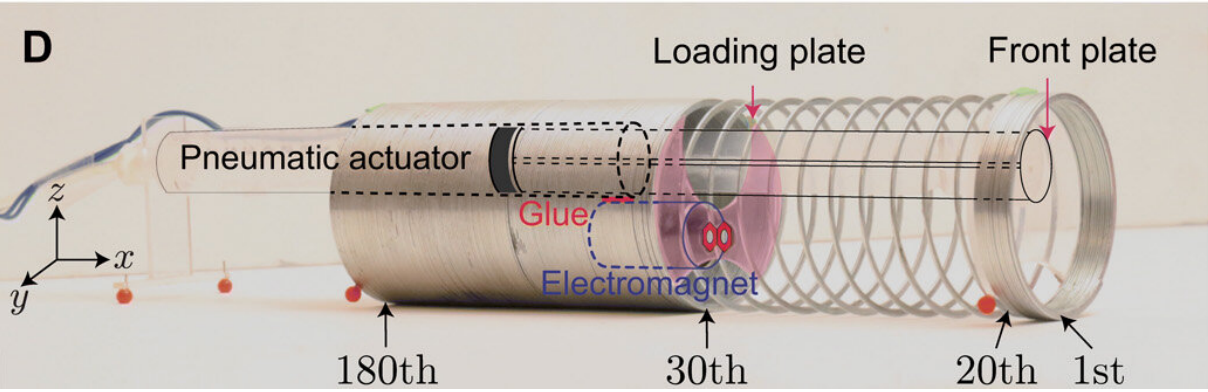
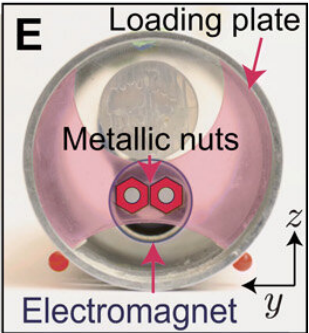
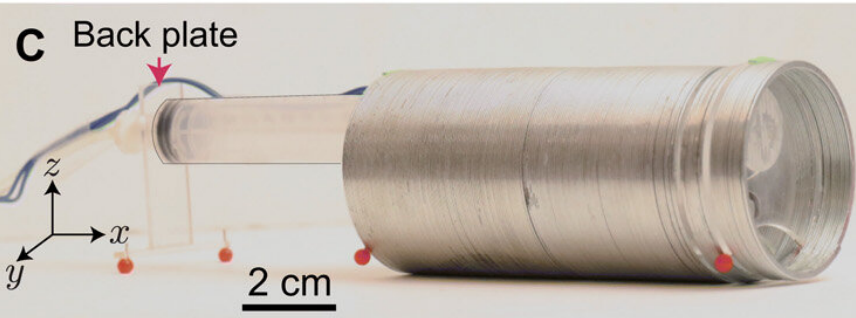
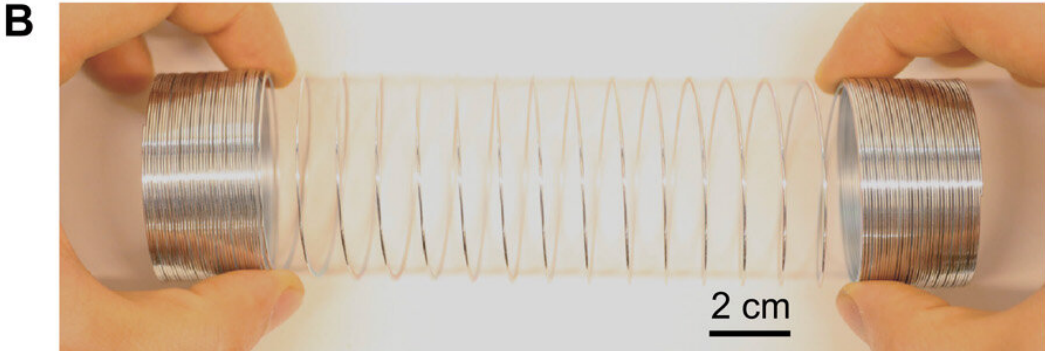
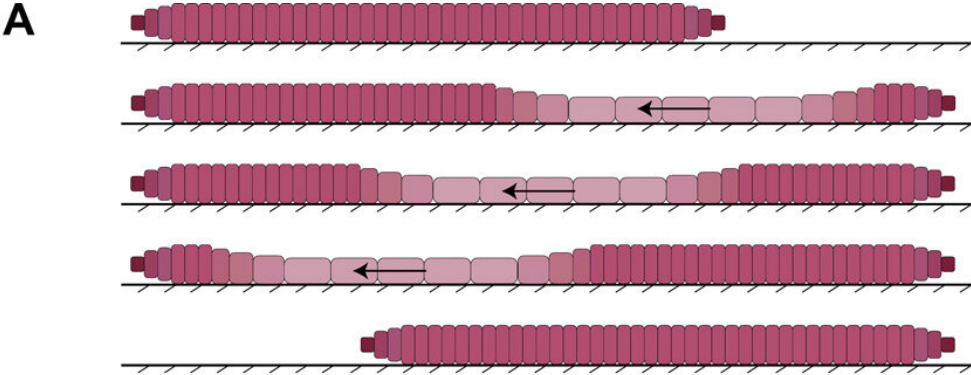


# Pulse-driven robot: Motion via solitary waves

May 8 2020, by Thamarasee Jeewandara

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The Slinky-robot. (A) Schematic showing the locomotive mechanism of an

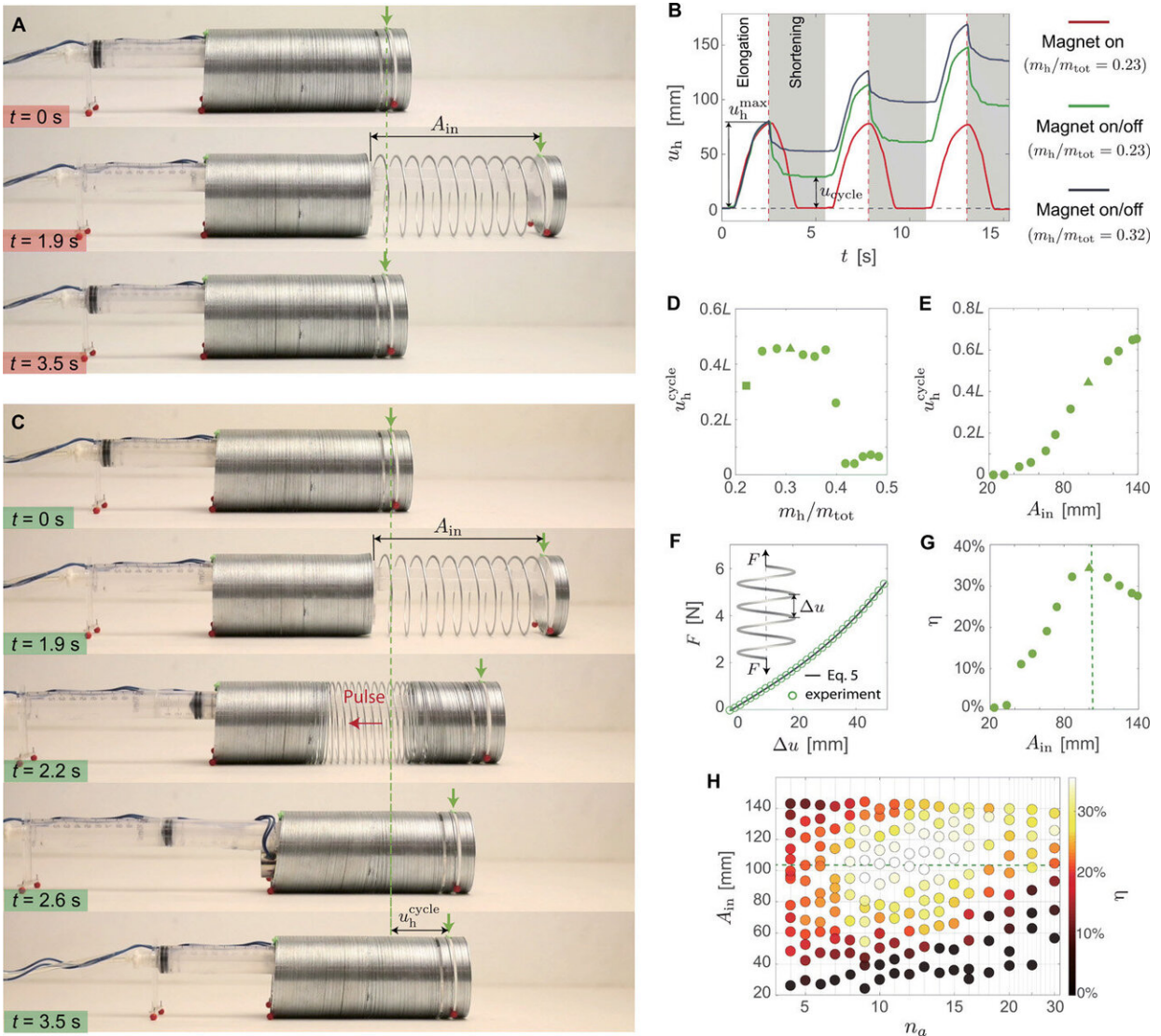
earthworm based on retrograde peristaltic waves (i.e., waves that propagate in the opposite direction to locomotion). (B) Picture of metallic Slinky used in this study. (C and D) Pictures of our Slinky-robot (C) before and (D) after the pneumatic actuator is elongated. (E) Front view of the Slinky-robot showing the electromagnet. Note that several red plastic spheres are glued on to the Slinky to prevent it from rolling. Photo credit: Bolei Deng, Harvard University. Credit: *Science Advances*, doi: 10.1126/sciadv.aaz1166

Scientists have recently explored the unique properties of [nonlinear waves](#) to facilitate a wide range of applications including [impact mitigation](#), asymmetric transmission, switching and focusing. In a new study now published on *Science Advances*, Bolei Deng and a team of research scientists at Harvard, CNRS and the Wyss Institute for Biologically Inspired Engineering in the U.S. and France harnessed the propagation of nonlinear waves to make flexible structures crawl. They combined bioinspired experimental and theoretical methods to show how such pulse-driven locomotion could reach a maximum efficiency when the initiated pulses were [solitons](#) (solitary wave). The simple machine developed in the work could move across a wide range of surfaces and steer onward. The study expanded the variety of possible applications with nonlinear waves to offer a new platform for flexible machines.

Flexible structures that are capable of large deformation are attracting interest in [bioengineering](#) due to their intriguing static response and their ability to support elastic waves of large amplitude. By carefully controlling their geometry, the elastic energy landscape of highly deformable systems can be engineered to propagate a variety of nonlinear waves including vector solitons, transition waves and [rarefaction pulses](#). The dynamic behavior of such structures demonstrate a very rich physics, while offering new opportunities to manipulate the propagation of mechanical signals. Such mechanisms can allow

[unidirectional propagation](#), [wave guiding](#), [mechanical logic](#) and [mitigation](#), among other applications.

In this work, Deng et al. were inspired by the biological retrograde [peristaltic wave motion](#) in earthworms and the ability of linear elastic waves to generate motion in [ultrasonic motors](#). The team showed the propagation of nonlinear elastic waves in flexible structures to provide opportunities for locomotion. As proof of concept, they focused on a [Slinky](#) – and used it to create a pulse-driven robot capable of propelling itself. They built the simple machine by connecting the Slinky to a [pneumatic actuator](#). The team used an electromagnet and a plate embedded between the loops to initiate nonlinear pulses to propagate along the device from the front to the back, allowing the pulse directionality to dictate the simple robot to move forward. The results indicated the efficiency of such pulse-driven locomotion to be [optimal with solitons](#) – large amplitude nonlinear pulses with a constant velocity and stable shape along propagation. The study expanded applications of solitary waves (solitons) while showing how they can be explored as simple underlying engines to assist flexible machines to move.

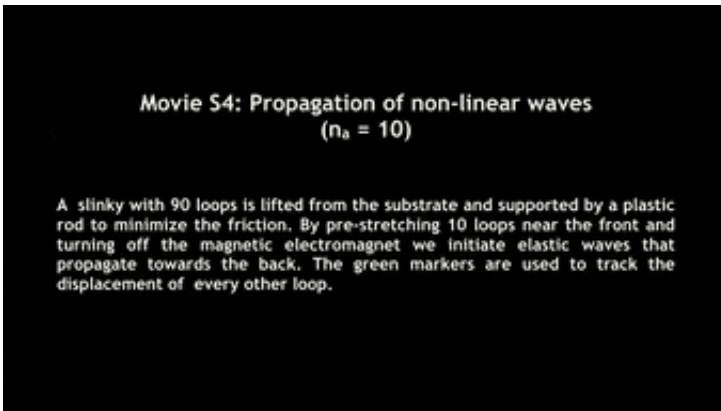


Performance of the Slinky-robot. (A) Snapshots taken during a test in which we extend the front 10 loops to  $A_{in} = 100$  mm while keeping the electromagnet on. (B) Displacement of the head during three cycles for tests in which (i)  $m_h/m_{tot} = 0.23$  and we keep the electromagnet on (red line), (ii)  $m_h/m_{tot} = 0.23$  and we turn off the electromagnet after stretching (green line), and (iii)  $m_h/m_{tot} = 0.32$  and we turn off the electromagnet after stretching (blue line). (C) Snapshots taken during a test in which  $A_{in} = 100$  mm and we turn the electromagnet off after stretching the front loops. (D) Evolution of  $u_h^{cycle}$  as a function of  $m_h/m_{tot}$  for tests in which  $A_{in} = 100$  mm. The square and triangular markers correspond to  $m_h/m_{tot} = 0.23$  and  $0.32$ , respectively. (E) Evolution of  $u_h^{cycle}$  as a function of  $A_{in}$  for tests in which  $m_h/m_{tot} = 0.32$ . The triangular marker



corresponds to  $A_{in} = 100$  mm. (F) Static response of the Slinky as measured in a uniaxial test. (G) Evolution of  $\eta$  as a function of  $A_{in}$  for tests in which  $m_h/m_{tot} = 0.32$ . The triangular markers correspond to  $A_{in} = 100$  mm. The green dashed line corresponds to the amplitude of the supported soliton,  $A_s$ . (H) Evolution of  $\eta$  as a function of  $n_a$  and  $A_{in}$  for tests in which  $m_h/m_{tot} = 0.32$ . Photo credit: Bolei Deng, Harvard University. Credit: Science Advances, doi: 10.1126/sciadv.aaz1166

To create the Slinky robot, Deng et al. used a metal Slinky with a length of 50 mm and 90 loops, to then test and understand how to explore its intrinsic flexibility, and create a simple machine capable of movement. They connected two slinkies in series (100 mm, 180 loops) for a simple actuation strategy based on a pneumatic actuator, an electromagnet and three acrylic plates. They could stretch and shorten the setup using the pneumatic actuator while keeping the electromagnet on. The team tested the response of the machine by placing it on a smooth surface and monitoring it with a high-speed camera. Deng et al. then turned off the magnetic field in an attempt to break symmetry and cause the machine to crawl. They did not observe a reflected wave in the Slinky due to the large energy dissipation upon collision of the loops and instead observed clear forward movement of the robot. The team therefore explored the directionality introduced by the elastic waves to make the robot move—even in the presence of identical friction coefficients.



Propagation of non-linear waves. A slinky with 90 loops is lifted from the substrate and supported by a plastic rod to minimize the friction. By pre-stretching 10 loops near the front and turning off the magnetic electromagnet we initiate elastic waves that propagate towards the back. The green markers are used to track the displacement of every other loop. See full movie on Credit: Science Advances, doi: 10.1126/sciadv.aaz1166

Attempts to make the flexible machine crawl via elastic pulses however revealed the experimental conditions to be suboptimal. For instance, they noticed backsliding immediately after turning off the electromagnet. To limit this motion, Deng et al. increased the mass at the head of the Slinky robot while optimizing the value to identify an optimal range. The Slinky maintained 10 loops between the front and loading plates in the setup. The team designated the maximum distance between the loading and front plates as  $A_{in}$ , which approximated 100 mm. To understand how the efficiency of the robot was a maximum for  $A_{in} = 100$  mm Deng et al. carefully investigated the propagation of large-amplitude pulses through the Slinky.

For these experiments, they focused on a single Slinky and monitored the position of green markers located at every other loop. They then initiated elastic waves that propagated towards the back by pre-stretching 10 loops near the front and turning off the electromagnet. The tests

allowed the team to gather deeper insights to the propagation of pulses by monitoring the displacement of each loop. The scientists realized two main features of the robot; 1) the backward-propagating waves moved the center of mass of the Slinky forward and 2) the Slinky supported the propagation of large-amplitude solitary waves.

**Movie S3: Effect of  $n_a$  on locomotion  
( $m_h/m_{tot} = 0.32$  and  $A_{in} = 100$  mm)**

For  $n_a = 4$  the pulses are too strong and their energy dissipates via collisions between the loops. For  $n_a = 30$  the pulses are too weak and barely propagate.

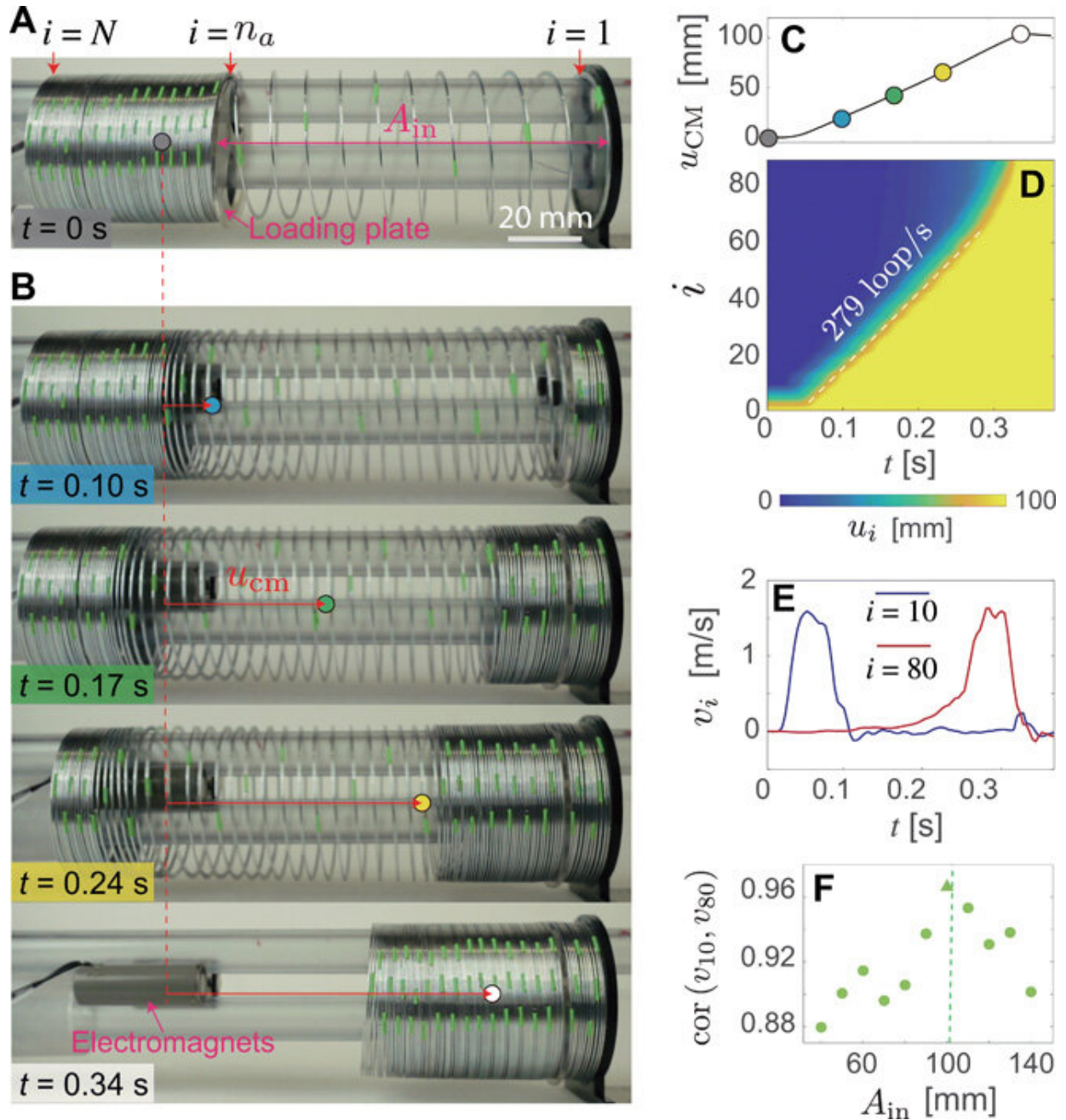
For  $n_a = 4$  the pulses are too strong, and their energy dissipates via collisions between the loops. For  $n_a = 30$  the pulses are too weak and barely propagate. See full movie on Credit: Science Advances, doi: 10.1126/sciadv.aaz1166

To gain further insight into the experimental results, Deng et al. developed a mathematical model that represented the mass and elasticity of an individual loop. The calculated results matched extremely well with the experimental outcomes and the model confirmed the experimental observations. The analysis further confirmed the efficiency



of the Slinky robot to be at a maximum when the initiated waves were solitons. The nondispersive nature and compactness of solitary pulses made them extremely efficient to transfer the energy provided from the pneumatic actuator into motion in order to obtain the most efficient pulse-driven locomotion.

In this way, Deng et al. showed how backward propagating solitons could efficiently move a Slinky robot forward. Even though limbless organisms have [previously bioinspired](#) engineers to design a variety of robots, the team believe this work to be the first robotic system to rely on elastic pulses to move. The principles presented in the study were different from those used by ultrasonic motors, since the flexible Slinky robot used nonlinear pulse waves to change the position of the center of mass, ultrasonic motors are in contrast powered by linear sinusoidal waves. The team only focussed on [rectilinear forward crawling](#) in this work, but they can explore the flexibility of the Slinky to achieve a range of motions.



Wave propagation in the Slinky. (A) Experimental setup used to test the propagation of pulses in the metallic Slinky. At  $t = 0$  s,  $n_a = 10$  loops between the loading plate and the front of the Slinky are stretched to  $A_{in} = 100$  mm. (B) Snapshots of the propagation of the pulse in the Slinky at  $t = 0.10$ ,  $0.17$ ,  $0.24$ , and  $0.34$  s. The circular markers indicate the positions of the center of mass of the Slinky. (C) Displacement of the center of mass of the Slinky,  $u_{CM}$ , as a function of time. Circular markers correspond to the time points considered in

(A) and (B). (D) Spatiotemporal displacement diagram of the propagating pulse. (E) Velocity signals measured at the 10th and 80th loops. (F) Evolution of the cross-correlation of  $v_{10}(t)$  and  $v_{80}(t)$  as a function of the input amplitude  $A_{in}$ . The triangular marker corresponds to  $A_{in} = 100$  mm. The green dashed line corresponds to the amplitude of the supported soliton,  $A_s$ , predicted by equations derived in the study. Photo credit: Bolei Deng, Harvard University. Credit: *Science Advances*, doi: 10.1126/sciadv.aaz1166

The team next intend to steer the robot by twisting the last loop at the back of the device and control the steering angle, while emphasizing the existing possibility to move the [robot](#) across a broad range of surfaces. Although Deng et al. only used a Slinky to realize [pulse](#)-driven locomotion in this work, the principles are general and can be expanded to a broad range of stretchable systems across scales to open avenues for microscale crawlers suited for medical applications.

**More information:** Bolei Deng et al. Pulse-driven robot: Motion via solitary waves, *Science Advances* (2020). [DOI: 10.1126/sciadv.aaz1166](https://doi.org/10.1126/sciadv.aaz1166)

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