load is driven centrally by one chain (concentrated load), thus the main calculations should be centered at the chain. From literature, the coefficient of friction (μ) between rubber 60 A and steel is 0.82 for a dry surface. In the following calculations the surface is assumed to be not lubricated.

Coulomb's force of friction (F_r) is the product of coefficient of friction multiplied by the normal reaction force (in magnitude), and directed against the motion.

$$F_r = \mu N \qquad (1)$$

Then the lifting force (F_t) must be greater than the weight of the robot to result in upward motion. Since the length of the tower is 60 meters, the weight of the robot changes. We can compensate this change by a safety factor of two ending up with (2):

$$F_t > 2m \times g \qquad (2)$$

The mass of the robot is denoted by m. Then the normal support can be estimated to be greater than (2×9.81×m/0.82) which 22.39×m. Then the stress (S) on the rubber obtained by the contraction of the eight pistons can be determined to be as in (3):

$$S = \frac{Normal\ Force}{Area} = 14.92m \qquad (3)$$

In other words, the forces exerted by pistons are 8 radially perpendicular forces all around the tower. Note that S depends on the modulus of elasticity (E) of rubber. Thus the strain (Ɛ) is calculated to be:

$$\mathcal{E}=(22.39\times m) / (E\times A)= (1.4926\times 10^{-5}) \times m \qquad (4)$$

Hence the change in length (dL) depends on intial length (d_o) by (5):

$$dL = (1.4926 \times 10^{-5})m \times d_o \qquad (5)$$

At the base d_0 is the perimeter of the tower =3.14×5 = 15.7 meters, hence dL at the base is (2.3434×10^{-4}) ×m.

$$Per\ piston = \frac{[(2.3434\times10^{-4})\times m]}{8} = (2.9292 \times 10^{-5})m (6)$$

At the top, d_0 is the perimeter of the top = 3.14×3 = 9.42 meters, hence dL at the top is (1.406×10^{-4}) ×m

$$Per\ piston = \frac{[(1.406\times10^{-4})\times m]}{8} = (1.7575 \times 10^{-5})m\ (7)$$

Thus is the mass of the robot is to be up to 500kg (including the tools to be lifted) then change of the length will be 1.4646 cm at the base and 0.87875 cm at the top.

Now assume that dL is some unknown value at a known height, then calculating the rate of change in dL with respect to vertical distance travelled becomes feasible. The rate of change of dL is linearly proportional to the change in diameter, hence its equal to the slope of the surface of the tower with respect to the perpendicular axis. The equation of the surface line is given by (8) (assume our fixed x-y frame is at the center of the base of the tower where x is radius and Y is the height at any time along the path):

$$Y = ax + b \qquad (8)$$

Then at Y=0 then 0 = 2.5a + b and at top Y=60= then 60 = 1.5a + b. Solving for a and b will yield a = -60 and b = 150. Hence Y = -60x + 150 is the equation of the surface and by multiplying it with $1.4926\times10^{-5}\times$ m×3.14 which is the value we calculated by calculating stress and engineering extensional strain Ɛ to get dL at any height. Rearrange the equation to get x in terms of Y and then multiply by two to get diameter:

$$2x = dL = \frac{150-y}{30} = (1.5622 \times 10^{-6})(150 - Y)m \qquad (9)$$

C. Motion Description

Accomplishing task of motion can ensure promising results from the robotics perspective with respect to the quality of performing a certain motion, particularly at high speed and accuracy. The system must be modeled by joints and links, whose equivalences will represent the desired path plan of a certain robot trajectory for complicated routes. The motion of robot over the tower (with the cone shape) allows examining the path as a helix with small pitches, can relate such motion to a set of joints and links, which will result a similar path on the end-effector.

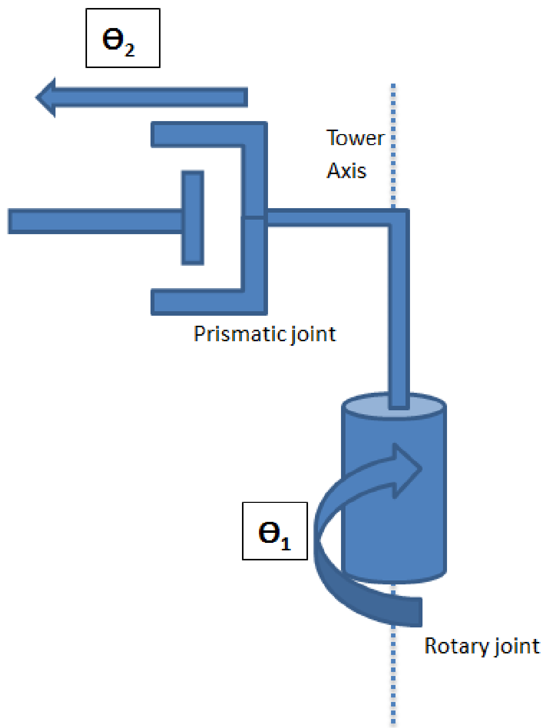

Fig. 5. Modeling the tower and the robot as one entity made up of joints and links

Then the motion cans described as product of exponentials as given in

$$T(\theta) = e^{[S_1]\theta_1} e^{[S_2]\theta_2} . M \tag{10}$$

M is a special Euclidian of order three that represent the robot configuration when it is in home position.

Finding S1 and S2 will yield the following:

$$S1 = \begin{bmatrix} \omega 1 \\ v1 \end{bmatrix}$$

$$\omega 1 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

$$q1 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$h = \frac{10}{2\pi} \ \ \& \ v1 = -\omega 1 \times q1 + h.\omega 1$$

$$=> v1 = \begin{bmatrix} 0 \\ \frac{10}{2\pi} \\ 0 \end{bmatrix}$$

$$=> S1 = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ \frac{10}{2\pi} \\ 0 \end{bmatrix}$$

$$S2 = \begin{bmatrix} \omega 2 \\ v2 \end{bmatrix}$$

$$\omega 2 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$q2 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$v2 = -\omega 2 \times q2 + h.\omega 2$$

$$=> v2 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$=> S2 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$$\frac{\theta 1}{\theta 2} = \frac{5}{2\pi} => T_{oh} = e^{[s1]\theta 1} \ e^{[s2]\frac{2\pi\theta 1}{5}} M$$

Fig.6 illustrates the fact that our model of the robotic motion is confirmed with the fact the robot starts from the base of the windmill and undergoes a radially decreasing circular spiral motion in the y-direction which is considered to be the screw axis.

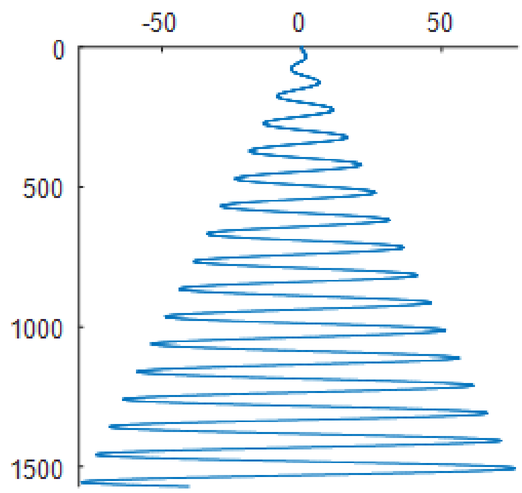

Fig. 6. The robot undergoing screw motion

III. Conclusion

This paper suggests a design of a robot that can circumference the tower of the wind mill and climb upwards through means of rubber chains. The robot may have an integrated arm to perform desired tasks (ex. Tower and rotor blade maintenances of wind turbines). Chasles Mozzi theorem has been implemented to verify the motion of the proposed Robot design. In the future, the forces must be considered in more details in addition to the control system.

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