The SlothBot: A Novel Design for a Wire-Traversing Robot

Gennaro Notomista, Yousef Emam and Magnus Egerstedt

Abstract—This paper presents the SlothBot, a wire-traversing robot envisioned for long-term environmental monitoring applications. The SlothBot is a solar-powered, slow-paced, energy-efficient robot—hence its name—capable of moving on a mesh of wires by switching between branching wires. Unlike ground mobile robots or aerial robots employed in environmental monitoring applications, the use of wire-traversing robots allows for longer-term deployment because of the significantly lower energy consumption. Wire-traversing, coupled with the use of solar panels, facilitates the self-sustainability of the SlothBot. Locomotion and wire-switching maneuvers are performed in a fail-safe fashion, inasmuch the robot is always firmly attached to the wires, even when switching between branching wires. This is achieved by employing a two-body structure featuring an actuated decoupling mechanism. In this paper we show the design and the motion control of the SlothBot, together with the results of long-term monitoring experiments.

I. INTRODUCTION

Wire-traversing robots are able to move along cables, wires, and similar infrastructure. Due to their wire-traversing capability, these robots are suitable for applications in agricultural robotics [1], environmental monitoring [2] or maintenance in hazardous places, as in the case of power line inspection [3]. The latter has been the main catalyst for the development of wire-traversing robots, see e.g. [4], [5], [6]. The geometric and mechanical design of wire-traversing robots varies a lot among the existing mechanisms developed over the past 20 years, as discussed in [7]. Nevertheless, common features shared, to a certain extent, among many of the architectures are: (i) simplicity of the system design and, consequently, of the motion control; (ii) reduced localization errors and navigation complexity; (iii) low energy requirements. These characteristics have allowed wire-traversing robots to gain increasing interest in different applications domains.

The objective of this paper is to present the SlothBot (Fig. 1), a wire-traversing robot capable of moving on a mesh of wires, which is envisioned for long-term environmental monitoring tasks. Long-term environmental monitoring finds its application in agricultural robotics and, more in particular, in plantation growth and health state monitoring [1], where robots, generally quadcopters, are used to keep track of specific characteristics of plantations. The SlothBot—whose name stems from its energy efficiency and slow pace while traversing wires—is self-sustaining in that it is equipped with a pair of solar panels for autonomous charging. The mechanical design has been conceived to be simple and compact, while at the same time allowing the robot to switch between branching wires and to remain safely attached to them even during the switching maneuvers. In order to reduce the maintenance efforts and to minimize the risk of failures, robots targeting long-term applications should, in fact, be fail-safe and as simple as possible. We refer to long-term tasks as tasks that occur over extended periods of time and, in particular, which require multiple battery charges. In this sense, quadcopters, which are extensively used for agriculture robotics applications, are not suitable for long-term tasks because of the high power they require to remain operational [1].

A. Existing Wire-Traversing Robot Designs

Surveys of the state of the art of robots designed to traverse cables are presented in [7] and [8]. In [9] a robot consisting of multiple units allowing wire switching and obstacle avoidance is presented. More recent work on the development of wire-traversing robots can be found in [3], [10], [11], [12]. In [3], the presented robot has got folding capabilities that allow it to avoid obstacles. A modular robot that is able to slide on horizontal wires as well as climb on vertical ones is presented in [10]. In [11], the proposed robot uses a caterpillar-like locomotion strategy that allows it to climb up and move on ropes. In [12], the authors present a robot that is able to locomote using different methods, such as inchworm-like or brachiating motion patterns, which allow it to move fast and avoid occasional obstacles.

The obstacle avoidance feature has been subject of research because the designed robots have been mainly employed in power cables or suspension bridge maintenance. In
these applications, since the robots have to adapt to existing infrastructures, the capability of avoiding obstacles along the wires constitutes an essential design requirement. Consequently, the resulting designs feature multiple robotic-arm-like attachments, each of which needs several motors to be fully actuated. The few existing robots capable of switching-wires also rely on similar multi-joint arm mechanisms that are large and complex. Furthermore, relatively little design effort has been put into designing energy efficient robotic platforms capable of staying out in the field for long-term missions. The maintenance operations of bridges and power cables mentioned above are, in fact, usually limited to a few hours. The robots shown in [13], for instance, only have up to 6 hours of autonomy.

Because of the long-term applications targeted by the SlothBot, in this paper we consider two aspects that have not been explicitly taken into account in the state-of-the-art designs, namely energy efficiency and fail-safeness. The definition of fail-safeness adopted in this paper is the ability of a wire-traversing robot to remain hung on the wire at any point in time given the undetectable failure of one of its actuators. Table I shows a comparison between the SlothBot and other existing wire-traversing robotic platforms. The metrics considered for the comparison are the wire-switching capabilities, the fail-safeness (as defined above), and the actuation complexity. The SlothBot possesses all the characteristics desirable for the long-term applications mentioned before, and has the minimum number of actuators among the platforms capable of wire-switching. How energy efficiency and fail-safeness shaped the design of the SlothBot will be the subject of Section II.

B. Specification-Driven Design

As discussed in the beginning of Section I, we envision the deployment of the SlothBot for long-term environmental monitoring tasks, required, for example, in agricultural robotics applications. In order to move in an agricultural field, the SlothBot has to be able to traverse a mesh of wires and, therefore, to overcome crossings. Fig. 2 represents an idealized agricultural field. The crosshatched areas represent different crops in the field, while the thick black lines show a mesh of wires that go across the field. The objective of the robot deployed in the field is that of monitoring phenomena that take place over long time scales, such as crop growth. For this task to be successfully completed, energy efficiency and fail-safeness are required features, so that maintenance and risk of failure are minimized. Moreover, as mentioned before, in order to be able to move on the mesh of wires across the field, the robot has to traverse intersections of wires. For this to be possible, the robot has to have the capability of switching between different wire branches.

To summarize, the objectives that drove the design and development of the SlothBot are:

- energy efficiency
- wire-switching capability
- fail-safeness.

Among the existing wire-traversing robotic platforms, the ones that fulfill all the listed requirements exhibit complex designs that are, generally, less energy-efficient and not easy to control, requiring careful motion planning.

The remainder of the paper is organized as follows. Section II describes the mechanical design of the SlothBot and, in particular, the locomotion principle, the wire-switching mechanism, and the hardware architecture. Section III proposes a motion control strategy that is particularly suitable for controlling the SlothBot to move on the wires. Finally, Section IV reports the results of an environmental monitoring experiment.

II. MECHANICAL DESIGN

The SlothBot is composed of two bodies connected by an actuated hinge, as seen in Fig. 1. Each body, depicted in Fig. 3, houses a driving motor connected to a rim on which a tire is mounted. The use of wheels for locomotion is simple, energy-efficient and makes the SlothBot safer when compared to brachiating robots. The switching maneuver is made possible through four pairs of spur gears. Each pair is stacked vertically with the top gear having a circumferential gap of 20°. The four gears with such a gap will be referred to as C-shaped gears throughout the paper. The bottom gear is driven by a servo-motor and allows orienting the C-shaped gear’s...
TABLE I
Comparison between the SlothBot and existing wire-traversing robot designs.

<table>
<thead>
<tr>
<th>Locomotion Principle</th>
<th>Wire-Switching Capability</th>
<th>Fail-safeness</th>
<th>Number of Actuators</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LineScout [3]</td>
<td>Wheels</td>
<td>No</td>
<td>Yes</td>
<td>100</td>
</tr>
<tr>
<td>SkySweeper [12]</td>
<td>Pulley Arms</td>
<td>No</td>
<td>Yes</td>
<td>0.466</td>
</tr>
<tr>
<td>Expliner [14]</td>
<td>Wheels</td>
<td>Yes</td>
<td>No</td>
<td>6</td>
</tr>
<tr>
<td>Modular robot [9]</td>
<td>Wheels</td>
<td>Yes</td>
<td>Yes</td>
<td>10</td>
</tr>
<tr>
<td>SlothBot</td>
<td>Wheels</td>
<td>Yes</td>
<td>Yes</td>
<td>1</td>
</tr>
</tbody>
</table>

Fig. 4. Kinematic scheme of the SlothBot highlighting its degrees of freedom. $\theta_{ff}$, $\theta_{fr}$, $\theta_{rf}$, $\theta_{rr}$ are the angles of which the front and rear top gears of the front and rear body, respectively, can rotate. These degrees of freedom are actuated by 4 servo motors. $\theta_h$ is the relative angle between the two bodies of the SlothBot, and is also actuated by a servo-motor. $\omega_f$ and $\omega_r$ are the speeds of the 2 DC motors that move the SlothBot.

gap to three different positions. These positions are top, left and right, which correspond to the robot going straight, turning right and turning left, respectively. This novel wire-switching mechanism minimizes the required actuation to only one servo-motor per gear pair, thus significantly increasing the simplicity and compactness of the design. The fail-safeness of the SlothBot is guaranteed through the use of the two bodies connected by a hinge: this consists of a rotational joint, whose axis lies in the longitudinal plane of the robot, and it is actuated by a servo-motor. The servo-motor ensures the alignment of the bodies with respect to the branches they are traversing. The switching maneuver itself will be explained in more detail in Section II-B. Fig. 4 depicts the scheme of the robot highlighting its degrees of freedom. Relative to existing designs that are capable of wire-switching, thanks to its locomotion principle and wire-switching mechanism, the SlothBot is more energy-efficient as well as fail-safe.

A. Locomotion Principle

The wire that the SlothBot has to traverse is compressed between the tires and the top lids of both bodies. This lets the friction force remain high enough to allow the tires to move the robot. Fig. 5 depicts the forces involved in the dynamic equilibrium of the robot. The triangular supports represent hinges/carts capable of reacting with the forces drawn in the figure. The horizontal and vertical equilibrium equations reduce to:

$$\sum_{i=1}^{4} F_i = 2T_d, \quad 2N = 4R,$$

where $T_d$ is the force generated by the motor used for locomotion, $F_i$, $i = 1, \ldots, 4$ are the horizontal reaction forces exerted by the body due to friction, and $N$ and $R$ are the forces and the reactions of the constraints, respectively, due to the weight of the robot and of the payload. Starting from (1), we can calculate the motor torque required to carry a payload of a given mass. Let $m$ be the mass of the payload the robot has to move around. Examples of payloads can be sensor modules or hard drives used to store collected measurements. The minimum value of motor torque $\tau$ provided by each motor that is required to move the robot along the wire is given by:

$$\tau = T_d r = 2F r = 2\mu R r = \frac{(m + M)g}{2} \mu r,$$

where $r$ is the effective rolling radius of the tires [15], $F = \frac{\mu g}{2}$ (from (1) assuming reaction forces equally distributed among the 4 support points), $\mu$ is the friction coefficient between the wires and the robot body, $R$ the normal reaction force exerted by the supports (Fig. 5), $M$ is the mass of the robot, and $g$ is the acceleration due to gravity.

While moving on a mesh of wires, the SlothBot has to overcome wire crossings by switching to different wire branches. The switching maneuver is the subject of the next section.
B. Fail-Safe Wire Switching

Switching between different wires is required in all applications where the robot is constrained to move on a mesh of wires. As discussed in the Introduction, there have been several solutions proposed to the wire-switching problem for wire-traversing robots. The mechanism we propose in this paper is robust against failures of the actuators and of the actuators’ controller. More specifically, we designed the SlothBot in such a way that it firmly remains on the wire in case the actuators fail during the wire switch, or in case the motors are actuated at the wrong time. This is a key feature for robotic systems designed for long-term monitoring tasks. In fact, as the probability of failures increases with time, a way of at least mitigating unsafe consequences of these failures is required. The switching method presented in this section fulfills this requirement.

Fig. 6a to Fig. 6d show the sequence of actions performed by the SlothBot to switch to a different wire branch:

- Fig. 6a: Both bodies of the SlothBot are on the same wire, indicated by branch A, the servo motors keep all the gaps of the C-shaped gears straight up, holding the top lids on the wire while not allowing the wire to disengage. The objective is switching from branch A to branch B.
- Fig. 6b: Body 1 is at the junction between the wires, its C-shaped gears are both open allowing the branch C to disengage from it.
- Fig. 6c: Body 2 performs the same maneuver that Body 1 completed in Fig. 6b, disengaging from branch C and moving onto branch B.
- Fig. 6d: Both bodies are on the same wire, and the SlothBot successfully switches from branch A to branch B.

The described switching maneuver is made possible by the use of the C-shaped top gears, with a circumferential gap of 20°. In Fig. 7 the operation of these gears is shown in more detail. In order to be able to switch between branching wires, the parts of the robot that are above and below the wires, depicted in red and green, respectively, have to be disconnectable. In fact, referring to the sequence in Figures 6a to 6d, the robot that has to switch from branch A to branch B, has to cross over branch C. Thus, at some point in time, opening a gap between the red and green parts is required. Nevertheless, in order to keep the robot hung to the wires at any point in time, parts above and below the wires have to remain connected.

In order to accomplish what has been described, an actuated decoupling mechanism is proposed. This consists of a train of two spur gears per side per body of the SlothBot. One gear is mounted on the servo motor (green gears in Fig. 7); the other one (blue gears in Fig. 7) has a C-shape that allows the top lid to be held for any orientation of the gap (i.e. for any value of the angles $\theta_{fr}, \theta_{rr}, \theta_{fr}, \theta_{rr}$ of Fig. 4). At the same time, the shape of this gear allows wire branches to disengage from the left (Fig. 7a) and from the right (Fig. 7c) of the robot. While the robot is driving straight on a wire, the C-shaped gears are oriented as in Fig. 7b.

Because of the fail-safeness constraint on the switching maneuver, the SlothBot does not have the ability of traversing crossings with more than 3 branching wires. However, this is not a substantial limitation, since any crossing can be turned into a sequence of 3-way crossings as shown in Fig. 8. Moreover, from Fig. 6 it is clear that the SlothBot cannot traverse crossings when the turning angle is smaller than 90°. However, this situation can always be avoided by performing a two-step maneuver in which two obtuse-angle crossings are overcome instead of one acute-angle crossing. Nevertheless, with the technique shown in Fig. 8, all the resulting crossing angles can be made strictly larger than 90°. Furthermore, the inability of the SlothBot to traverse crossings with more than 3 wire branches allows the synthesis of a motion control law that will be particularly suitable for navigating over meshes of wires, as will be explained further in Section III.

C. Hardware Architecture

A prototype of the SlothBot has been realized using rapid prototyping technologies. All the main components are 3D printed using standard PLA material. The printing time of an entire SlothBot is about 30 hours using a commercial 3D printer. Assembly time is 30 minutes since all the other components are off-the-shelf. The realized prototype of the SlothBot is 25.5 cm long, 11.2 cm high (13.5 cm with solar panels) and 6 cm wide (31.2 cm with solar panels). The 2 motors are Micro Metal Gear motors, operating at 6V, with 1000:1 reduction ratio, maximum speed of 32 rpm and maximum torque of 0.88 Nm, which allow the SlothBot to move at a maximum speed of 5 cm/s. The servo motors used to rotate the spur gears are standard 9-gram servo motors with an operating voltage of 5V and a maximum torque of 0.16 Nm. The servo motor used to actuate the hinge between the two bodies, required during the wire-switching maneuver, has a maximum torque of 1.52 Nm while operating at 5V. The robot is powered by a rechargeable 7.4V 1000 mAh LiPo battery. Two solar panels (visible in Fig. 1), mounted on the sides of the SlothBot, are used to recharge the battery when the light intensity is high enough. A maximum power point transfer (MPPT) solar charging circuit is used to regulate the charging current based on the solar cell characteristics. This way, the power efficiency, expressed as the ratio between the power that is transferred to the battery and the power received from the sun, is maximized at each time instant.

The main processing unit onboard the SlothBot is the ESP32, an IoT-enabled microcontroller. The microchip directly controls all the 5 servo motors, and, through a dedicated motor controller, the 2 DC motors that drive the tires.

The SlothBot is designed to carry sensors for environmental monitoring applications. In Section IV we show the results of a 1-day experiment during which the SlothBot measured its environment’s temperature and luminosity. The ESP32 connects to the sensors using the I2C protocol, usually available on sensor data acquisition boards. Moreover, the microcontroller hosts a web server which handles requests of sensor data by a client running on a desktop computer.
planar and known a priori by the robot. Then, let this end, we assume, from now on, that the mesh of wires is to monitor events and collect data in the environment. To law for the SlothBot that will allow it to move on the wires for the SlothBot to achieve environmental monitoring tasks.

responsible for storing the collected measurements, thus enabling remote environmental monitoring.

The next section is dedicated to the motion control of the SlothBot on a mesh of wires. Control laws will be introduced, which are suitable to control the robot to achieve environmental monitoring tasks.

III. MOTION PLANNING AND CONTROL

In this paper, we are interested in synthesizing a control law for the SlothBot that will allow it to move on the wires to monitor events and collect data in the environment. To this end, we assume, from now on, that the mesh of wires is planar and known a priori by the robot. Then, let $X \subset \mathbb{R}^2$ be a closed and convex polygon, representing the environment in which the robot is deployed. Provided that there is no slip between the driving tires of the robots and the wires, we can assume that, by acting on the torque $\tau$ of the two DC motors, we can control the speeds $\omega_R$ and $\omega_L$ (Fig. 4) to regulate the robot to a desired velocity. The simplified robot model is then given by:

$$\dot{x} = u,$$  \hspace{1cm} (3)

where $x \in X$ is the robot position and $u \in \mathbb{R}^2$ is the velocity control input. In the environment $X$ there are wires, that are represented by line segments, on which the robot can move.

In this context, an environmental monitoring task for the SlothBot, consists of driving as close as possible to a location $p(t) \in X$, that moves in space over time, in order to collect measurements. Motion planning algorithms for wire-traversing robots typically use graph or road-map search [16] to find a path to a goal point on the graph. Given that the graph is known, once the route to the goal location on the graph is planned, the robot is driven by a lower level controller to the goal. However, in order to derive a continuous-time control law that will continuously drive the robot to the point on the wires closest to $p(t)$, we proceed as follows.

We define the task of getting to a point on the wires closest to a given location $p(t)$ as the following constrained optimization problem:

$$\min_{x \in X} \frac{1}{2} \|x - p(t)\|_2^2 \quad \text{s.t.} \quad x \in G,$$  \hspace{1cm} (4)

where $G$ denotes the mesh of wires, or, more precisely, the set of points in $X$ that belong to the line segments defining the wires. In [17], a motion control algorithm, which allows to continuously map the velocities of an unconstrained robot onto the velocities of a robot constrained to move on wires, is formulated. With this in mind, we can then solve the unconstrained optimization problem

$$\min_{q \in X} \frac{1}{2} \|q - p(t)\|_2^2$$  \hspace{1cm} (5)

using the gradient flow method, obtaining:

$$\dot{q} = -\left(\frac{\partial}{\partial q} \frac{1}{2} \|q - p(t)\|_2^2\right)^T = p(t) - q.$$  \hspace{1cm} (6)

At this point, we can map $\dot{q}$ onto the wires obtaining $\dot{x}$. The expression of the mapping from the unconstrained velocity, $\dot{q}$, to the constrained one, $\dot{x}$, derived in [17] becomes significantly simpler when the robot moves on triangle meshes of wires. Since triangle meshes only contain 3-way crossings, they are extremely suitable for the design of the SlothBot. The resulting control law is given by the expression

$$u = \dot{x} = \dot{q} \tilde{M}(t),$$  \hspace{1cm} (7)

where $\dot{q} \tilde{M}(t)$ is the velocity $\dot{q}$ mapped onto the wires, which brings the robot to a point on the wires that is closest to $p(t)$. 

---

**Fig. 6.** Simulated wire-switching maneuver: the SlothBot switches from branch A to branch B. The top lids, that ensure that the wire is in contact with the tires, have been hidden to make the orientation of the top gears visible.

**Fig. 7.** The switching mechanism for the SlothBot. The red components of the robot always remain above the wires, while the green components are confined to stay below them. The C-shaped blue gear allows the red and green parts to be held together, while, at the same time, allowing the wires to disengage from the robot during wire-switching maneuvers.

**Fig. 8.** Example of turning one 4-way crossing into a sequence of four 3-way crossings. This modification is required since the SlothBot is only able to traverse 3-way crossings.
The mapping \( \tilde{M}(t) \) is referred to as a \textit{continuous-onto-wires} mapping, which depends on the geometry of the environment and the arrangement of the wires in it. We refer to [17] for the derivation and the details of (7).

Fig. 9 schematically depicts the monitoring scenario described Fig. 2 formulated in terms of the quantities introduced in this section. The robot, initially positioned at \( x_0 \) has to go and collect measurements at location denoted by \( p(t) \). Since it is constrained to move on the wires (black lines), a continuous projection of the unconstrained path (orange dotted line) onto the wires is generated using (7), resulting in the constrained path (red solid line). Following this projected path, the robot arrives at location \( x^* \), that is the point on the wires closest to \( p(t) \).

IV. EXPERIMENTS

To show the effectiveness of SlothBot, we performed a long-term monitoring experiment during which we left the robot in the environment for 24 hours. Note that a battery life can keep the robot operational for about 12 hours, without any motors being activated. For this reason, according to the definition given in Section I, this classifies as a long-term experiment.

As the SlothBot uses solar power to recharge its battery, we equipped it with a luminosity sensor and recorded sun light intensity together with battery voltage data which will be useful for identifying the dynamical model of the battery. This model can be incorporated in the control framework to prevent the robot from completely discharging its battery, e.g. using the framework introduced in [18]. We report the collected battery voltage and light intensity data in Fig. 10.

V. CONCLUSIONS

In this paper we have presented the SlothBot, a novel design of a robot that is able to traverse a mesh of wires by switching between different branches. Compared to the state-of-the-art designs, both the locomotion and, in particular, the wire-switching maneuvers are executed using a simpler actuation mechanism, which, nevertheless, results in fail-safe executions. The SlothBot, in fact, remains firmly hung on the wires even in case of failure of all its actuators.

The design choices that have been made are justified by the objective of creating a robotic platform that is energy efficient, that has the capability of switching wires, and that is fail-safe. We envision the use of the SlothBot for long-term environmental monitoring applications, found, for instance, in agricultural robotics. To this end, a way of planning and control the motion of the SlothBot on a mesh of wires is proposed, which allows the achievement of monitoring tasks. Finally, the results of a 1-day monitoring experiment in the field are reported.

REFERENCES


