Numerical Simulation of Stable Propagation of Mechanical Signals by Cylindrical Origami

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Abstract: To transmit mechanical signals across long distances, unattenuated transmission lines have been proposed. However, these are difficult to design and manufacture and require external power supplies. Instead, we propose using coupled cylindrical origami units to make up signal lines. Cylindrical origami is easily assembled from a single sheet and can have bistable properties with adjustable energy curves, such as by applying additional springs. This enables continuous mechanical signal transmission down the line. We numerically simulated these systems and confirmed their feasibility for transmitting signals as well as for creating diodes and logic gates.

Keywords: triangulated cylindrical origami, telecommunication, bistable

Classification: Transmission systems and transmission equipment for communications

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1 Introduction

Sensor systems for long term monitoring, such as those that monitor soil moisture as a countermeasure against landslides, must either wake up the sensor nodes regularly or have environmental changes trigger activation. However, when wireless sensor monitors are operated in such modes, energy consumption is large, which limits the duration for long-term operation. In addition, slow environmental changes may result in signals that are too small, getting mixed with noise during transmission, and ultimately fail to wake up the sensing device. Therefore, a system has been proposed where a signal generated based on the state of the environment reaches the sensor node without attenuation to provide an activation trigger, like a domino toppling. Such mechanical signal lines based on bistability have been used, but they are difficult to design and manufacture, and thus and cannot be practically deployed [7]. Furthermore, conventional un-dissipated signal lines made in this fashion can transmit the signals in one direction only, logic gates are destroyed by operation, and as a result, used signal lines must be replaced before the signal can be transmitted again [2].

As an alternative, we propose constructing the signal line with a cylindrical origami that enables significant shape change with small elastic deformation, thus enabling an un-dissipated signal line that can transmit signal without destruction of the signal line. Cylindrical origami is a crease pattern that appears when a cylinder is twisted and folded as shown in Fig. 1A. It can be assembled easily from a single sheet-like origami, and properties like rigidity, bistability and energy curves can be adjusted based on the number of corners and the angles of the folding pattern. Cylindrical origami has already been used successfully as a functional mechanism for memory and as a damper [1]. It is bistable—its two stable states are when the twist in the cylinder is either unfolded or folded—and can transmit signal by sequentially causing folding transitions from one unit to the next as shown in Fig. 1B.

This method stores energy in each unit through the spring and elastic deformation of the folded sheet. Therefore, unlike in conventional systems which typically require standby power to compensate for dissipated energy (as shown in Fig. 1B), our signal line does not require an external power supply because energy is stored in the mechanical configuration of the line itself. This signal line makes it possible to semi-permanently monitor sensors and their reuse. As a result, it is possible to realize a more energy-efficient sensor that is buried in the ground and generates a signal according to the water level to give a warning of a landslide, a fire alarm that needs fewer battery replacements, and so forth. The symmetry of each cylindrical origami unit enables bidirectional communication, the ability for origami to generate large movements with signal line has the following characteristics. A table comparing these advantages with existing methods is shown in Fig. 1C.
Signal propagation with stored energy

Fig. 1. A: Cylindrical origami, the unit of signal line combining cylindrical origami and their stable states. B: The concept of proposed signal line with stored energy. Stored energy in spring compensates the attenuation. C: Comparison with other methods.

2 Un-dissipated signal line using cylindrical origami

In this paper, we proposed creating an un-dissipated signal line using a connected cylindrical origami units. We call two cylindrical origami units connected in series a “cylindrical origami pair.” By fixing the total length of the cylindrical origami pair, a stable cylindrical origami pair can be set such that there is always one united contracted and one unit expanded. Then, the position of the middle connection between the pair (the signal plane) $h_1$ changes depending on which cylindrical origami is contracted. The pair saves the state since these states are stable. Cylindrical origami is known to have bistability depending on the angle. In this study, the unit is constructed based on the model shown in Fig. 2B, which shows clear bistability [4]. The elastic energy of a cylindrical origami pair of fixed length has two stable states, as shown in Fig. 2A. A cylindrical origami pair is symmetrical and has two stable states. Using this property, the cylindrical origami pair has been successfully used as nonvolatile memory [5]. It is known that the elastic energy generated by the expansion and storage of the cylindrical origami can be calculated by the truss model [6]. For a model like Fig. 2 A and B (Length = 100, $\alpha = 45^\circ$, $\beta = 75^\circ$, Height = 160, $\frac{a}{b} = \frac{1}{2}(1 + \sqrt{3}) \approx 1.366$).

Bistability is usually symmetric like a solid line, so simply joining the units in series does not cause continuous folding down the line like dominos toppling. We adjusted the elastic energy curve by applying an external force in the form of internal and external springs (Fig. 2C and Fig. 2D). We calculated the dash and dash-dot elastic energy curves for external axial and rotational in Fig. 2A using an external spring(0.05) configured as shown in Fig. 2D. For axial force, two springs pull to the right. For rotational force,
Fig. 2. A: Elastic energy of cylindrical origami pairs without force, with axial (dash) and rotational (dash-dot) force. $\Delta \phi$ is the stored energy, and $\Delta \psi$ is the energy required for the transition. B: Net of the cylindrical origami. C: Signal line with cylindrical origami pairs connected in series. D: Example of how to mount external springs two springs pull from a position 150 away from the center at an angle of 40.89 degrees from resting, with $h_1 = 80$.

There are two ways to apply force to the signal plane. The signal plane moves axially as well as rotationally during the state transitions, so, applying either axial force or external rotational force like in Fig. 2D causes a difference in elastic energy, as shown in Fig. 2A. If $\Delta \phi > \Delta \psi$, transition of the following unit in the chain can be caused by connecting each signal plane by internal springs as shown in Fig. 2C.

We can reverse the left and right of Fig. 2C by changing the direction of the external spring force, which reverses the direction of propagation. Thus, our signal line can support two-way communication.

2.1 Diode and logic gate of cylindrical origami signal line

We can also create a diode and a logic gate using cylindrical origami by changing the material of the folded sheet or angle of the folding pattern. A unit made of a hard material needs more energy to deform, and a unit made of a soft material needs less energy to cause the transition. Similarly, a hard unit releases more energy, and a soft unit releases less energy for the next transition. Although the signal is easily transmitted from a hard unit to a soft unit, the reverse transition is impossible. By using this property of asymmetry in the required forces, it is possible to make a “diode” that can transmit signal only in one direction.

Even if a soft unit can only deliver a small amount of energy after transition, a hard unit can still be triggered by soft units if there are multiple soft units transmitting small signals. By using this property, an AND gate can be realized. Alternatively, if a signal line has two inputs, the transition
of either unit of the input can cause the next transition, which results in an OR gate.

Even if the material of the signal line is uniform, the logic gate can still be constructed by connecting the signal plane with a logic spring whose spring constant is adjusted. If \( \tau_k \) is the force on the logic spring with the spring constant \( k_{\text{logic}} \) and \( \Delta \psi < 2\tau_k \), then the unit becomes an AND gate. Similarly, if \( \Delta \psi < \tau_k \), the unit becomes an OR logic gate. This method can be easily extended to multi-input logic gates by only adjusting spring constants.

3 Numerical simulation

We simulated these signal lines as a mass spring damper system and confirmed stable signal propagation using the proposed method. The signal plane has a mass (0.5), internal springs (0.5) connect the signal planes, and each signal plane receives a damping force such that the speed becomes of original 60% in 1. The step time was 0.01, the side length of the cylindrical origami is 100, and the total width of the cylindrical origami pair was fixed at 160. The potential energy of the cylindrical unit was calculated by the Truss model [6], and the derivative was given as the force applied to the signal plane. We simulated three signal lines: only connecting the cylindrical origami pair with internal springs (the signal dissipates; normal), with additional external axial force (axial), and with additional external rotational force (rotational). The transmission was started by transitioning only the

![Fig. 3.](image)

Fig. 3. Signal transmission (a) without force, (b) with axial force, and (c) with rotational force.

state of the first unit and observing the movement of the successive units. The state of the transition is shown in Fig. 3. In the case of simply connecting a cylindrical origami pair with internal springs (normal), the transmission stopped halfway due to attenuation. On the other hand, the transmission propagates successfully reaching the end with external axial or rotational force. Only ten units are shown in the figure, but the transmission continued through at least 100 units. Also, the last unit changes state and carries momentum because there is no successive unit. Thus, we can use this leftover
momentum as an activation trigger, for example, by applying this force to a piezoelectric element.

Furthermore, the transition was transmitted stably regardless of the speed and momentum of the first transition. Regardless of whether the transition of the first unit is performed in 0.01 (fast) or 10 (slow), the signal is transmitted at least by 100 units. Thus, it is also possible for minute environmental changes to generate large enough signals to trigger transmission.

The logic gates were similarly simulated to derive the spring constant connecting the inputs and output. With an axial force, a spring with a constant of 0.05–0.14 will make an AND gate, and a spring with a constant over 0.15 will make an OR gate. With rotational force, a spring with a constant of 0.07–0.25 will make an AND gate, and a spring with a constant over 0.26 will make an OR gate.

These results show that a stable un-attenuated signal line can be constructed using cylindrical origami and external springs, as well as functional diodes and logic gates. The transition of the first unit does not require speed, and even small changes can trigger signal transmission. Moreover, the simulation shows that the logic gate can be implemented by only adjusting the strength of the spring connecting the front and back signal planes.

4 Conclusion

In this paper, we propose methods to create an un-attenuated signal line, a diode, and logic gates for mechanical signal transmission using bistable cylindrical origami units coupled with internal and external springs. By using the large transformation of origami, the signal line, the diode, and the logic gates become nondestructive and reusable. This structure can transmit the signal in both directions simply by switching the direction of external force applied and making the units symmetrical. We confirmed these properties by numerical simulation and derived the mechanical parameters required for producing logic gates.

This structure consumes no standby power if elastic energy is set with external springs. In addition, by adjusting the structure and material of the first unit, it is possible to construct a unit that makes a transition due to environmental changes. Likewise, since the final unit has the leftover momentum to make the next unit transition but no successive unit, this energy can instead be used to wake up another device, such as a unit that transmits a radio signal. By combining these functionalities, cylindrical origami signal lines can be used to build a distributed sensor monitoring system that does not need standby power in the transmission lines, and thus reduces energy consumption of the system and prolongs long-term deployment of such systems.

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