World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:2, No:5, 2008

Design and Fabrication of a Column-Climber Robot (Koala Robot)

Maziar Sadeghi, and Amir Moradi

***Abstract*—**This paper proposes a robot able to climb Columns. This robot is not dependent on the diameter and material of the columns. Some climbing robots have been designed up to now but Koala robot was designed and fabricated for climbing columns exclusively. Simple kinematics of climbing in the nature inspired us to design this robot. We used two linear mechanisms to grip the column. The gripper consists of a DC motor and a power screw mechanism with a linear bushing as a guide. This mechanism provides enough force to grip the column. In addition we needed an actuator for climbing the column; hence, two pneumatic jacks were used. All the mechanical parts were designed according to the exerted forces and operational condition. The prototype can be simply installed and controlled on the column by an inexperienced operator. This robot is intended for inspection and surveillance of pipes in oil industries and power poles in electric industries.

***Keywords*—**Robot, Column-climber, Gripping mechanism, Koala.

I. Introduction

DIFFERENT kinds of climbing robots have been designed and fabricated up to now. In [1]-[4] some climbing robots have been proposed. As these designs are not exclusively for climbing columns so none of them is completely suitable for this application. The goal of this project is designing and fabricating a robot which can be controlled manually and semi autonomously to climb up and down a column safely. In this robot we try to gain these abilities:

- Ability of being installed and uninstalled on the column
- Ability of carrying a weight or equipment on the column
- Simplicity of the mechanisms, proper operational speed and lightness and cheapness of the robot parts

Researchers have proposed a great variety of climbing robots for various applications. In general these robots use one of three types of adhesion mechanism; vacuum suction, magnetic attraction, or gripping with claws or grasping mechanism.

The most common type is suction adhesion [1, 2] where the robot carries an onboard pump to create a vacuum inside cups which are pressed against the wall or ceiling. This type of attachment has some major drawbacks associated with it. The suction adhesion mechanism requires time to develop enough vacuum to generate sufficient adhesion force. Another issue associated with suction adhesion is that any gap in the seal can cause the robot to fall.

Another common type of adhesion mechanism is magnetic adhesion [3, 4]. In specific cases where the surface allows, magnetic attachment can be highly desirable for its inherent reliability. Despite that, magnetic attachment is useful only in specific environments where the surface is ferromagnetic, so for most applications it is an unsuitable choice.

The third method is grasping which is applicable for rough surfaces but it is not suitable for smooth surfaces. Climbing down is difficult in this method of gripping. [5] has used this method for climbing the 85° slopes.

The proposed method for climbing in the koala robot is gripping the column from its sides by a "V" type gripper. The surfaces of the grippers have been equipped with rubber strips to increase the friction between grippers and the surface of the column. The benefit of this method is that the climbing process is less dependent on the material of the column. In addition, for columns with special profiles, suitable grippers can be designed accordingly [6].

Maziar Sadeghi is with the Mechanical Engineering Department, Tehran University, Kargar-shomali St, Tehran Iran (phone: +98-912-5157332; e-mail: maziar.sadeghi@gmail.com).

Amir Moradi is with the Mechanical Engineering Department, Amirkabir University of technology, 424, Hafez Ave, Tehran Iran (e-mail: amir.moradi@gmail.com).

II. Nomenclature

A_3	Minor diameter area of screw (mm^2)
C	Dynamic load factor (N)
C_0	Static load factor (N)
d	Nominal major diameter of gear (mm)
d_1	Pitch diameter of gear (mm)
D_2	Flank diameter of screw (mm)
d_2	Pitch diameter of pinion (mm)
d_A	Bearing bore (mm)
d_3	Minor diameter of screw (mm)
E	Modulus of elasticity (N/mm^2)
F	Face width (mm)
F_a	Thrust load (N)
F_{rA}	Radial load on bearing A (N)
F_{rB}	Radial load on bearing B (N)
f_s	Motion smoothness index
F_{12}^r	Radial load exerted by the first gear against the second gear (N)
F_{12}^t	Tangential load exerted by the first gear against the second gear (N)
G	Shear modulus (N/mm^2)

W	Robot weight (N)
H_1	Thread depth from base profile (mm)
K_a	Surface factor
K_b	Size factor
K_c	Load factor
K_d	Temperature factor
K_e	Miscellaneous-effects factor
K_f	Fatigue stress-concentration factor
L	Bearing life in million cycles
L_h	bearing life in hours (h)
m	Modulus (mm)
Mt	the exerted torque to the screw (Nm)
n	Motor rotational speed (rpm)
N_1	Number of pinion teeth
N_2	Number of gear teeth
n'	Number of cycles per minute
p	Pitch (mm)
P	Equivalent dynamic load (N)
P_0	Equivalent static load (N)
P_g	Gauge pressure (Pa)
p_n	Standard pressure (101325 Pa)
q_b	Air consumption ($l/\min$)
r	compression ratio
$R_e(R_{p0.2})$	Yield stress
S	Stroke (cm)
S_e	Corrected endurance–limit (Mpa)
S_e'	Endurance–limit (Mpa)
S_{ut}	Ultimate tensile stress (Mpa)
S_y	Yield stress (Mpa)
t	Tooth thickness (mm)
T_{a1}	Torque exerted by shaft a against the first gear
W_t	Section modulus
Y	Lewis form factor
ρ'	Angle of friction (deg)
σ	Bending stress (Mpa)
σ_d	Compression/tension stress (Mpa)
$\sigma_{d,p}$	Allowable compression/tension stress (Mpa)
τ_t	Shear stress (Mpa)
$\tau_{t,p}$	Allowable torsion stress (Mpa)
τ_{tw}	Torsion strength (Mpa)
ϕ	Pressure angle (deg)
φ	Pitch angle (deg)

III. ROBOT DESIGN

This robot prototype has been built in size of 50×20×70 cm and weight of 12 Kg. This prototype climbs 15 cm in each step and it is able to climb the columns with variable diameters (10 to 30 cm). The CAD drawing of robot is shown in (Fig. 1).

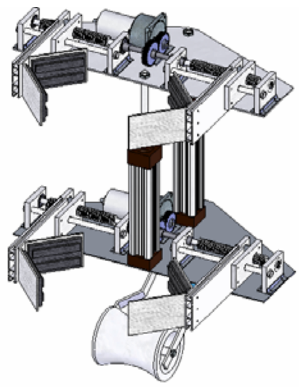

Fig. 1 Schematic view of robot

After choosing the adhesion method, we need two mechanisms to provide enough force for gripping and climbing the column. The gripping force is calculated and after comparing several mechanisms which can produce enough force, the mechanism of power screw is chosen. The mechanism consists of a pair of screws, nuts, guide bars, a 24 Watts DC motor and a 12V off board power supply. A pair of parallel pneumatic jacks is installed between two main stages to move the robot along the column. All the parameters of designing pneumatic parts like pressure and Stroke are considered. An electrical valve for pneumatic jacks and a switch board for electrical motors are used to control the robot but most of the Tests have been done by a manual control. Therefore it is possible to control the robot semi or full autonomous.

IV. KINEMATICS AND MOTION PLANNING

The main locomotion of the robot is the result of three secondary motions. The motion of lower gripper, horizontal axis (spine) and the upper gripper. The sequence of climbing contains the following steps:

First of all the robot should be located on the column while the grippers are open and the jacks are closed, then the lower gripper should be closed while the column is in the middle of the grippers, hence the robot becomes fixed to the column. In the second step the jacks should be open to push up the open upper gripper. The second step is finished by closing the upper gripper (the first and second steps are shown in (Fig. 2)). In the third step the lower gripper gets open while the upper gripper is being closed. Finally the jacks get closed to retract the piston and move up the lower gripper, then the lower gripper gets closed and by opening the upper gripper the robot is ready for the next sequence. During the climbing, a part of the robot is always fixed to the column.

By this motion planning complex dynamic motion equations change into simple static equations.

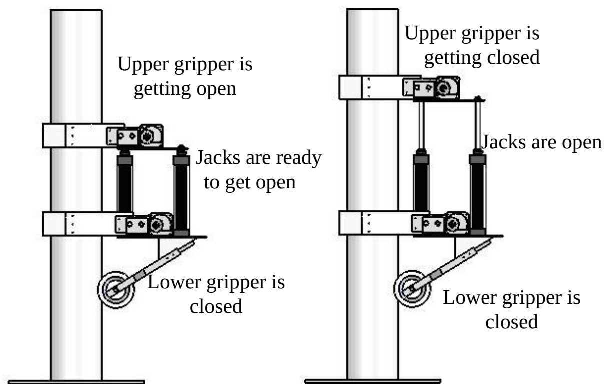

Fig. 2 The first and second steps of climbing

V. Robot Parts

After choosing the suitable mechanisms, we should design all mechanical elements; it means that we should choose geometry and material of the parts according to proper factors of safety and input parameters like velocity of the robot and limitations of the actuators.

A. *The Design of Gears*

Rotational force of the electrical motor transmits to the power screw shaft by two spur gears. Technical specifications of the gears are shown in Table I.

TABLE I
Technical Specification of Gears

m	N_1	N_2	ϕ
1	40	48	20

The force exerted by the first gear against the second gear is calculated in equation (1).

$$d_1 = N_1 \times m \Rightarrow d_1 = 40\ mm \quad \text{(a)}$$
$$d_2 = N_2 \times m \Rightarrow d_2 = 48\ mm \quad \text{(b)}$$
$$T_{a1} = F_{12}^t \times {d_1}/{2} \Rightarrow F_{12}^t = \frac{2\times 1}{0.04} = 50N \quad \text{(c)} \qquad (1)$$
$$F_{12}^r = F_{12}^t \times tg20 = 0.0181\,KN \quad \text{(d)}$$
$$F_{12} = {F_{12}^t}/{\cos 20} = 0.53\,KN \quad \text{(f)}$$

B. *Bending Stress Calculation*

The bending stress is calculated by W. Lewis formula. To drive the basic Lewis equation a cantilever of cross-sectional dimensions F and t, having a length l and a load F_t uniformly distributed across the distance F is assumed. Therefore the bending stress in equation (2) is:

$$\sigma = \frac{6F_t l}{Ft^2} \qquad (2)$$

C. *Dynamic Effect*

Barth equation (3.a) is used to calculate the velocity factor and according to [7] the Lewis form factor is 0.3817 which is used in (3.b). Hence according to (3.c) the bending stress is 13.52 MPa.

$$V = \frac{\pi dn}{60} = \frac{3.14\times 0.04\times 95}{60} = 0.198\ {m}/{s} \quad \text{(a)}$$
$$K_v = \frac{6.1}{6.1+V} = 0.968 \quad \text{(b)} \qquad (3)$$
$$\sigma = \frac{F_t}{K_v fmY} = \frac{50}{0.968\times 10\times 1\times 0.3817} = 13.52\ \text{Mpa} \quad \text{(c)}$$

The motor works with the maximum power at the end stroke of the mechanism. If we assume that all the nominal power converts into torque, bending stress will be 32.47 MPa according to equation (3).

D. *Material Selection Based on Obtaining an Infinite Life*

The material is (HR)AISI 1006 steel, the mechanical properties of this material is shown in Table II.

TABLE II
Material Properties of AISI 1006 Steel

S_{ut} (MPa)	S_y (MPa)
300	170

According to equation (4), the endurance–limit without considering the modifying factors is 151.2 MPa.

$$S'_e = \begin{cases} 0.504\,S_{ut} & S_{ut} \le 1400 Mpa \\ 700 Mpa & S_{ut} > 1400 Mpa \end{cases} \qquad (4)$$

The factors that modify the endurance limit are surface, size, load, temperature and miscellaneous-effects factors. Each of which is intended to account for a single effect. Using this idea we may write equation (5):

$$S_e = K_a K_b K_c K_d K_e\ S'_e = 0.99\times 1.109\times 1\times 1\times 0.735\times 151.2 = 122.01 \qquad (5)$$

To obtain the factor of safety in maximum power consumption we refer to equation (6) and calculate n=3.47.

$$\text{n} = \frac{S_e}{\sigma_{\max}} = \frac{122.01}{32.47} = 3.47 \qquad (6)$$

E. *Design and Selection of the Bearings*

The shaft diameter in the position of the bearing A is 10 mm and in position of the bearing B is 15 mm (Fig. 3).

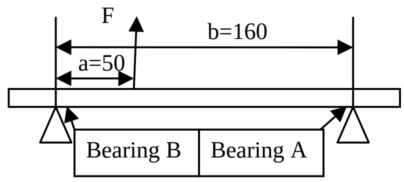

Fig. 3 Schematic drawing of the exerted radial force against the system

According to [8] static and dynamic load factors have been extracted (as shown in Table III and IV).

TABLE III
BEARING A SPECIFICATION

Bearing A(63 Series spherical bearing)		
$d_A(mm)$	$C_0(N)$	$C(N)$
10	4×10^3	7×10^3

TABLE IV
BEARING B SPECIFICATION

Bearing B (603 Series spherical bearing)		
$d_A(mm)$	$C_0(N)$	$C(N)$
15	2×10^3	3.5×10^3

To calculate the bearing loads, the critical situation has been studied. This situation happens when the robot is clamped to the column by its grippers; thus, the robot weight is exerted to the bearings. According to the symmetry of the gripper system it can be inferred that each set of the power screw and its bearings bear half of the robot weight. (Fig. 3) shows the exerted radial force to the shaft. Because of the accelerated movement and the jack impacts some extra forces are exerted to the robot. As a result, for safety in the equation (7) a larger force is used in calculations.

$$F = \frac{W}{2} \times n \xrightarrow{n=2, W=12\ Kg} F = 120\ N \quad (7)$$

According to (Fig. 3) the radial loads on bearing B and A are calculated by torque and force equilibriums (equation 8).

$$F_{rB} = \frac{F \times (b-a)}{b} = 82.5 \quad \text{(a)}$$
$$F_{rA} = F - F_{rB} = 37.5\ N \quad \text{(b)} \qquad (8)$$

Bearing A is fixed on the shaft; thus, the thrust load is added to the radial load on bearing A. Bearing B only carries the radial load. The thrust load on the power screw is $F_a = 465\ N$.

F. Calculation of the Bearing Life and Motion Smoothness

For bearing A coefficients X, Y, X_0, Y_0, e have been extracted from [8] and equations (9.a, 9.b).

$$\frac{F_a}{C_0} = 0.116 \Rightarrow e = 0.32 \quad \text{(a)}$$
$$\frac{F_a}{F_{rA}} = \frac{465}{37.5} = 12.4 \Rightarrow \frac{F_a}{F_{rA}} > e \Rightarrow \quad \text{(b)}$$
$$X = 0.56 \quad , \quad Y = 1.38$$
$$P = XF_r + YF_a \Rightarrow 0.56 \times 37.5 + 1.38 \times 465 = 662.7 \quad \text{(c)}$$
$$P_0 = X_0F_r + Y_0F_a \Rightarrow 0.6 \times 37.5 + 0.5 \times 465 = 255$$
$$L = \left[\frac{C}{P}\right]^3 \quad , \quad C = 7\times10^3 \quad \Rightarrow \quad \text{(d)} \qquad (9)$$
$$L = \left[\frac{7\times10^3}{662.7}\right]^3 = 1178.5$$
$$L_h = \frac{L \cdot 10^6}{60n} \quad , \quad n = 95\left[\min^{-1}\right] \Rightarrow \quad \text{(e)}$$
$$L_h = \frac{1178.5\times10^6}{60\times95} = 206760 \quad [h] \quad \text{(f)}$$

Equivalent static and dynamic loads according to equations (9.c, 9.d) and the bearing life in hours and million cycles according to equations (9.e, 9.f) have been calculated.

Considering the bearing life in equation (9.f) and the table of bearing-life recommendations for various classes of machinery in [8], bearing A is able to work continually by high factor of safety. In addition, according equation (10) motion smoothness in bearing A is very good.

$$f_s = \frac{C_0}{P_0} \Rightarrow f_s = \frac{4\times10^3}{255} = 15.7 \quad (10)$$

For bearing B, equivalent static and dynamic loads in equations (11.a, 11.b) and the bearing life in hours and million cycles in equations (11.c, 11.d) have been calculated.

$$P = F_{rB} = 82.5 \quad N \quad \text{(a)}$$
$$P_0 = F_{rB} = 82.5 \quad N \quad \text{(b)}$$
$$L = \left[\frac{C}{P}\right]^3 \quad , \quad C = 9\times10^3 \quad \Rightarrow \quad \text{(c)}$$
$$L = \left[\frac{3.5\times10^3}{82.5}\right]^3 = 76356 \qquad (11)$$
$$L_h = \frac{L \cdot 10^6}{60n} \quad , \quad n = 95\left[\min^{-1}\right] \Rightarrow \quad \text{(d)}$$
$$L_h = \frac{76356\times10^6}{60\times95} = 13395762 \quad [h]$$

Considering the calculated life in equation (11.d) and the table of experimental life in mechanical systems in [8], bearing B is able to work continually by high factor of safety. In addition, according to equation (10) motion smoothness is very good.

G. Design and Selection of the Power Screws and Nuts

According to the negligible loads and to lighten the robot, aluminum (G-Al Si 12) with the following specification has been used (Table V).

TABLE V
MATERIAL SPECIFICATION OF ALUMINUM (G-AL SI 12)

G	E	τ_{tw}	R_e
27E4	7E4	40	70

Considering our limitations in manufacturing, a screw with the following specification (Table VI) was chosen.

TABLEVI
SPECIFICATION OF THE SELECTED SCREW

A_3	$H_1 = 0.5\times p$	d_3	D_2	p	d
189	2	15.5	18	4	20

The friction angle in dry friction condition is 12º and the exerted torque to the screw is 1.2 N.m . Pitch angle in equation (12.a) and the maximum thrust load in equation (12.b) are calculated.

$$\tan\varphi = \frac{P}{d_2\pi} = \frac{4}{18\pi} \Rightarrow \varphi \approx 4^\circ \quad \text{(a)}$$
$$T = M_t = F \times \frac{D_2}{2} \times \tan(\varphi \pm \rho') \xrightarrow{T=1.2} F \approx 465\ N \quad \text{(b)} \qquad (12)$$

According to equation (13) allowable compression/tension stress and compression/tension stress are calculated.

$$\sigma_{d,p} = \frac{R_e}{1.5} \quad \text{(a)}$$
$$\sigma_d = \frac{F}{A_3} = \frac{465}{189} \approx 2.5 \quad \leq \sigma_{d,p} \quad \text{(b)} \qquad (13)$$

The compression stress is so negligible that there is no need to be compared with the allowable stress.

According to equation (14.a) allowable torsion stress is calculated. Calculation of the section modulus is according to equation (14.b) and torsion stress is calculated by equation (14.c).

$$\tau_{t,p} = \frac{\tau_{tw}}{2} \quad \text{(a)}$$
$$W_t = 0.2 d_3^{\ 3} = 744.775 \quad \text{(b)} \qquad (14)$$
$$\tau_t = \frac{M_t}{W_t} = \frac{1200}{744.775} = 1.61 \leq \tau_{t,p} \quad \text{(c)}$$

The torsion stress is so negligible that there is no need to be compared with the allowable stress.

H. Calculation of Nut Length

Allowable pressing pressure according to the material of the screw and nut from the table of Allowable pressing pressures in [9] is 10 Mpa; thus, the length of the nut is calculated in equation (15).

$$\frac{F \cdot P}{p_p \cdot D_2 \cdot \pi \cdot H_1} < l_1 < 2.5d \Rightarrow 1.64 < l_1 < 50 \Rightarrow l_1 = 29mm \qquad (15)$$

As the grippers should be self-locked, the condition of self-locking according to equation (16) is studied.

$$\varphi = 4° \text{ and } \rho' = 12° \Rightarrow \varphi < \rho' \qquad (16)$$

VI. Fabrication and Assembly

The most important part from the assembly point of view is the gripper system. The rotational force transmits to the power screw shaft by two spur gears as shown in (Fig. 4). A bearing is assembled on the each side of the shaft.

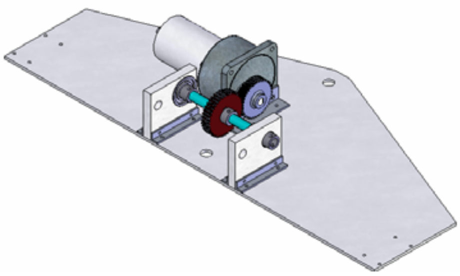

Fig. 4 Transmitting the rotational force from the electrical motor to the power screw shaft

There are two power screws along the shaft and a bearing at each end of the screw. Aluminum cubic square parts are used for mounting the bearings. All the gripper parts are screwed to the base plate by equal leg angle beams.

We need a guide to keep the arms of the gripper parallel while the mechanism of the gripper is opening or closing the arms. Therefore a silver rod used as a guide. As shown in (Fig. 5) the silver rod is parallel with the power screw.

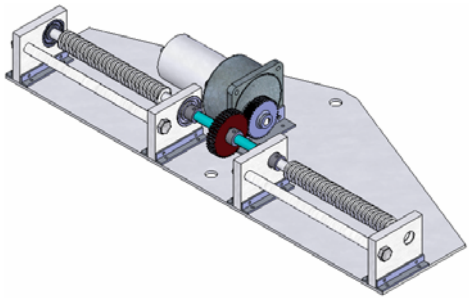

Fig. 5 Assembling silver rod as a guide

The arm of the robot consists of a power nut, a linear bushing and the arm of the gripper as shown in (Fig. 6).

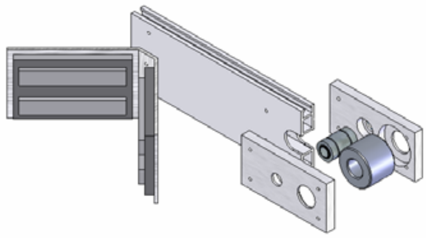

Fig. 6 Components of the robot arm

The screw should be parallel with the silver rod and it is the most important point in this mechanism, otherwise the mechanism is locked. Some special rubber strips are stuck on the V shape gripper to increase the friction.

VII. Auxiliary Mechanism

The arm of the robot is not completely rigid, in addition the friction layers of the gripper are elastic; hence, the robot tilts while climbing the column as shown in (Fig. 7). It is necessary to exert an upward force to prevent tilting.

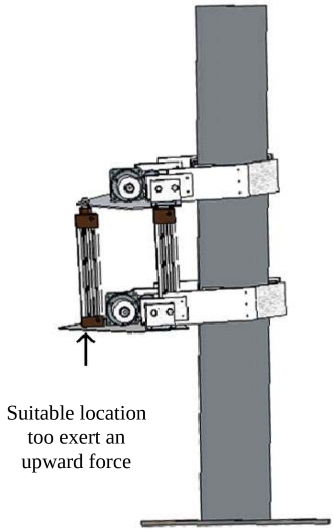

Fig. 7 Suitable location to exert an upward force

For this reason another mechanism was designed and assembled to the lower gripper system of the robot. This mechanism consists of an adjustable arm which exerts an upward force to the farthest point of the robot from the column as shown in (Fig. 8).

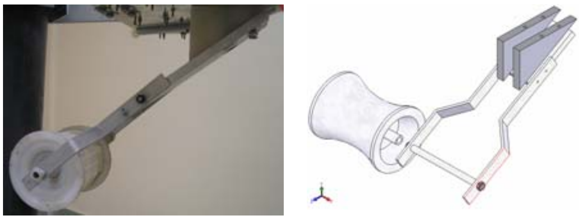

Fig. 8 Auxiliary mechanism

VIII. Pneumatic Supply

A. Demand Air Pressure

The critical case in the jacks movement is when the most massive parts move. When the lower gripper system and its equipments move up the maximum weight of 10 Kg should be carried by the jacks. Concerning the diameter of the jacks (32 millimeters) the demand pressure according to equation (17) is 1.2 bar.

$$W = M \times g \Rightarrow 10\ Kg \times 9.8 = 98\ N \quad \text{(a)}$$
$$A = \pi(\frac{D}{2})^2 \Rightarrow A = \pi \times \left(\frac{32\times10^{-3}}{2}\right)^2 \approx 8\times10^{-4}\ m^2 \quad \text{(b)} \qquad (17)$$
$$W = P \times A \Rightarrow P = 1.2 \quad bar \quad \text{(c)}$$

B. Air Consumption

In order to provide the demand air, knowing the air consumption is important. By knowing the operational pressure, diameter and stroke of the jacks, compression ratio and air consumption can be calculated by equation (18). The calculated air consumption is the total consumption of two jacks [10].

$$r = \frac{p_n + p_g}{p_n} = 2.184 \quad \text{(a)}$$
$$q_b = [s \times n' \times \frac{D^2 \times \pi}{4} + s \times n' \times \frac{(D^2 - d^2)\times \pi}{4}] \times r \quad \text{(b)} \qquad (18)$$
$$\Rightarrow q_b = 15.68 \quad l/\min$$

The demand air for this prototype is supplied by a compressor and the proper air pressure is adjusted by a pressure regulator. The jacks are controlled by an electrical control valve.

IX. Experiments

After manufacturing the prototype, a PVC pipe was used as a column. Considering our limitations in manufacturing, the climbing speed is about 2 centimeters per second. The installation time on the column is maximally 8 seconds. The exerted force to the column by grippers is 400N. (Fig. 9) shows the picture of the built prototype.

Fig. 9 Photo of the koala robot climbing on a column

X. Conclusions and Further Work

Experiments show the robot was able to climb up and down a column with various diameters according to the climbing strategy. Further work on the robot will be concentrated on several fronts. One is using lighter and better mechanical parts. For instance, to improve the speed and power of the robot, it is possible to use ball screws, linear and pneumatic actuators. Another improvement is automating the robot by an autonomous control unit.

References

[1] R.T. Pack, J.L. Christopher, and K. Kawamura, *"A Rubber actuator-Based Structure-Climbing Inspection Robot"*, Proceedings of the IEEE International Conference on Robotics and Automation, 1997, pp. 1869-1874.

[2] A. Nagakubo and S.Hirose, *"Walking and running of the quadruped wall-climbing robot"*, Proceedings of the IEEE International Conference on Robotics and Automation, 1994, pp. 1005-1012.

[3] H.R. Choi, S.M. Ryew, T.H. Kang, J.H. Lee, and H.M. Kim, *"A wall climbing robot with closed link mechanism"*, Proc. Of the Intelligent Robotic Systems Conference, 2000, pp. 2006-2011, vol. 3.

[4] L. Shuliang, Z. Yanzheng, G. Xueshan, X. Dianguo, and W. Yan, *"A wall climbing robot with magnetic crawlers for sand-blasting. Spray-Painting and Measurement"*, High Technology Letters, 2000, pp 86-88, vol. 10.

[5] C. Menon, M. Murphy, and M. Sitti, *"Gecko Inspired Surface Climbing Robots"*, IEEE International Conference on Robotics and Biomimetics (ROBIO), Shenyang, China, 2004.

[6] DT Pham, and Wilfred B. Heginbotham, *"Robot Grippers"*, 1986.

[7] J.E.Shigley, C.R.Mischke, *"Mechanical Engineering Design"*, New York: McGraw-Hill, 2007.

[8] DIN 616, 1993

[9] DIN 103,1977

[10] Andrew Parr,. "Hydraulics and Pneumatics", Butterworth- Heinemann , 1999.