Conceptual Design and Analysis of Pipe Climbing Robot

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Abstract: Robotics is one of the most emerging technologies in the current scenario. In this fast-growing technological world automation through robotics finds its place in almost all the fields. Climbing robots became more popular due to their versatile applications like inspection of tall buildings, tanks, structures, facade cleaning, fruits harvesting on tall trees (coconut) and many more. It became most adaptive as working on height may lead to dangerous incidents for human beings. Operations like visual inspection, crack detection of tall structures and pipes can be made possible with specially designed pipe climber robot. It finds its applications where human cannot reach, like hazardous applications. Specially design robots for a specific application also performs well with precision. This paper presents the novel design and analysis of pipe climbing robot for Chemical plant pipeline fault and leakage detection purpose. Design of all components of the robot is done with the basic mathematical consideration and then its analysis is carried out using FEA tools and MATLAB. Results of Forward and Inverse kinematic analysis of robot are obtained for certain specific points of trajectory. Dynamic analysis has been performed for motor selection and torque calculation. Presented conceptual design and analysis can be useful for pipe inspection purpose.

Keywords: Climbing Robots; Pipe climbers; inspection

1. Introduction

Technological development in last 3 decades motivated human beings to find alternative ways of doing work. Automation through robotics is the choice of most of the industries now a days. In the field of robots, the climbing robots are the emerging technology. [1][2] Tall Buildings, structures, overhead chemical tanks, light poles, big monuments, statues are the places where visual inspection, crack and corrosion detection and cleaning has become a most crucial problem for human being due to non-availability of skilled manpower and safety issues. For such repetitive and periodic application climbing robots’ deployment on field is the safe, best suited, cost effective and efficient solution. For this purpose an exhaustive literature survey is carried out and design and analysis of pipe climbing, façade cleaning, tank inspection, crack detection, coconut tree climber robots are studied [3]–[11]. Majority of the literature are based on the special purpose application robots intended to perform certain desired task [12]–[14]. Also, majority of the tall structure has frame, pipe or pillar type attachments that can be utilize as a support for climbing up and move down. This paper presents the conceptual design and analysis of a pipe climber robot for inspection of pipes for chemical process industry. As the objective of the work focus on the specific application of inspection of chemical pipes an exhaustive literature review is conducted which highlights the gap that no pipe climber design
available in literature is directly applicable [15-18]. Based on the specification of pipeline network a compact gripping device and climbing device are required to design. Literature highlighting grippers indicate magnetic, adhesive, vacuum type, mechanical and many more [19-20]. As application requirement is to detect leakage detection in pipe magnetic, adhesive and vacuumed grippers may not give satisfactory performances while operating on the wet and dry surfaces both. Mechanical grippers with a layer of friction material on the contact surfaces is designed for ensuring firm grip between robot and pipe. It is also required to collect the information for dimensions and structures of pipeline network based on which primary specification of robot can be decided [21]. Considering primary specifications as cylindrical pipe of diameter ranging from 3 cm to 10cm a pipe climber robot is designed with basic mathematical steps. Gripper for holding a pipe is required to design. A gripper design literature survey is also done [22]-[28]. Static structure analysis of the components is performed in Ansys. Design and analysis of climbing robot with gripper are presented in section 2 of this paper. Forward and Inverse kinematic analysis is performed in MATLAB for certain specific points of trajectory on the pipe surface (Included in section 3). Dynamic analysis is also done for torque calculations and based on that selection of motors can be done. Singularity and degeneracy of the robot is checked and results shows that the design of robot is capable of climbing up on the pipe satisfactorily. (Section 4) Discussion on the pros and cons of the proposed design and concluding remarks are included in section 5 and 6.

2. Conceptual Design of Pipe climbing robot

Design of a pole climber robot is done with basic mathematical considerations. It is required to collect certain primary information like range of diameter of pipes in chemical plant, its material characteristics and space availability between the network pipes in which the robot has to move. Here a robot gripper is designed can hold pipe diameter Ranges from 3cm to 10cm, Pipe material steel is taken [29]. 3D Model of robot and gripper shows self-weight of a robot approximately 3kg, the payload of visual inspection system 0.8 kg [30]. Design of all components of the robot link and grippers are done manually and its modelling is done in solid works. Analysis of the same is carried out using ANSYS.

Design of link is based on the consideration that three such link with three revaluate joints are attached together and two grippers attached at two ends. If the maximum step size of 30 cm while climbing up on the pipe, then maximum length of each link is considered as 20 cm. With the basic load calculation, its width and thickness are calculated. Being main member of robot, link is designed and modeled in solid works and considering motor weight 0.7 kg analysis is performed and results shows stress on links came within the safe limits as shown in figure 1 and 2. Then its Conceptual design is done using solid works as shown in figure 3.

![Figure 1. Design of Link.](image-url)
A robust design of a holding device is required as it is the main gripping member of the robot. Gripper is designed to hold pipe diameter ranging from 3 cm to 10 cm. Coating of high friction material is done at inner surface of the plates for holding pipe. Considering pipe reaction and co-efficient of friction as 0.6, force analysis is carried out and reaction exerted on each plate is calculated as 85 and 170 N as shown in the figure 4.

Force required to exert on each plate is calculated as

\[ F = 85 + 170 \times \cos 45 + \frac{170 \times \sin 45}{u} = 405 \text{ N} \]  

(1)

Linear force required to exert is \( F' = 600 \text{ N} \)

Width of the plate = 3cm (as Min. diameter required to clamp is 3cm) and thickness of the plate is taken as 1 mm. Dimensions of Links, Length of the link-1 = 70mm, Width of the link = 5mm and Height of the link = 25mm. (Height to width ratio assumed as 5) For operating gripper a lead screw is selected based on gripping force required, pitch and torque.

- Force required to exert = 600N
- Efficiency of lead screw = 90%
- Pitch of the lead screw = 2mm
Required torque,
\[ T = \frac{16 \cdot F}{2 \cdot 3.14 \cdot p \cdot \text{Efficiency}} = 0.4 \text{Nm} \]  \hspace{1cm} (2)

Solid works model and its analysis results are shown in figure 5 and 6. In order to ensure proper grip the inner surfaces of the gripper are to be covered with high friction cotton paddings. While analysis that cotton padding layer is also considered. Results shows that forces on the surface of the gripper are within the limits and can withstand the mention loadings.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{gripper_conceptual.png}
\caption{Conceptual design of gripper.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{gripper_force_analysis.png}
\caption{Force analysis of gripper.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{robot_assembly.png}
\caption{Assembly of a robot.}
\end{figure}
Figure 7 shows assembly of a robot with two grippers. Each gripper is a two-jaw gripper can open and close with a leadscrew. Gripper-1 opened and loses the contact with the pipe and body of robot stretches and moves ahead climb upon the pipe. Gripper -2 is holding the pipe at that time. Gripper-1 hold the new advanced position on pipe, then gripper-2 actuates and advances on the pipe. This sequential actuation helps in achieving desired movement of a robot on the pipe. Fig 8 shows the extended vertical view of a robot.

3. **Forwards and Inverse Kinematic analysis for specific Trajectory Points**

In order to have smooth motion of a robot, variation of the joint torque should be gradual. There should not abrupt changes in the value of the torque. Therefore, variation of the joint angle should be in smooth manner. A Trajectory planning is required to find the value of joint angle, its first order derivative angular velocity and second order derivative angular acceleration. As the motor is controlled in joint-space, for trajectory generation joint-space consideration is taken. For the smooth variation of the angle, cubic polynomial is selected as trajectory function. Considering initial conditions,

At \( t = t_i \), \( \theta = \theta_i \) and \( \omega = 0 \). At \( t = t_f \), \( \theta = \theta_f \) and \( \omega = 0 \).

Applying Cubic polynomial,

\[
\theta(t) = C_0 + C_1 t + C_2 t^2 + C_3 t^3
\]

\[
\omega(t) = C_1 + 2C_2 t + 3C_2 t^2
\]

(3)

solving the same will get,

\[
\theta(t) = \theta_i + \frac{(3(\theta_f - \theta_i)t_2)}{t_f} - \frac{(2(\theta_f - \theta_i)t_3)}{t_f}
\]

(4)

\[
\omega(t) = \frac{(6(\theta_f - \theta_i)t_2)}{t_f} - \frac{(6(\theta_f - \theta_i)t_3)}{t_f}
\]

(5)

\[
\alpha(t) = \frac{(6(\theta_f - \theta_i))}{t_f} - \frac{(12(\theta_f - \theta_i)t)}{t_f}
\]

(6)

For the straight climbing, limits of angular displacements of 3 joints are considered as,

\( \theta_1 = -90 \) to \( 90 \), \( \theta_2 = -90 \) to \( 90 \) and \( \theta_3 = -90 \) to \( 90 \)

Based on that kinematic parameter for cubic polynomial were obtained as show in figure 7.
As shown in figure 9, acceleration would be increase linearly with respect to time which causes smooth movement of angular joint.

3.1 Kinematics

Robot kinematic analysis requires for identifying all joint angles and end effector positions. Direct or forward kinematics results the position of the end effector in universal coordinate system for the given value of the joint angles, and Inverse kinematics gives all possible value of joint angle for the given location of the end effector. Frame assignment for the 3 degrees of freedom RRR robot is as shown in figure 8. For joint-space configuration forward and inverse kinematics were performed as follows.

3.1.1 Forward or Direct Kinematics. Coordinate system has been assigned to each joint and coordinates for them with respect global coordinates are as below. Robot co-ordinate frames for chosen RRR Configuration is as shown in figure 10.

![Articulated (RRR) arm frame configuration.](image)

**Figure 10.** Articulated (RRR) arm frame configuration.

**Table 1.**

| Frame | α | A   | D | Θ  |
|-------|---|-----|---|----|
| 1     | 0 | L₃  | 0 | 0  |
| 2     | 0 | L₂  | 0 | θ₁ |
| 3     | 0 | L₁  | 0 | θ₂ |
| 4     | 0 | L₄  | 0 | θ₃ |
Transformation matrix,

\[ T_{01} = \begin{bmatrix} 1 & 0 & 0 & L1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]

\[ T_{12} = \begin{bmatrix} \cos(\theta_1) & -\sin(\theta_1) & 0 & L_2 \\ \sin(\theta_1) & \cos(\theta_1) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]  

\[ T_{23} = \begin{bmatrix} \cos(\theta_2) & -\sin(\theta_2) & 0 & L_3 \\ \sin(\theta_2) & \cos(\theta_2) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]  

\[ T_{34} = \begin{bmatrix} \cos(\theta_3) & -\sin(\theta_3) & 0 & L_4 \\ \sin(\theta_3) & \cos(\theta_3) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]  

\[ T_{04} = T_{01} * T_{12} * T_{23} * T_{34} \]

\[ \begin{bmatrix} \cos(\theta_1 + \theta_2 + \theta_3) & -\sin(\theta_1 + \theta_2 + \theta_3) & 0 & L_4 * \cos(\theta_1) + L_1 \\ \sin(\theta_1 + \theta_2 + \theta_3) & \cos(\theta_1 + \theta_2 + \theta_3) & 0 & L_4 * \sin(\theta_1) + L_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]  

3.1.2 Inverse kinematics. Inverse kinematics gives the values of joint variables for the given pose. The equations of X and Y coordinates are non-linear and has to be solved by numerical method. LMA algorithm is used to solve the equation by considering the joint limits of -90° to 90° as parameters. With the given joint limits, unique solution is obtained.

4. Dynamic Analysis

Purpose of the dynamics is to determine amount of force or torque required for the movement. There is two approaches for the dynamics: Forward dynamics and Inverse dynamics. Forward dynamics gives the value of angular displacement, velocity and acceleration for the given joint torque. Inverse dynamics gives the value of torque for the given angular displacement, velocity and acceleration. Calculation of the torque is done using Lagrange approach. Lagrange is the difference between the energies associated with in the system. i.e. kinetic energy and potential energy of all the links.

\[ L = KE - PE \]

Where, KE = Kinetic energy of all the link

PE = Potential energy of all the link
Torque for the ith link can be found out by equation

\[ T_i = \frac{d}{dt} \left( \frac{\partial L}{\partial \omega_i} \right) - \frac{\partial L}{\partial \theta_i} \]  \hspace{1cm} (9)

Calculation and derivation of formula for torque is done using MATLAB software and subsequent plots are shown in figure 9.

Motor Torque-1  
Motor Torque-2  
Motor Torque-3  

**Figure 11. Motor Torque Plots.**

Dynamic analysis result outcome for all the positions were obtained using MATLAB. Figure 11 shows torque variations for all the three motors. It shows that maximum torque exerted to be 5 Nm. Considering higher factor of safety torque of 30Nm is taken for the calculation of gripper.

5. Discussion

Preventative maintenance of plant equipment’s is of prime requirement to prevent dangerous accidents and to safeguard man and machinery. One of the such sector is chemical industries. It’s a process industry where there is a huge pipeline network exist. In certain situation pipelines carries hazardous fluids inside. For the purpose of preventive maintenance, it is necessary to detect leakage and cracks in the pipelines. It is desired to have an inspection robot to identify defects and faults in pipe equipped with a desired vision system to detect faults and can be accommodated within the available space of tower networks. Design and analysis of a pipe climber robot is carried out in solid works and ANSYS. Specifications of the designed robot is as shown in Table -2.

**Table 2. specification of a robot and gripper.**

| Specification of a robot and Gripper |  |
|-------------------------------------|---|
| Robot configuration | RRR (Three revolute joint) |
| Degrees of freedom | 3 |
| Dimensions of each link | 20mm length x 10mm width x 4mm thickness |
| Two jaw gripper | Made up of joining two plates. |
| Plate dimensions | 20mm length x 4.5mm width x 2mm thickness |
| Thickness of cotton padding inside gripping plate | 1.5 mm |
| Holding capacity (completely closed jaws) | Min 3 mm diameter pipe |
| Holding capacity (completely opened jaws) | Max 10 mm diameter pipe |
| Lead screw | Open and close the gripper |
| Overall dimensions in vertical position. | 90 mm height x 20mm width x 20mm depth. |
After the design is over it is necessary to know all joint link parameters. Forward kinematics is carried out for certain trajectory points. Inverse kinematic analysis is also performed and in order to get motor specification its Dynamic analysis is also carried out. Analysis of newly designed robots arrived at a motor torque value as 5 Nm. That shows that for each joint motor requires is based on the maximum torque out come of each individual motor i.e 5 Nm.

6. Conclusions

Climbing robots finds their application in many fields now a days. Wall climber, building climber robots gain popularity for comfort and safe operations performances. Here a Pipe climber robot is designed and analysed, that can perform inspection of pipes of a chemical process industry. Conceptual design of a pole climber robot with gripper is done with basic mechanical considerations and then its analysis is carried out. Design of each component of the pipe climber robot is done and static structure analysis is performed. Analysis results based on loading condition shows that the deformation is under safe limits. Forward and inverse kinematics for specific trajectory points is done in MATLAB and then for selection of motor, dynamic analysis is also performed. Based on the results of analysis it is clear that the proposed design gives satisfactory performance. In future algorithms and gait planning for autonomous climbing robot can be explored. Also, dynamic stability is an important aspect and can be studied further,

References

[1] N. Melenbrink, J. Werfel, and A. Menges, “On-site autonomous construction robots: Towards unsupervised building,” Autom. Constr., vol. 119, no. June, p. 103312, 2020, doi: 10.1016/j.autcon.2020.103312.

[2] “Spm Pole climber.” https://sites.google.com/site/fsrlabisr/research/climbing-robots (accessed Sep. 08, 2020).

[3] R. Wang and Y. Kawamura, “A magnetic climbing robot for steel bridge inspection,” Proc. World Congr. Intell. Control Autom., vol. 2015-March, no. March, pp. 3303–3308, 2015, doi: 10.1109/WCICA.2014.7053262.

[4] W. Fischer et al., “Magnetic Wall Climbing Robot for Thin Surfaces with Specific Obstacles To cite this version : HAL Id : inria-00194494 Magnetic Wall Climbing Robot for Thin Surfaces with Specific Obstacles,” 2007.

[5] F. Wang, Y. Liu, and L. Guo, “Modeling and Steady Holding Strategy of a Climbing Robot,” vol. 86, no. Eame, pp. 321–325, 2017, doi: 10.2991/eame-17.2017.76.

[6] A. Albagul, A. Asseni, and O. Khalifa, “Wall climbing robot: Mechanical design and implementation,” Int. Conf. Circuits, Syst. Signal Telecommun. - Proc., no. June, pp. 28–32, 2011.

[7] A. Prakoso and R. Sriwijaya, “Design of climbing robot’s structure inspired by papilio memnon caterpillar,” Proc. - 2017 7th Int. Annu. Eng. Semin. Ina. 2017, vol. 00, pp. 17–20, 2017, doi: 10.1109/NAES.2017.8068559.

[8] J. Liu, F. Hu, H. Wang, and J. Chen, “Calculation and Analysis of The Safety of Pressure Vessel Wall Climbing Robot,” no. Iccse, pp. 1–8, 2016, doi: 10.2991/icse-16.2016.1.

[9] M. F. Silva, J. A. Tenreiro Machado, and J. K. Tar, “A Survey of Technologies for climbing robots adhesion to surfaces,” ICCC 2008 - IEEE 6th Int. Conf. Comput. Cybern. Proc., no. June 2014, pp. 127–132, 2008, doi: 10.1109/ICCCYB.2008.4721392.

[10] W. Shen, J. Gu, and Y. Shen, “Permanent magnetic system design for the wall-climbing robot,” IEEE Int. Conf. Mechatronics Autom. ICMA 2005, vol. 3, no. 3, pp. 2078–2083, 2005, doi: 10.1155/2006/143256.
[11] W. Dong, H. Wang, Z. Li, Y. Jiang, and J. Xiao, “Development of a wall-climbing robot with biped-wheel hybrid locomotion mechanism,” IEEE Int. Conf. Intell. Robot. Syst., pp. 2333–2338, 2013, doi: 10.1109/IROS.2013.6696683.

[12] I. Maurtua et al., “MAINBOT - Mobile robots for inspection and maintenance in extensive industrial plants,” Energy Procedia, vol. 49, pp. 1810–1819, 2014, doi: 10.1016/j.egypro.2014.03.192.

[13] C. Menon and M. Sitti, “Biologically inspired adhesion based surface climbing robots,” Proc. - IEEE Int. Conf. Robot. Autom., vol. 2005, no. April, pp. 2715–2720, 2005, doi: 10.1109/ROBOT.2005.1570524.

[14] K. Zhang, Y. Chen, H. Gui, D. Li, and Z. Li, “Identification of the deviation of seam tracking and weld cross type for the derusting of ship hulls using a wall-climbing robot based on three-line laser structural light,” J. Manuf. Process., vol. 35, no. August, pp. 295–306, 2018, doi: 10.1016/j.jmapro.2018.08.014.

[15] N. Melenbrink, J. Werfel, and A. Menges, “On-site autonomous construction robots: Towards unsupervised building,” Autom. Constr., vol. 119, no. June, p. 103312, 2020, doi: 10.1016/j.autcon.2020.103312.

[16] “Spm Pole climber.” https://sites.google.com/site/fsrlabisr/research/climbing-robots (accessed Sep. 08, 2020).

[17] B. Zhang, Y. Xie, J. Zhou, K. Wang, and Z. Zhang, “State-of-the-art robotic grippers, grasping and control strategies, as well as their applications in agricultural robots: A review,” Comput. Electron. Agric., vol. 177, no. April, p. 105694, 2020, doi: 10.1016/j.compag.2020.105694.

[18] C. Luo, Y. He, and S. Abubakar, “Solving Inverse Kinematics of the Shotcrete Manipulator Based on the Plane Two-Link Model and Trajectory Planning,” vol. 2020, 2020.

[19] M. Shim and J. H. Kim, “Design and optimization of a robotic gripper for the FEM assembly process of vehicles,” Mech. Mach. Theory, vol. 129, pp. 1–16, 2018, doi: 10.1016/j.mechmachtheory.2018.07.006.

[20] L. Birglen and T. Schlicht, “A statistical review of industrial robotic grippers,” Robot. Comput. Integr. Manuf., vol. 49, no. June 2017, pp. 88–97, 2018, doi: 10.1016/j.rcim.2017.05.007.

[21] “Opis petrochemwire.”

[22] IaiAURLhttp://www.intelligentactuator.com/partsearch/robocylinder/appndx74_Model_Selection_by_RCP2_Gripper.pdf

[23] A. Müller, M. Aydemir, A. Glodde, and F. Dietrich, “Design Approach for Heavy-Duty Soft-Robotic-Gripper,” Procedia CIRP, vol. 91, pp. 301–305, 2020, doi: 10.1016/j.procir.2020.02.180.

[24] B. C. Widanagamage, T. N. Gallege, S. Salgado, and J. Wijayakulasooriya, “Treebot: an autonomous tree climbing robot utilizing four bar linkage system,” Res. Symp. Eng. Adv., vol. 240, pp. 181–185, 2014.

[25] M. Shim and J. H. Kim, “Design and optimization of a robotic gripper for the FEM assembly process of vehicles,” Mech. Mach. Theory, vol. 129, pp. 1–16, 2018, doi: 10.1016/j.mechmachtheory.2018.07.006.

[26] S. Zodey and S. K. Pradhan, “Matlab toolbox for kinematic analysis and simulation of dexterous robotic grippers,” Procedia Eng., vol. 97, pp. 1886–1895, 2014, doi: 10.1016/j.proeng.2014.12.342.

[27] A. Hassan and M. Abomoharam, “Modeling and design optimization of a robot gripper mechanism,” Robot. Comput. Integr. Manuf., vol. 46, no. July 2016, pp. 94–103, 2017, doi: 10.1016/j.rcim.2016.12.012.

[28] L. Birglen and T. Schlicht, “A statistical review of industrial robotic grippers,” Robot. Comput.
Integr. Manuf., vol. 49, no. June 2017, pp. 88–97, 2018, doi: 10.1016/j.rcim.2017.05.007.

[29] N. Gas et al., “Corrosion / Coatings Ceramic Membranes, Preparation, Properties, and Investigation on CO2 Separation 26th European Symposium on Computer-Aided Process Engineering Biogas and Syngas Upgrading Natural Gas Dehydration and Mercaptans Removal Proceedings of the 8th International Conference on Foundations of Computer-Aided Process Design,” pp. 2018–2020, 2018.

[30] “vision inspection system.” https://www.visco-tech.com/english/application/.