DESIGN AND DEVELOPMENT OF PROTOTYPE MOBILE ROBOT FOR IDENTIFICATION OF DEFECTS IN PIPELINES

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The development of a fully autonomous pipelines inspection system requires design of a robot equipped with the required sensors. In this paper, it is designed a robot with suitable four bar mechanism that can give two linear motions one forward and another backward and carry a camera to capture the picture of defects if any in pipe lines. This self configurable robot has six powered wheels (rollers) chains with three belts and each wheel chain is operated by a micro DC motor. The new wheel chain mechanism is foldable by using a threaded rod. Using this foldable mechanism, a small-sized robot whose external diameter is 180 mm is designed. The velocity and acceleration analysis of each link is calculated for four bar mechanism. Validity of this new foldable wheel chain mechanism is proved through dynamic simulation. Based on this, the stiffness of the torsion threaded rod and the actuator size of DC motors are decided and a prototype of the pipeline inspection robot system is developed. It consists of a main body made from aluminum material and main DC motor and 6 micro DC motors to give motion to six rollers.

Keywords: Autonomous, Pipe inspection, Microcontroller, Obstacle sensor, GSM modem

INTRODUCTION

Autonomous pipe inspection method is introduced to improve the inspection efficiency by reducing the time and manpower in the inspection process. An autonomous robot can act on their own, independent of any controller. Many pipeline inspection robot systems have been developed and have been used in many areas to replace the human efforts. Specially, pipeline maintenance is challenging area for which robots can be employed. Industrial robots are very familiar to most type of industries since their capability to provide services or perform their job that human cannot make it in such a hazardous and dangerous environment. Robots also offer some

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advantages in maneuverability with the ability to adapt in-pipe unevenness, move vertically in pipes, and stay stable without slipping in pipes. A very important design objective is adaptability of the in-pipe robots to the inner diameters of the pipes.

**SELECTION OF MATERIAL**

The materials used for prototype robot are light and rigid. Different materials are used for different parts of the robot. Aluminum is chosen for the main body, two circular plates, three rods and bush. However, other suitable materials are chosen for the motor.

$$\phi = \sin^{-1}(16/60) = 15.4^\circ$$
$$\theta_2 = 180^\circ - \phi = 164.6^\circ$$
$$CD = r_3 = 33 \text{ mm}, \theta_3 = 0$$
$$DA = r_4 = 60 \text{ mm}, \theta_4 = 180^\circ + \gamma$$

The robot's height can be determined with the relation.

The maximum and minimum height of robot can be determined based on angle $\alpha$ (maximum and minimum limits) and the length of the element ($L_2$) as shown in Figure 3 and Table 1.

**STATIC ANALYSIS**

The linkage structure is represented as shown in Figure 4 is a four-bar mechanism consisting of three revolute joints and one prismatic joint.

In order to decide the actuator size, it is necessary to perform the static analysis. Noting $F_{cx}$ and $F_{cy}$ are the reaction force and

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the traction force exerted on the four-bar by the driving wheel, respectively as shown Figure 5. Applying principle of virtual work to the free-body diagram in Figure 4:

\[
\delta W = F_{cy}\delta y - F_{bx}\delta x = 0
\]

where \( F_{bx} \) is a spring force.

This is because only \( F_{cy} \) and \( F_{bx} \) contribute to work. The corresponding coordinates of these forces relative to the coordinate located at the \( O(0, 0) \) are expressed as:

\[
\cos\phi = X/60, \quad X = 60 \cos\phi \\
\sin\phi = Y/60, \quad Y = 60 \sin\phi
\]

\[
\delta W = F_{cy}\delta y - F_{bx}\delta x
\]

\[
\delta W = F_{cy}(60 \sin \phi \delta \phi) - F_{bx}(60 \cos \phi \delta \phi) = 0
\]

Rearranging gives

\[
F_{bx} = F_{cy} \tan\phi
\]

\[
F_{cy} = F_{bx}/\tan\phi
\]

at the maximum efficiency Torque = 1.63 m N.m

\[
F_{bx} = T/0.2*d
\]

\( d \) = diameter of threading rod

0.2 friction factor

\[
F_{bx} = 1.63/0.2*10 = 0.815 \text{ N},
\]

\[
F_{bx} = K\Delta X, \quad k = \text{Threading rod stiffness}
\]

\[
K = 0.815/5 \text{ mm} = 0.163 \text{ N/mm},
\]

The traction force \( F_{cy} \) determined by

\[
F_{cy} = F_{bx}/\tan\phi
\]

Table 1: Variation Between Height of Robot and Angle \( \phi \)

<table>
<thead>
<tr>
<th>( \phi )</th>
<th>2( r ) mm</th>
<th>2( d ) mm</th>
<th>L mm</th>
<th>2L( \cos\phi )</th>
<th>H mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.40</td>
<td>25</td>
<td>2( ^{16} )</td>
<td>60</td>
<td>115.69</td>
<td>172.69</td>
</tr>
<tr>
<td>22.20</td>
<td>25</td>
<td>2( ^{23} )</td>
<td>60</td>
<td>111.01</td>
<td>182.00</td>
</tr>
<tr>
<td>28.60</td>
<td>25</td>
<td>2( ^{28} )</td>
<td>60</td>
<td>105.35</td>
<td>186.35</td>
</tr>
<tr>
<td>35.73</td>
<td>25</td>
<td>2( ^{36} )</td>
<td>60</td>
<td>97.41</td>
<td>194.41</td>
</tr>
<tr>
<td>40.20</td>
<td>25</td>
<td>2( ^{41} )</td>
<td>60</td>
<td>91.65</td>
<td>198.65</td>
</tr>
<tr>
<td>48.80</td>
<td>25</td>
<td>2( ^{48} )</td>
<td>60</td>
<td>79.04</td>
<td>200.00</td>
</tr>
</tbody>
</table>

Figure 3: Variation of Height of Robot Depending on the Angle \( \phi \)

Figure 4: Linkage Structure

Figure 5: Static Analysis
\[
F_{cy} = \frac{F_{bx}}{\tan \phi}
\]

\[
F_{cy} = \frac{0.163}{\tan 15.4^\circ} = 0.815 \text{ N}
\]

| Table 2: Variation Between Traction Force \((F_{cy})\) and Angle \((\phi)\) |
|---|---|---|---|
| \(F_{bx}(N)\) | \(\phi\) | \(\tan \phi\) | \(F_{cy} = \frac{F_{bx}}{\tan \phi}(N)\) |
| 0.815 | 15.4 | 0.275 | 2.9 |
| 0.815 | 22.2 | 0.4 | 1.99 |
| 0.815 | 28.6 | 0.54 | 1.49 |
| 0.815 | 35.73 | 0.7 | 1.13 |
| 0.815 | 40.2 | 0.84 | 0.96 |
| 0.815 | 48.7 | 1.14 | 0.71 |

The traction forces \(F_{cx}\) exerted on the belt. Thus, each traction force \(F_{cx}\) is one sixth of the whole weight of the robot structure. Thus, the size of the actuator enclosed in the wheel is calculated by \(G = F_{cx} \times R = W \times R/6\).

where \(R\) is the radius of the wheel. From the above static analysis, it is known that the weight of the robot does not influence the foldable motion of the linkage.

**PROTOTYPE DEVELOPMENT**

Typical 3-D solid modeling of pipeline inspection robot components namely main body, circular plate, threaded rod, link, DC motor, PIR main component and micro DC motor are shown in Figures 7 to 13.  

Threaded Rod
Inner diameter 8 mm, Outer diameter 10 mm, Pitch 5 mm, Length 130 mm with diameter 10 mm, Length 10 mm with diameter 8 mm, Material – mild steel as shown as in Figure 9.
DC Motor
The specifications of DC motor are as follows:
Voltage: 12 V, torque: 1.6 mN.m, power: 0.5 W, current: 500 mA, RPM 100 rpm, as shown in Figure 11.

Micro DC Motor
A micro DC motor equipped with an encoder is enclosed inside the caterpillar wheel parts with following specifications: Voltage: 6V, torque: 1.6 mN.m, power: 0.45 W, current: 0.059 amp, RPM 2620 rpm, as shown in Figure 12.

Center Frame of Pipeline Robot
Central body is the frame of the robot (Figure 13). It gives two motion and connected with other components and supports all part and holds batteries at the centre of the body. The joints (net) are brazed on the central frame with six links at 120°. The central body threading rod, main part and main component fabricated from aluminum material, which the single aluminum is cut into rectangular sheets and circular of required length and breadth.
**DEGREE OF FREEDOM**

Degree of freedom of a pair is defined as the number of independent relative motion, both translation and rotational.

Degree of freedom for planer mechanism

$$DOF = 3(N-1) - 2j_1 - 2j_2$$

where

- $N$: Total number of link in a mechanism
- $j_1$: Number of pair having one degree of freedom
- $j_2$: Number of pair having one degree of freedom

For this pipeline inspection robot, the degree of freedom calculated as below for the shown in Figure 14.

- $N = 10$, $j_1 = 13$, $j_2 = 0$
- $DOF = 3(10-1) - 2*13 - 2*0$
- $= 27 - 26$
- $= 1$

**VELOCITY ANALYSIS**

Velocity analysis four bar mechanism which consisting of three revolute joints and one prismatic joint as shown in Figure 15.

where

- $AB = r_1 = 60 \text{ mm}$, $\theta_1 = 0$
- $BC = r_2 = 60 \text{ mm}$, $\theta_2 = 180^\circ - \phi$
- $\phi = \sin^{-1} \left( \frac{hg}{BC} \right) = 15.4^\circ$
- $\theta_2 = 180^\circ - \phi = 164.6^\circ$
- $CD = r_3 = 33 \text{ mm}$, $\theta_3 = 0$
- $DA = r_4 = 60 \text{ mm}$, $\theta_4 = 180^\circ + \gamma$

$$\phi = 15.4^\circ$$

$$CA = \sqrt{r_1^2 + r_2^2 - 2*r_1*r_2*cos15.4^\circ}$$

$$= [60^2 + 60^2 - 2*60*60*cos15.4^\circ]^{\frac{1}{2}}$$

$$= 16 \text{ mm}$$

$$DB = \sqrt{r_2^2 + r_3^2 - 2*r_3*r_2*cos15.4^\circ}$$

$$= [33^2 + 60^2 - 2*33*60*cos15.4^\circ]^{\frac{1}{2}}$$

$$= 29.5 \text{ mm}$$

$$\gamma = \cos^{-1} \left[ (r_1^2 + r_4^2 - db^2/2*r_1*r_4*cos15.4^\circ) \right]$$

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\( \gamma = 29.5^\circ \)
\( \theta_4 = 180^\circ + \gamma = 209.5^\circ \)
\( \bar{r}_1 = \bar{A}\bar{B} = r_1 \cos \theta_1, i + r_1 \sin \theta_1, j \)
\[ = 60 \cos 0 \, i + 60 \sin 0 \, j = 60 \, i \]
Velocity for link 1 \((V_1) = 0\) fixed link
\( \bar{r}_2 = \bar{B}\bar{C} = r_2 \cos \theta_2, i + r_2 \sin \theta_2, j \)
\[ \bar{r}_2 = \bar{B}\bar{C} = 60 \cos 164.6, i + 60 \sin 164.6, j \]
\( \bar{B}\bar{C} = -57.8i + 15.9 \, j \)
Velocity for link 2 \((V_2), \ W_2 = 10.5\ \text{rad/sec} \)
\[ \bar{V}_2 = \bar{B}\bar{C} \times W_2 \]
\[ \bar{V}_2 = \begin{vmatrix} i & j & k \\ 0 & 0 & 10.5 \\ -57.8 & 15.9 & 0 \end{vmatrix} \]
\[ = i(0-(10.5*15.9)) - j(0-(10.5*-57.8)) + k(0) \]
\[ \bar{V}_2 = -106.9 \, i - 607.67 \, j = 617 \, \text{mm/sec} \]

**PIPELINE MOBILE ROBOT TEST RESULTS**

The prototype mobile robot for identification of defects in Pipelines of proposed mechanism is built. The prototype was built for a robot with the weight of 1.5 kg. The body of the robot was fabricated mostly from aluminum. The Robot was driven by one main DC motor and six micro DC motors. Pipeline inspection robot tested successfully for movement in horizontal for forward and backward motion. The robot has a good mobility and ability to detected obstacles by using IR sensor. The static analysis and kinematic analysis is carried out.

**CONCLUSION**

Prototype mobile robot for pipeline inspection is designed and fabricated with aluminum material. The robot is applied to 180 mm pipeline maximum diameter and it has flexibility to adjust links to another diameter less 180 mm. The kinematic and static analysis of main robot has been carried out by consideration four bar mechanism and actuator sizing of this robot have been investigated. The robot has got one degree of freedom that is translation either to or forward with total weight 1.5 kg. Finally robot is tested for functionality and found suitable for inspection of defects pipelines with camera attach to it.

**REFERENCES**


