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Optically enriched and guided dynamics of active skyrmions

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Abstract: Light provides a powerful means of controlling physical behavior of materials but is rarely used to power and guide active matter systems. We demonstrate optical control of liquid crystalline topological solitons dubbed "skyrmions", which recently emerged as highly reconfigurable inanimate active particles capable of exhibiting emergent collective behaviors like schooling. Because of a chiral nematic liquid crystal's natural tendency to twist and its facile response to electric fields and light, it serves as a testbed for dynamic control of skyrmions

as a favorable testbed for stabilization of topological solitons because of the facile ability to control the energetic landscape within materials such as solid-state magnets and LCs [23–35]. Chiral nematic LCs provide a favorable host for stabilization of twisted solitons, such as so-called skyrmions [31] and hopfions [23,24], because of the material's natural tendency to twist and the ensuing nonlinear nature of the free energy functional. [36–38] The simplest two-dimensional elementary skyrmion is an axi-symmetric translationally-invariant structure in which the field vectors exhibit -twist radially outward from the center to the periphery [31]. Like their higher-dimensional counterparts, the two-dimensional elementary skyrmion cannot be eliminated or destroyed by smooth perturbations of the field and is therefore stable under a variety of conditions and external field manipulations [37]. One can drive skyrmion motion by electric currents in magnetic materials [29,30]. Skyrmion motion can also be realized in chiral LCs by means of rotational dynamics of the LC director field **n(r)** prompted by modulation of electric fields, in which the electric power is applied via electrodes on confining substrates, similar to those used in display technologies [9,15,16,39,40]. However, this electrically-induced active motion has only limited types of collective emergent behavior. Previous developments only allow for one "setting" of motion where all skyrmions tend to synchronize to move together at a constant velocity and in the same direction [9]. Inspired by complex dynamics that one observes in crowds of people and other active systems interacting with various obstacles and environments, we present an experimental approach for selective control of skyrmion motion using diverse optical manipulation techniques. Optical tweezers are used to create obstacles and to set directions in the field of motion whereas patterned blue light illumination, coupled with photo-tunable cholesteric pitch behavior [17], provides hands-off manipulation of the energetic landscape within the sample. The combination of these optical manipulation tools is used to guide, deflect, and reconfigure skyrmion motion. The electrically-powered skyrmion motion [39], optical manipulation using laser tweezers [37], and photo-manipulation using patterned light illumination [17,41,42] are combined to enhance collective motion controllability. We demonstrate reconfigurations of the dynamic skyrmion "crowds" into single-file lines, steer and inhibit skyrmion motion by changing polarization of patterned light illumination, optically induce skyrmion jamming and unjamming transitions, and other means of controlling complex motion with emergent active behavior.

2. Materials and methods

We employ experimental implementation of samples reminiscent of LC displays, as is shown in the experimental schematic, Fig. 1(a). These inch-square samples are created by infiltrating a chiral nematic LC mixture into a glass cell constructed by gluing two conductive substrates together and setting the cell gap with 10 µm glass spacers. The inner surfaces of the glass substrates have transparent conducting layers of indium-tin oxide and were pre-treated for finite-strength vertical surface boundary conditions via spin-coating with SE-1211 (purchased from Nissan) at 2700 rpm for 30 s. To induce crosslinking of the alignment layer, the substrates were then baked for 5 min at 90°C and for 1 h at 190°C. The LC mixture is composed of a nematic host with negative dielectric anisotropy, either MLC-6609 (Merck) or ZLI-2806 (EM Chemicals), that has been heated to the isotropic phase for thorough mixing with a chiral additive (Table 1). For experiments done in samples without photo-sensitivity to low-intensity blue light, the additive CB-15 from EM Chemicals was used. Alternatively, mixing the nematic hosts with the QL-76 additive (obtained from the Air Force Research Lab [39]) enabled photo-tuning of the chiral pitch, p_0

power of the QL-76 dopant [44] which, in our samples, enables tunability from $p_0 = 10\,\mu m$ to p_e

[redacted]

generated using a Jones matrix method [39,15] in which the optical properties of the material (Table 1) and the sample thickness are taken as numerical inputs for calculating the resulting polarizing optical microscopy textures that one would expect to see. The material parameters used in these computer simulations presented in Fig. 1

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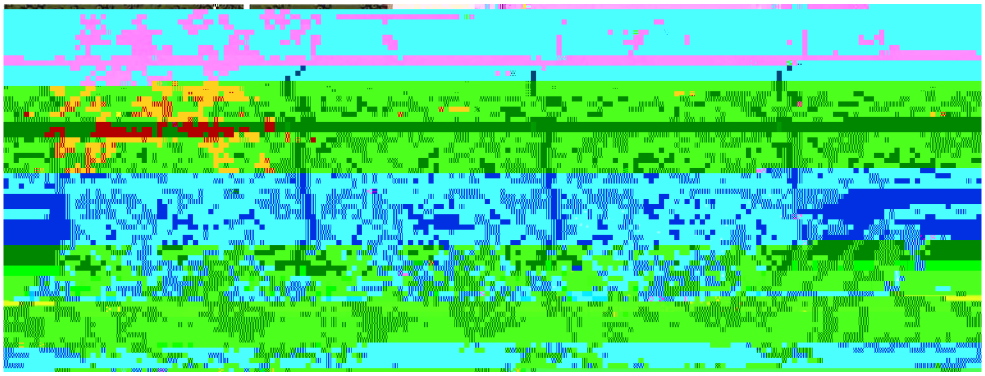

Fig. 2. Jamming skyrmion crowds with optically-induced obstacles. (a) Polarizing optical images corresponding to frames taken from Visualization 2 (played at 30x speed). Motion is powered at by oscillating electric field with voltage U = 3.5 V and oscillation frequency f = 60 Hz. Red points in the first and last frames denote skyrmions selectively-pinned to the confining substrates using optical tweezers. White double arrows mark polarizer orientations in a polarizing optical microscope. (b) Displacement of the skyrmions in the bottom right region as jamming occurs, with corresponding skyrmion velocity shown in the inset.

initial skyrmions and obstacles (Fig. 3, Visualization 3), where the jamming still occurs but differently than in the previous case. Once we observe jamming start to occur during the U = 3.5 V motion, we increase the applied field to U = 4 V, which induces more squeezing of the asymmetric skyrmion structures [37] and allows them to compress themselves into closer-packed clusters and overcome the jamming. The clusters at higher voltage, which are comprised of skinnier skyrmions of smaller lateral dimensions, then regain their motion and smoothly traverse through the remaining obstacles.

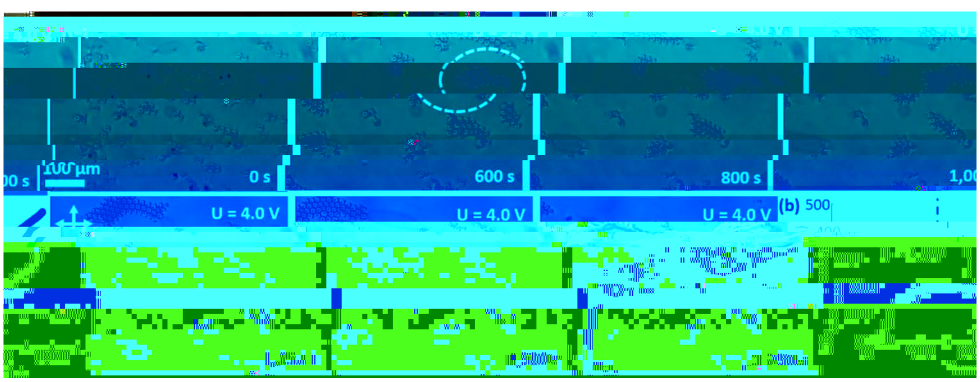

Fig. 3. Using applied voltage to manipulate skyrmion size and overcome jamming. (a) Polarizing images corresponding to frames taken from Visualization 3 (played at 110x speed). The motion is powered by the voltages marked in the top right corners of each frame (with U = 4.0 V corresponding to the smaller skyrmion size) and f = 60 Hz. Red points in the first and last frames denote skyrmions selectively-pinned to the confining substrates using optical tweezers. Skyrmion trajectories are overlaid on the last frame, color-coded according to elapsed time (inset). White double arrows denote the crossed polarizer orientations in an optical microscope. (b) Displacement of the cluster marked with a white dotted circle in part (a) versus time; changing the amplitude of applied voltage from 3.5 V to 4.0 V at the time marked by the vertical dashed line is used to overcome jamming marked.

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Instead of being used to induce jamming, the obstacles can also be created in a way that mediates continuous, uninterrupted motion of many skyrmions at once. By organizing the obstacles into channels (Fig. 4, Visualization 4), the skyrmions can be funneled from a dispersed "crowd" into neat single-file lines. Qualitatively reminiscent of crowds of people passing through security gates, Figs. 1(b)–1(d), the skyrmions demonstrate short-range persistence of the directional motion induced by the obstacles, Fig. 4(b), though we point out that this analogy is limited as solitons are just localized topological structures of director field that have no physical boundaries. Because this funneling behavior occurs through both short and long "gates", or rows of pinned

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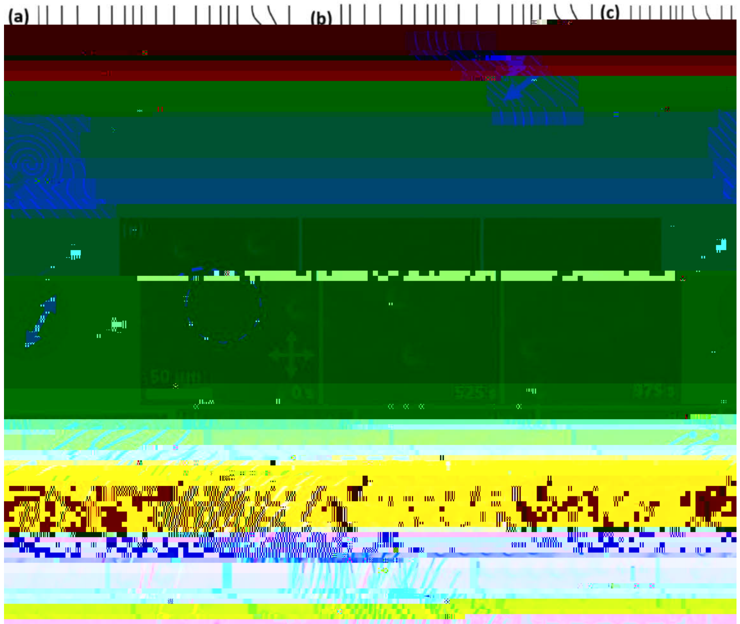

Fig. 5. Dynamic response of skyrmions in motion to patterned linearly polarized light. (a-d) Schematics of the midplane director field showing the director orientation in the midplane of the sample for (a) a region with asymmetric skyrmions before patterned illumination and (b) the same region with skyrmions and a small exposure area (blue); the corresponding change in the midplane director field is shown with blue lines within the area where the midplane director field turns to be perpendicular to the polarization direction of the illumination light (blue double arrow). (c-d) Schematics of the midplane director field for a single skyrmion in motion (c) without illumination and (d) with illumination, where the polarization is the same as in part (b). Black arrows mark the direction of motion. (e) Polarizing optical images of a few skyrmions in motion, with the skyrmion that passes through the illuminated region (marked with dotted circle in the first frame) being deflected (re-directed) by the light. (f) Corresponding schematic illustrating the skyrmion trajectories with dotted lines, illumination area in blue, and the blue-light polarization with a double-headed blue arrow. (g) Polarizing optical images of a lattice of skyrmions in motion, with the illuminated region marked with a dashed blue box. Color-time-coded trajectories in the last frame show the starting (blue dots) and ending positions (red dots) for three skyrmions. The inset in the 3rd frame shows the time-color-coded scale. (h) The initial polarizing image from (g) with all skyrmion trajectories overlaid and colored according the inset in the 3rd frame of (g). Motion in (e-h) is powered by applied oscillating electric field at U = 3.5 V with f = 1 kHz (carrier frequency), modulated at 2 Hz. White double arrows in (e) mark polarizer orientations.

this sample's region of illumination, they slow down from 0.30 µm/s to 0.25 µm/s then, upon overcoming the energetic barrier induced by the blue light, accelerate to 0.36 µm/s within the illumination area. Once outside of the blue-light region, the velocity falls back to the average 0.30 µm/s, Figs. 5(e) and 5(f). This dynamic behavior can be understood as a combined effect due to both tuning pitch with optical illumination and rotating the cell midplane's director to orient orthogonally to the polarization of the blue illumination light.

Our experimental projection setup enables application of various illumination shapes and patterns, which we utilize to show the tunability of directional steering. To do this, a pattern

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5). As the self-assembled chains move towards the left side of the frame in Fig. 6, one chain in particular travels into the channel then "feels" the exposure near the center of the channel, where the reorientation is arguably the strongest, and then rotates to travel upwards in a trajectory parallel to the direction of the linear polarization of illumination light (Fig. 6).

Fig. 6. Directional steering of dynamic skyrmion chains using patterned light illumination. Polarizing optical images, taken as frames from the Visualization 5 (played at 60x speed), of self-assembled chains of skyrmions in motion at U = 3.5 V and f = 1kHz (carrier frequency), modulated at 2 Hz. Blue dashed lines in the first frame mark the sample region exposed to patterned light illumination, with blue double arrows marking the direction of the blue light's linear polarization. White double arrows mark the optical microscope's crossed polarizer orientations.

3.3. Reconfiguring skyrmion motion using laser-patterned obstacles and light

We have now developed an experimental system with multifaceted, adjustable properties that can be used to influence skyrmion motion. Next, we investigate how a combination of these semi-permanent and short-term control tools can be used to facilitate new emergent behavior within the collective migration of school-like assemblies. One such example of emergent behavior lies in the dynamic rearrangement of skyrmion chains (Fig. 7, Visualization 6), in this case utilizing both pinned obstacles and the steering mechanism induced by blue-light illumination, with the polarization direction set to be perpendicular to the un-exposed trajectories of motion. In this case, the laser-pinned obstacles act as nucleation sites for the oscillatory motion of chains that elastically attach themselves to the stationary obstacle sites and then swirl and reconfigure their snake-like assemblies, moving in and out of the exposure area and thus individually changing their orientations and motionar66

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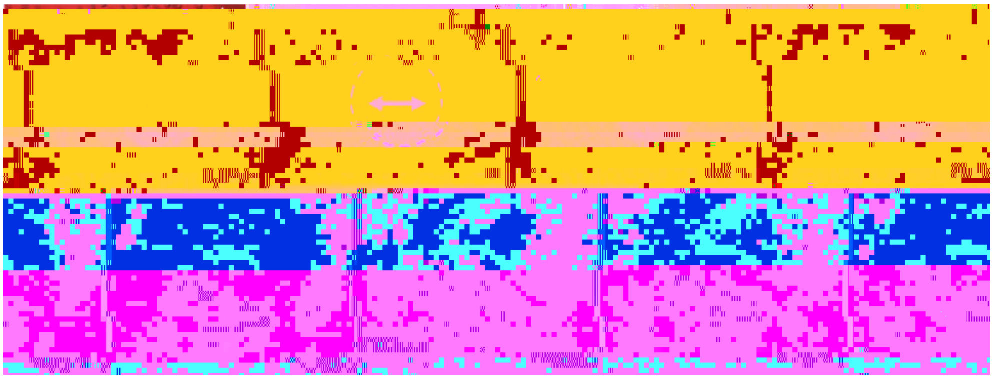

Fig. 7. Reconfigurable motion and self-assembly of skyrmions under light illumination interacting with pinned obstacles. Polarizing images taken as frames from Visualization 6 (played at 70x speed), where motion is powered at U = 3.5 V and f = 1 kHz (carrier frequency) modulated at 2 Hz. The blue dashed circle in the 1st frame denotes the illumination area with a blue double arrow marking the direction of blue-light linear polarization. White double arrows mark the microscopy polarizer orientations. Two pinned skyrmions are marked with white crosses in the last frame.

when skyrmions in motion come near the defect, they are deflected and sidetracked according to the direction of the local tilt directionality field, moving orthogonally to it. This likewise has long-range effects on the trajectories of motion, which develop complex swirling pattern that persists over long periods of time, Figs. 8(d)–8(g). During this motion, random skyrmions in motion temporarily get stuck on various pinning sites (marked by red crosses within the experimental images in Figs. 8(d) and 8(f) and, favorably, can free themselves from the pinning sites and persist with their emergent collective movement. This finding demonstrates that the technique for pinning obstacles with laser tweezers can either be used as a permanent or a temporary means of hindering and adjusting trajectories of motion. This observation also provides a number of new experimental knobs to turn for controlling and guiding active topological solitons. In particular, one can envisage optical or other types of patterning of the director field in the midplane that can lead to electrically powered transport of LC skyrmions along well-defined pre-programmed trajectories. Although trajectories of motions of similar skyrmions can be defined by real-time scanning infrared laser beams of optical tweezers with velocity that allows for skyrmions following the laser traps without escaping them, Figs. 8(h) and 8(i), the demonstrated capability of combining ambient-light-based control of electrically powered skyrmion motions, Figs. 8(a)–8(g), can be used over much larger areas and without sophisticated laser tweezer setups. Additionally, it can be combined with the very same laser trap scanning to manipulate skyrmion dynamics in even more versatile ways, for example, to accelerate and re-direct skyrmion motions within localized sample regions, Fig. 8(i).

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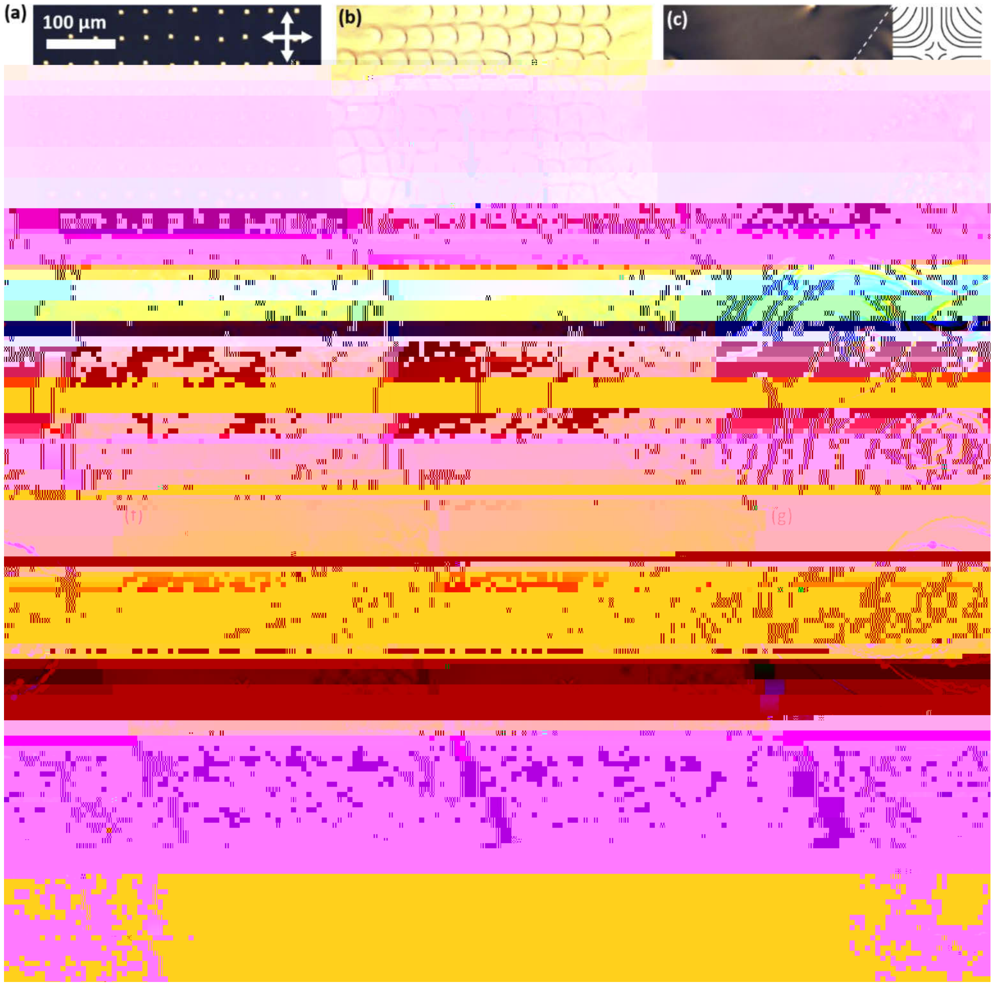

Fig. 8. Complex spiraling dynamics of skyrmions defined by light and oscillating electric fields. (a-c) Polarizing optical images of the skyrmion lattice taken from Visualization 7 (played at 15x speed) (a) prior to voltage application at U = 0 V and (b) at the onset of voltage application at U = 3.5 V and f = 1kHz (carrier frequency), modulated at 2 Hz. Patterned blue-light illumination is applied at the onset of motion for 10s within a sample region defined by the blue dashed box, with the blue double arrow denoting polarization of the illumination light. (c) Polarizing optical image obtained during voltage modulation and showing the texture of an unpaired umbilical defect (containing 4 dark and 4 bright brushes), with the corresponding field director profile (inset). (d) Polarizing optical images during complex skyrmion motion, where the dashed white box marks the same umbilic defect as described in part (c), but now observed in a brightfield imaging mode. (e) Trajectories of the skyrmion motion for the entire field of view shown in part (d), which are color-coded with time accord0.993 0 0 1, T

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4. Conclusions

In this work, we have established multifaceted means of control over topological solitons in collective emergent motions by manipulating the velocity, size, directionality, jamming and sorting behavior, and through the reconfigurability of skyrmion assemblies. We have accomplished this by utilizing a combining optical manipulations that have never been used in harmony to enhance this active behavior and uncover new means of experimental control. By selectively pinning topological solitons to the surface alignment layer on the glass substrates using a focused optical laser tweezer setup, we create semi-permanent stationary obstacles around which skyrmions can move smoothly or exhibit jamming behavior or movement qualitatively reminiscent of crowds of people funneling through security gates. A photo-sensitive chiral additive enables precise steering and accurate manipulation of motion for both individual structures and self-assembled groups of skyrmions upon exposure by tuning the polarization of the blue-light illumination. When these techniques are used together, we gain multifaceted control over trajectories of motion and oscillatory-like behavior such as slithering and swirling of skyrmion chains. As these

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4. D. Needleman and Z. Dogic, "Active matter at the interface between materials science and cell biology," Nat. Rev. Mater. **2**(9), 17048 (2017).
5. T. Sanchez, D. T. N. Chen, S. J. DeCamp, M. Heymann, and Z. Dogic, "Spontaneous motion in hierarchically assembled active matter," Nature **491**(7424), 431–434 (2012).
6. V. Narayan, S. Ramaswamy, and N. Menon, "Long-lived giant number fluctuations in a swarming granular nematic," Science **317**(5834), 105–108 (2007).
7. N. Kumar, H. Soni, S. Ramaswamy, and A. K. Sood, "Flocking at a distance in active granular matter," Nat. Commun. **5**(1), 4688 (2014).
8. S. J. Decamp, G. S. Redner, A. Baskaran, M. F. Hagan, and Z. Dogic, "Orientational order of motile defects in active nematics," Nat. Mater. **14**(11), 1110–1115 (2015).
9. H. R. O. Sohn, C. D. Liu, and I. I. Smalyukh, "Schools of skyrmions with electrically tunable elastic interactions," Nat. Commun. **10**(1), 4744 (2019).

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