DESIGN OF A CLIMBING ROBOT FOR CYLINDRO-CONIC POLES BASED ON ROLLING SELF-LOCKING

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This work is about designing Pobot V2, a robot capable to climb poles with a cylindrical or conical shape. It is original because of its rolling self-locking concept: rolling allows continuous ascension whereas self-locking guarantees a null energy consumption while staying still on the pole. The robot is also capable to avoid tangential obstacles, to cross small collars and to regulate passively its normal contact force on conical poles with a diameter that evolves from 300 to 100 mm. The concept is validated by experiments.

1. Why climbing poles?
Crisis conditions such as natural catastrophes, chemical contamination or riots require a precise, fast and reliable estimation of the situation all along the crisis. The collected data can be provided by cameras or any type of suitable sensor. They are generally collected from different observation points and are then centralized to the coordination center. Observation data from an elevated point of view could bring a significant advantage, particularly in urban landscape, where many obstacles prevent direct vision. Unmanned Aerial Vehicles (UAVs) could be considered as a solution but their use is restricted for the moment because of their potential danger in case of crash and limited endurance. The preferred solution presented here is a climbing robot that is capable to bring, with minimum energy, sensors and communication devices on top of common elevated urban structures such as poles, lampposts or water evacuation pipes.

2. Existing climbing and pole-climbing robots
Patent databases allow to find several robots dedicated to trestle structure [1] or ladder [2] climbing. Those systems generally use grippers mounted on an

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1 This work is supported by Thales Optronics.

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extensible frame and are not suitable to what we call “a pole” in this paper.

This work covers poles that are of tubular form, with cylindrical or conical shape and circular or polygonal section. Concrete poles with a square or H-shape section are not covered. A small study on typical urban poles [3] has allowed to define their characteristic properties (Table 1). Dimensions were measured directly. For friction property, a rubber pad was pressed against the pole surface and submitted to a constant tangential force $T$. The friction coefficient was calculated by $\mu = T/N$, the normal force $N$ being measured with a spring just at the beginning of slipping.

Table 1. Characteristic properties of some typical poles [3].

<table>
<thead>
<tr>
<th>Pole</th>
<th>Photo</th>
<th>Material</th>
<th>Coating</th>
<th>Section shape</th>
<th>Low diameter (mm)</th>
<th>Top diameter (mm)</th>
<th>Height (m)</th>
<th>Friction coef. $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1" alt="Photo" /></td>
<td>Wood</td>
<td>None</td>
<td>Circular</td>
<td>253</td>
<td>169</td>
<td>8,86</td>
<td>0.47</td>
</tr>
<tr>
<td>2</td>
<td><img src="image2" alt="Photo" /></td>
<td>Metal</td>
<td>None</td>
<td>Circular</td>
<td>150</td>
<td>75</td>
<td>8.02</td>
<td>1.16</td>
</tr>
<tr>
<td>3</td>
<td><img src="image3" alt="Photo" /></td>
<td>Metal</td>
<td>Paint</td>
<td>Circular</td>
<td>147</td>
<td>73</td>
<td>7.33</td>
<td>0.78</td>
</tr>
<tr>
<td>4</td>
<td><img src="image4" alt="Photo" /></td>
<td>Metal</td>
<td>None</td>
<td>Octagonal</td>
<td>218</td>
<td>109</td>
<td>10.45</td>
<td>0.58</td>
</tr>
<tr>
<td>5</td>
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<td>Metal</td>
<td>Paint</td>
<td>Octagonal</td>
<td>150</td>
<td>75</td>
<td>8.24</td>
<td>0.58</td>
</tr>
</tbody>
</table>

It can be concluded that poles generally measure up to 10m high, with a low diameter comprised between 300 and 150 mm and most of the time a strong conicity. The lowest friction coefficient was measured on wooden poles and will be considered low (around 0.45). Many poles also include obstacles that may complicate their ascension: tangential panels, traffic lights, wires, various electrical or phone equipments inside boxes and fixed with rings or steel bands.

Several patents present machines that are capable to climb cylindro-conic structures. The most common are machines for tree climbing and branch pruning [4-6]. They generally completely circle the trunk and actively compress it with actuated rollers. They use many actuators and have a heavy structure.

However, pole climbing systems are more rare. Some keep the same circular structure as tree pruning machines and are unable to cross tangential obstacles [7]. Others grip the pole laterally [8,9] and rely on pneumatic cylinders [8] or springs [9] to press rollers against the pole. All of them are vulnerable in case of energy failure.

From this brief overview, specifications of the robot can be summarized. It has to be compact (inside a cube of 500mm) for an easy setup by a single person, capable to bring a cubic payload of 10cm and 1kg on top of a pole at around 50mm/s. Cylindrical and conical poles will be considered with diameters from 300mm to 100mm and possible obstacles such as tangential panels and collars. No energy should be used to maintain the robot statical on the pole.
3. Climbing based on rolling self-locking

Self-locking or butting is a physical phenomenon where locking is obtained only by friction and whatever the intensity of external forces [10-11]. This is an interesting feature as it guarantees that no energy is used to maintain the robot at the top of the pole. Static self-locking has been used since the beginning of the 20th century for climbing shoes [12-13] (Fig. 1a) or tree climbing stands for hunting [14]. Strangely, it does not appear that any climbing machine or robot uses this principle up to now. For this reason, it was decided to choose this principle for our robot.

![Figure 1. Self locking on a pole: for a man [12] (a) or a robot (b).](image)

To be capable to maintain itself, the robot has to comply with locking criterion. One necessary condition is that the center of mass G is sufficiently shifted laterally with respect to the contact points P1 and P2 (Fig. 1b), depending on the friction conditions.

To create a climbing robot based on self-locking principle, it is possible to equip two frames with the locking system and to connect them by a contracting mechanism. However, it appears much simpler to locate the contact points directly on rollers. This allows to achieve “rolling self-locking”, which is the original principle that will be used for the robot. At least two rollers are required. Both can be actuated but it is simpler to actuate only the one that is closer to the center of mass, near the heavy parts (e.g. the electric motor and batteries).

The resulting robot is represented in Fig. 2. Roller R1 is the only one to be actuated. On the contact point C1, R1 transmits a reaction force from the pole to the robot: a normal force \( N_1 \) but also a tangential force \( T_1 \). On the contrary, roller R2 is a free one and only transmits a normal force \( N_2 \) at the contact point C2, provided that R2 is mounted on roller bearings that guarantee very low resisting torque. This means that only roller R1 serves to propel the robot.

The rolling self-locking condition derives from the fundamental principle of statics. Equation (1) comes from its horizontal projection along y:

\[
N_1 = N_2 \tag{1}
\]

A vertical projection along z gives (2) with \( m \) being the mass of the robot and \( g \) the acceleration of gravity.

\[
T_1 = mg \tag{2}
\]
Figure 2. Rolling self-locking with two contact points.

The sum of torques around $x$ with respect to point $C_1$ gives (3), with $a$ being the overhanging distance $GC_1$, $b$ being the distance between the contact points $C_1C_2$ and $\theta$ the tilting angle of the robot.

$$mg a \cos(\theta) = b \sin(\theta) N_2$$  \hspace{1cm} (3)

Equation (4) is the non-slipping condition at point $C_1$, based on Coulomb friction law and using the friction coefficient $\mu$.

$$T_1 \leq \mu N_1$$  \hspace{1cm} (4)

(2) and (4) allow to re-write the non-slipping condition:

$$N_1 \geq mg / \mu$$  \hspace{1cm} (5)

(1) and (3) allow to obtain the expression of $N_1$:

$$N_1 = \frac{a mg}{b \tan(\theta)}$$  \hspace{1cm} (6)

Finally, (5) and (6) give the rolling self-locking condition:

$$a \geq \frac{b \tan(\theta)}{\mu} \quad \text{with} \quad \theta = \arccos(d/b)$$  \hspace{1cm} (7)

It can be seen that (7) does not depend on the mass but only on geometry and friction properties. Self-locking occurs only when the overhanging distance $a$ is long enough. The higher the friction (great values of $\mu$) and the shorter can be $a$. According to (7), when the tilting angle $\theta$ decreases, locking is maintained with shorter values of distance $a$. This is because normal forces increase when $\theta$ angle decreases (6). For a quasi-horizontal robot, forces tend towards infinite. Practically, no robot can keep a perfect horizontal level because of structure deformation. This leads to the extension of distance $b$ and automatic creation of a small $\theta$ angle that generates locking if (7) is verified.
4. Designing the Pobot V2 climbing-robot

Another interesting mobility for the robot is axial rotation around the pole for self orientation at a given altitude. This can be achieved by horizontal rolling. For this reason, the roller $R$ is mounted on a turret $T$ and the second contact point $C_2$ is made compatible with horizontal rolling thanks to a spherical joint $S$ (Fig. 3a).

![Diagram](image)

Figure 3. Rolling self-locking with three contact points, rotating turret and obstacle avoidance.

Tangential obstacles such as road signs, sometimes fixed on the pole, must be crossed by the robot. This is possible if the second contact point $C_2$ is split into two points $C_{21}$ and $C_{22}$ that do not interfere with the obstacle (Fig. 3b).

The final constraint is to climb poles with strong conical shape (e.g. 300 mm diameter at the base and 100 mm at the top). The rolling self-locking property is ensured provided the $b$ distance can be continuously adjusted (Fig. 2). This is equivalent to adjust the support triangle $C_1, C_{21}, C_{22}$ so that it stays equilateral with an edge length depending on the pole diameter [15]. If $C_1$ is supposed fixed, $C_{21}$ and $C_{22}$ must be displaced simultaneously by the movable arms $M, N$ actuated by a suitable mechanism (Fig. 4).

![Diagram](image)

Figure 4. Kinematics of the linkage to adjust the holding forces $F_c$ and $F'_c$ on the movable arms.
This linkage uses revolute joints for simplicity and allows to move $C_{21}$ and $C_{22}$ on circular trajectories that approximately ensure the equilateral condition mentioned above. This mechanism must be actuated when the pole diameter varies in order to maintain a suitable value of length $b$. It can also be interpreted in term adjustment of the holding forces $F_c$ and $F_c'$. In future versions, the mechanism could be actuated with an electric motor and a control loop for optimal holding-force regulation. In this paper, a simpler solution based on springs was chosen to decrease complexity and energy consumption. An even number of springs $2n_s$ is used to equilibrate traction on both sides of a sliding rail $WO$. The springs are connected to the robot frame in $W$ on one side and on a slider $S$ on the other side. Two connecting rods $US$ and $VS$ connect the slider $S$ to the holding arms $UMC_{21}$ and $VNC_{22}$ via revolute joints.

The arms were given a folded shape with an angle $\alpha$ at $M$ and $N$ points respectively. The folded shape of the arm $UMC_{21}$ is necessary to ensure at the same time compact dimensions and that lever $UM$ is much longer than $MC_{21}$. This ratio is important because internal forces inside the frame are important and must be compensated by springs, that can apply only a limited force. As no spring can extend sufficiently to cover the complete range of diameters from 100 to 300 mm, three ranges of diameters can be selected by adjusting $\alpha$ angle to a value of 95°, 110° or 125° thanks to locking clips. This allows to configure the robot for a pole with diameters in the 100-200, 150-250 or 200-300 mm ranges respectively. This 100 mm variation on the diameter corresponds typically to the existing conical poles (Table. 1).

Figure 5. Complete assembly of the robot with the linkage for adjustment to conical poles [3, 15].
Another interesting point in this linkage is that the holding forces $F_c$ and $F'_c$ depend non-linearly of the spring length $WS$. The extreme case is the singular configuration of the mechanism where the arms $UMC_{21}$ and $VNC_{22}$ hold the pole at their maximum. At the same time, the connecting rods $SU$ and $SV$ become parallel and the springs, that are completely loose in this position, do not need to apply strong forces to keep the robot arms closed. The stiffness of the mechanism in this configuration tends towards infinite, or more realistically equals the stiffness of the structure.

The complete assembly of the Pobot V2 climbing robot is represented in Fig. 5. One can see the frame (1) made of aluminum square tubes; the propel-
ing roller (2) with worm gear transmission; the orientable turret (3) with crown gearing; one spherical joint $S$ (4); the mobile arm $MC_{21}$ (5); the arm pivot (6) that corresponds to point $M$; the rear part of the arm $UM$ (7); a diagonal reinforcement plate for the arm (8); the clip holes for adjusting the $\alpha$ aperture angle of the arm (9); the connecting rod $US$ (10); the tubular slider $S$ (11); the tubular sliding rail $WO$ (12); the mobile attachment for springs (13); the fixed attach-
ment for springs (14); the electric DC motor of 70 W (15); the programmable controller with Bluetooth remote control (16); the power module including a power controller card with Pulse-Width-Modulation amplification and batteries (17). 16 springs (not represented) connect (13) to (14) and have the following specifications: stiffness 274 N/m; min. length 100 mm; max. length 384 mm.

5. Experimental results

The final robot has dimensions of 72x50x22 cm for a total weight of 10.5 kg. It respects the specifications as it is capable to bring a 1 kg payload on top of the pole at a top speed of 66 mm/s. It includes a clutching device to commute between climbing and turret rotation, although two motors are also possible. It can be tele-operated via a Bluetooth connection. Two experiments were made:

- The first one at Thales Group (Fig. 6a) on a steel cylindrical pole of around 200mm of diameter. The robot climbed easily with eight springs. Helicoidal trajectories could also be demonstrated with an angle of 45° on the turret.
- The second one at IFMA (Fig. 6b) on a wooden conical pole with a low friction coefficient of around $\mu = 0.47$, 8 m height and max./min. diameter of 210/140 mm [16]. On this conical shape, the force regulation linkage demonstrated its absolute necessity. The system was temporarily deactivated and the robot could not climb a single conical pole: it was either slipping on the surface because insufficient pressure of the arm, or unable to climb because of too much pressure. With the linkage properly activated, the robot was able to climb 6 m of the total 8 m height. After that, slipping occurred. The tests allowed to exhibit the extreme sensitivity of the robot to the overhanging distance $a$ of the centre of mass and to the number of springs. Six springs were optimal and allowed to climb 6 m of the pole at an average 29 mm/s with top speed of 66 mm/s between 3 and 4 m. The holding forces reached 300 N and could even create grooves at the wood surface. Going down along the pole could also generate stick-slip motion and would require contact pressure decrease. Axial rotation was not always stable and would also require more contact points $C_{2j}$. 
6. Conclusion

This work describes the design of the pole climbing robot Pobot V2 based on the innovative principle of rolling self-locking that uses no energy to maintain itself at a given altitude. The robot can also perform axial rotation, can cross tangential obstacles and climb poles with a strong conical shape thanks to passive normal force regulation with springs and a force amplifying linkage. The first experiments showed excellent stability during vertical climbing. Future work must be done to make the robot more rigid, more compact and lighter. The robot was jointly patented by Thales and IFMA [17].

References

15. F. Guiet, Conception et réalisation d'un robot grimpeur de poteaux, IFMA Final project (2007).