Electronic Supplementary Material (ESI) for Nanoscale.
This journal is © The Royal Society of Chemistry 2015

Mechanical Design of DNA nanostructures Supporting Information

Carlos E. Castro[1,2], Hai-Jun Su[1], Alexander E. Marras[1], Lifeng Zhou[1], Joshua Johnson[2]

[1]Department of Mechanical and Aerospace Engineering, The Ohio State University, Columbus, OH 43210
[2]Biophysics Graduate Program, The Ohio State University, Columbus, OH 43210

Table of contents:

- Cadnano design of 6-hb and staple sequences…… 2
- Staple list for 6-hb design…… 3
- Persistence length from conformational distribution……. 8
- Calculation of persistence length for rigidly coupled DNA origami bundles…… 9
- Stochastic simulations of DNA origami conformations……. 10
- Cadnano design of universal joint and staple sequences…… 12
- Staple list for universal joint…… 13
- Cadnano design of scissor mechanism and staple sequences……. 17
- Staple list for scissor mechanism structure……. 18
- Design and assembly of universal joint and scissor-mechanism structures…… 23
- Gel and TEM characterization of universal joint and scissor mechanism……... 24

6hb cadnano design (p7560 scaffold)

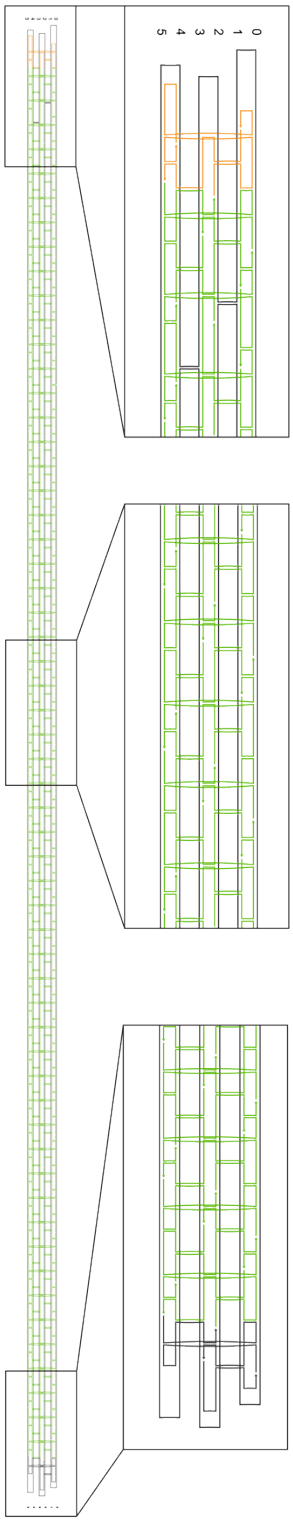

Figure S1: 6-helix bundle design utilizes a 7,560 nucleotide long scaffold. The green staples represent the core of the structure and staples at the edges were marked with different colors (black and orange).

Table S1: 6hb staple list

Sequence	Length	Color
GATGTGCTGAATTTAAGCGTTAAATAAGAAAAAAGGAAGCTT	42	black
TAATTGTATCGGTTTATTCGAGGTGAATTTTTACGCCAGGGG	42	black
TCTGACCTACAAGGCGGGGCCTCTTCGCTACTTAAACGCCTT	42	black
AAAATCACCAACGTAGCCAGCAGAAGATAATTAGAGCAAAGT	42	green
AAAGATTCAAAAAACAGCCCCAGCAGGCGACTTTACAGGGAG	42	green
AAAGGCCGCCAGCTTTGTGGATGTTCTTCTGGGTTATTAGGG	42	green
AAATAAACAGAAAGCGTGAATTACCTTATGATGTGTATGGGC	42	green
AAATACGTAGGAACAAGGAGTGACTCTATGTTAATTTGACAA	42	green
AAATATTTAGCCGGAATTGATATAAGTATACAAGTACATTTC	42	green
AACAAAATTCTGACCTATCAGCTCATTTTTCGGAGATTCAGA	42	green
AACCAAAATTGAAAAGGAACGTGGACTCCAGTCAGTTATCTT	42	green
AACCTTGCTCATCTGTATGTGAGCGAGTAACCTAAAACCGTA	42	green
AAGAATACGTAACCACAGTACCTTTAATTGAAGACTTGGGAG	42	green
AATAATAAGATAATCAACCCTCGTTTACCAACTAATAGAACA	42	green
AATACCGAACGGCGAAACATGTTTTAAATAATAAATCCCAGC	42	green
AATAGCCCGACTAACATAACCCACAAGAATAGAGCCAAGTAA	42	green
AATGAGTGAACGTAAATTTGAAGCCTTAAAAACAGTGCGTAA	42	green
AATTAACTGACCACCCAGATTTAGGAATACTAAAGCTGTTTG	42	green
AATTACCTGACGTGGTAACGTTAATATTTTCGACCTGATAGG	42	green
AATTTACGACTCAGAAGAAACAAAGTACAATAACCAACATTT	42	green
ACAAAACAATATTACCATAGAACCCTTCTGTTAATGCTCCAA	42	green
ACAATAGATGATAGCACTAAAACACTCATCTCCTGTAGAATA	42	green
ACACCAGAAATATTCAAAACCTGTCGTGCCATTGTTTTACCA	42	green
ACACTGAGTTGTTCAGATCGTCGCTATTAAATACCGATCGGA	42	green
ACATACGAGAACGTCAGAACGCGAGGCGTTGAACCTAGAGTA	42	green
ACCACCAGAGTTTTTCGCAATGCCTGAGTACGATTTTTTAAA	42	green
ACCCAAAAGGAAACCAAATATTCATTGAATAGTTGATAGCAC	42	green
ACCGAAGCCATTTTCGGGCTTTTGCAAAAGATTTTCAAGGGC	42	green
ACCGCCACCGCATGTATTTAACAATTTCATCATAAATTAGGA	42	green
ACCTTATGACAATAGTTCGAGCCAGTAATAACGATCTTTGAG	42	green
ACGACCAGTAGCACGTGGTACGCCAGAATCCGAGTAATAGAA	42	green
ACGCCATCACAAGCGCCCGCCACCCTCAGAATATCCCACCTT	42	green
ACGCTAACGCATGGCTTAAATTGGGCTTGAAGTCAAATTAAT	42	green
ACGGTGTCTGTTCAGACCATTACCATTAGCTTATTACGTGAG	42	green
AGAAGCCTTAACGAACTTGACAGGAGGTTGAGCAGCCTTAAT	42	green
AGACTACCTCACGACTCGACAGTATCGGCCAGCAGCGGTATG	42	green
AGAGAGAATGCCAGCATAACGGAACAACATTACTTTTGCAAG	42	green
AGAGCCGCCAACATAAAAATCCTTTGCCCGAGTTGCAGCGGG	42	green
AGAGGTCATAAAGATTCGGAAATTATTCATAAGTTTATTAGT	42	green

AGAGTCCACTGAAAGGAACAATGAAATAGCATTAGCGATAAA	42	green
AGATGATGGAACGCGCGAAAGGCCGGAGACGATGGTTCAGTA	42	green
AGATTCAAAATCATTGCAGTCTCTGAATTTTTGCCAGTTATC	42	green
AGCAAAATTCATAACGGAGCCGCCACCCTCGGGTAATATAGA	42	green
AGCATTAACTATCATAAAATCACCGGAACCTGAGTTAATATC	42	green
AGCGTCATAAGCGTCTTCAATATAATCCTGAGCTGCATCACC	42	green
AGGATTAGGCGCCCAAATAACGGATTCGCCCATGGTCCCGGT	42	green
AGGGGGTAAGTCAATAGGGCGATGGCCCACACCTTGCAACAA	42	green
AGTGCCGTCACAAGCATCGCGCAGAGGCGATAAAGACTAAGC	42	green
AGTTACCAGAAGTTTGATGTTTAGACTGGAATTAGATACCAT	42	green
ATAAACAGTGGGAGGTACAGAAATAAAGAACCTGGGGATCAG	42	green
ATAAGTTTTCACCCAGGAAGGGTTAGAACCTGCGCTCATGCC	42	green
ATAATGCTGTACCCTGTGAGCCATTTGGGAAAGGTGGTTAAA	42	green
ATACCAAGTTACCGAGCCCAAAAACAGGAATCAATCAGGATA	42	green
ATACTTCTGAGTCGGGACCGTTCTAGCTGACCCTGACTGGTA	42	green
ATAGAAAGGTTACCAGTGCAAATCCAATCGGTGCCAAGAAAC	42	green
ATCAACAGTTATTAAAGTGGCATCAATTCTGACGACGTTTGC	42	green
ATCAATATGCGAGTAGTTTGATGATACAGGTGAATCTGGATT	42	green
ATCACCGTCAACGCAAGATAGCCCTAAAACAAGGGAATGAAT	42	green
ATCCCCGGGTACAAAAAGCCGTTTTTATTTACCAGGCTAAGG	42	green
ATCGCGTTTATTAGAGCACACCCGCCGCGCACCTGAACAAAG	42	green
ATCTTGACATGAGAGTCATAAAGTGTAAAGATTGCGTACCTC	42	green
ATGCAGATAAAGCAATCGGCAAAATCCCTTGCCGTCATGAGC	42	green
ATGGTGGTTTGAGGATTGAACAAAGTCAGAAGAACCGAACTA	42	green
ATGTTAGCAAGTAGCAAAACGAGAATGACCTGCAACTTTGAC	42	green
ATTAAATTTGATAAATGGAGGTTTAGTACCATCGGCTAAGAA	42	green
ATTATTTGCGCTAACTTTTGAGAGATCTACAAATCAACCCGT	42	green
ATTCATGCGTTTTAACCATATTTAACAACGATTTTCTAAAGA	42	green
ATTCCACAGAAAGGTAATAGCGATAGCTTACCGCTTCGATAG	42	green
ATTCTGCGACGTCATATCGATAGCAGCACCTAATAACTGAGA	42	green
ATTTTCAGGAAGTCCTACATAAATCAATATTGGGCACGCCAG	42	green
CAAAGCTGCAGCTATTCACATTAATTGCGTTACCATATAGTT	42	green
CACCCAAATAAATGAACCGAGGAAACGCAAGTAATCACAATA	42	green
CACGTTGAACTAGAAACAAATATATTTTAGCGCCAGGGTTGG	42	green
CACTCCAGCTTTTGCGCTTTCAACAGTTTCTCAACAGATAAC	42	green
CAGCATCGGGGGACGATAAGTGTCCTTAGTCATAGGTGTAAT	42	green
CAGGCAAAGGATATATAAAGGAATTGCGAATCATATGAAGAA	42	green
CAGGTCAGGTAATTCGGGGCGACATTCAACCCAGCGCAGCGT	42	green
CAGTTTGAGAACGAGGACGTTAGTAAATGACCAACATCTGAG	42	green
CATCTTTTCAGCAAGAAATTGAGGAAGGTTCAGTTTGGTAGT	42	green
CCAGATACCTTGCTGGTAATATCCAGAAAGCTTCAAAGCGAA	42	green

CCATTGCAACTATCGGATCAGTGAGGCCACCTGAGAATGGTT	42	green
CCCAGTCACACTTTTTAAGCCTGTTTAGTATAATAATGCCCA	42	green
CCGACTTGCTAATGCCGATATTCATTACCCAAAGGCTTGCCT	42	green
CCGCTTTCCAATAATGCTACAATTTTATCCAGTGTACGAGAA	42	green
CGAAAGGAGGCGAACTAGACACCACGGAATTAAAGGTGCGGA	42	green
CGATTATACAAAATAAGCTGACGCATTTCATTGAATTATCCT	42	green
CGATTGGCCTTTAACGACATTATCATTTTGACGGGCAGAACC	42	green
CGCATAACCCGCCATTTAAAACGACGGCCACAAGACACGTTA	42	green
CGCGAGAAAGACGTTGCGCCATTCAGGCTGAACCATCTTTTT	42	green
CGCTGCGCGTGGCACAATTCATATGGTTTACGATTGACAAAT	42	green
CGGCCCTGCTCTGTAACTAATGCAGAACGCCCATGTACGAAA	42	green
CGGTAATCGGGCGCATTTAAGAGGCTGAGAGATATAGCCTTT	42	green
CGGTCCACGTCGTATTAAACAGGGAAGCGCAGAACCAGGTAG	42	green
CGTTAATAATATTTCACCTGGCCCTGAGAGAACGTTATTTAC	42	green
CTCAAATATTCTATCAACCTGTTTAGCTATAAGTTTTGCGTT	42	green
CTCAGAGCCAACACCCTTAGAAGTATTAGAAAATCCTAAATC	42	green
CTCAGGAGAATGCTGATATAAAGCCAACGCAGCGGAGGAGTT	42	green
CTCATATATTATACCATCACAAACAAATAACAAATAAAAGAA	42	green
CTCCGAACTAATTACAGAAACCAATCAATAGCCACCCTTGTA	42	green
CTGAAACATATTCTAAGATGAATATACAGTCAATTCCATGAA	42	green
CTGCGGAATACGAGTATTTGGGGTCGAGGTGCCACGCGGAAT	42	green
CTGGCTCATTTTAAATTTTTCACCAGTGAGCGGAACAGAAAC	42	green
CTTAATTGATAAACAAGGATCGTCACCCTCTCAGGAATGTGA	42	green
CTTTAAACAGGAAGTTAGGGAGCCCCCGATAACAGAGGCAGT	42	green
CTTTAATGCCGGGCGCGATGGCTTAGAGCTAAGCAAAGAATT	42	green
CTTTCATCAGAATACAAGCCCAATAGGAACGCCTGTTTGAAT	42	green
GAAAAACCGCAAACCCAGAAAAGTAAGCAGCTGTAGCGCCAG	42	green
GAACCGAACGAAAAGCCTCGAATTCGTAATTGATTGCAGGAA	42	green
GAACTCAAACAGGAAAGGGACATTCTGGCCCGTACTAGTGTT	42	green
GAAGGGCGAAGTTGCGAAAAAAAAGGCTCCTAAACACCATCT	42	green
GAATCGGCCCAATTCATTCCAGAGCCTAATACCGTTCTAATT	42	green
GACAGAATCAAGGAAAAAATCTAAAGCATCTACGTGAACATT	42	green
GACTAAAGAGTGTAGACCGCCAAAATAACCGATTAAGATAAA	42	green
GAGAAGAGTCAATGTCTGGGCGCATCGTAAAGAGGCTAAAGT	42	green
GAGCAACACATCCAATGTTGAGTGTTGTTCATCTAAAAGCCC	42	green
GAGGCAAAAACATTAAAAGCAACTCGTCGGATGTGAGTATCA	42	green
GATACCGATTCGGTGCATTAAGTTGGGTAATTAATTTCGGAA	42	green
GATTTTTTGTTGATATGTCAGGACGTTGGGATTTTTAACAGC	42	green
GCCAGAATGGCCATATGAATTATCATCATATGCGTATGGTAA	42	green
GCCAGCAGCCAAGTTTGATTTAGTTTGACCTAGCGTCGTAGC	42	green
GCCAGGGTGAGGAGCGTATTTATCCCAATCATCCTCAAAGAA	42	green

GCGGTCAGTACCCTAATCATTCCATATAACCCCCCTCGAAAC	42	green
GCTAATATCTCCCTCACCAAAAGGAATTACAGGCAAAAAAAG	42	green
GCTATTTTGAACGGGGGTGAATAAGGCTTGTAAATTAACTGC	42	green
GCTTAAGCTAGCAAAAAACGGGTATTAAACGCCCGGACTCCA	42	green
GCTTTGACGAATAAAAAACGCTCATGGAAAGCCTGAGAAGAG	42	green
GGAACCGCCAGAGAGAACTAATAGATTAGAATAAATCGAATT	42	green
GGAAGGTAAATAGAAAGACAATATTTTTGAGTGTAGCTGATA	42	green
GGAGAGGGTTCATTCATCAGTGCCTTGAGTTCAAGATTCAAA	42	green
GGATTTTGCGAATCGCCTCCGGCTTAGGTTAAGTGGTGATCG	42	green
GGCGCGAGCAGCGAGAGTCATAGCCCCCTTAATAGCTGGCAA	42	green
GGGGAAAGCCGAACCAAAAATACATACATAATTAGAGAAAAA	42	green
GGTTGTACCTCAGTTGTCAGAGCCGCCACCATTAGACAACAA	42	green
GTACCGACAACAGCCCATGAGGAAGTTTCCGTAATGGTAATC	42	green
GTCACCAATAACTGGCCCGCCTGCAACAGTGCCGTAATCCCA	42	green
GTCACGTTGCTTTTTCTCATAGTTAGCGTAAGAGAATACGCT	42	green
GTCATTGCCAGAACCGCCCTGCCTATTTCGTTAGCGAAGATT	42	green
TAAACAACATTCGTCATACGAAGGCACCAACAACCCGCAGTG	42	green
TAAATCGGAATTAACAATGATTAAGACTCCAAGGCCGAAATG	42	green
TAATACATTCCGAAATAAAGCCTCAGAGCACACATTCCCACC	42	green
TACAAATTCAACAACTTCGGTCGCTGAGGCGGTGCCGGCTTT	42	green
TACAGACCATAAAACTTTGTTATCCGCTCAAACAGTAAAGGC	42	green
TACATCGGGTGTGAAAAGCATGTCAATCATAGATGAAAGAGA	42	green
TAGAATCCTTCGCCCTACGGCGGATTGACCATTAAACGTAGC	42	green
TAGGGGCCTAAACAGTGAACAAGAAAAATAGCCACCACCCAG	42	green
TATAAAAGAACCGACTACTATTATAGTCAGTAATTGCGAAAG	42	green
TATATGTAAAGCCAGGCCGGCACCGCTTCTTTGCAGGTGAGA	42	green
TATTTACGCTGAAAACAAGTAATTCTGTCCAACGCCTGGGTA	42	green
TCAACTTTAAGGGTGAGGGGAGAGGCGGTTTTCCTGATTACA	42	green
TCACAATCAATATTGAAAGAGGAAGCCCGACTCCTTTGGTCA	42	green
TCAGGTCTTTAGCTCACGTGGCGAGAAAGGATCGCCACAACA	42	green
TCATAATTAAATCTCCCCGACAATGACAACCGCAACTGTTTT	42	green
TCATCGAGAGAGAGGGCGAGGCGCAGACGGGATTGTAGGAGG	42	green
TCATCGCCTTTGTTAACCTGGTTGGTGTAAAAACATCGTCTT	42	green
TCATTACCGATTAGCGCTTTGAAAGAGGACATGTACCATAGC	42	green
TCCTTATCAGTACTCATGTGTCGAAATCCGGTTAAAAACAGG	42	green
TCGCAAATGTAGTAAACCTTTAGCGTCAGAATAGCCGTGAAC	42	green
TGATAATCATGACCAAGGGTTTTGCTCAGTTCATCGTTTTGA	42	green
TGATTGCCCTTGAGTATCAAAAATGAAAATAGGCAGGATCTA	42	green
TGTATCACCTTCCAAGGAAGATGATGAAACTGAGTAATTCGC	42	green
TGTTACTTAAATTGTAGCTTGTTACCTCGAATTATTCCGCAC	42	green
TGTTTCCTGAGAAACATAGCAAGCAAATCACTCCTCACGGTG	42	green

TTAGGCAGATTTCCAGGTAGCAACGGCTACCCGTGCATGTCA	42	green
TTATCCGGTGAAAGTAAGGCTGGCTGACCTAGAATCGACACA	42	green
TTCAGGTTTCCGGAAGCTGGAGCAAACAAGTCATCAATTATT	42	green
TTCATCGGCCTTTTTATCAATCAATATCTGACGTCAATTTGG	42	green
TTCGACAACCTGGTTTTTATGACCCTGTAATATTACACCACC	42	green
TTCTCCGTGATGCCACCCAGTACAAACTACAGACGACTCCCT	42	green
TTGCATCAATTTTGCGTAGGGCGCTGGCAAATGGCTATTTTG	42	green
TTTAAAAGTTTCACCGACGCAAGGATAAAAAAGAAAATCAGA	42	green
TTTACCGGAAGCAAACGCCGCTACAGGGCGAACAGAGGCCAG	42	green
TTTAGGAGCAGATAGGAAATCATACAGGCAGAGGCATCCACC	42	green
TTTGTCGTCGGCATTTGAATTTATCAAAATGCTGAATTCTGC	42	green
TTTTAATGGTGAATCGTTCGCGTCTGGCCTTTTGACCCCCTC	42	green
GACGCTCAATCGTCTGTTTACATTGGCAGATCGTTAGAAAGG	42	orange
GATTTTAGACACGCAATAATAACATCACTTTACCTACGTCAC	42	orange
TCTGTCCATCAGGAACATAACGTGCTTTCCTTCACCAATTTT	42	orange

Persistence length from conformational distribution of DNA origami 6-hb

6-hb nanostructures were designed using the computer aided design software cadnano[1] and folded, purified, and prepared for transmission electron microscopy imaging following protocols from Castro et al.[2]. We assumed that filament trajectories are reflective of 2D fluctuations due to the surface deposition. Based on this expression, Isambert et al.[3] derived a relation between the filament L_p and the variance of the transverse fluctuations (i.e. the splay width), $\langle [D(s)]^2 \rangle$, as a function of arc length, s:

$$\left\langle \left[D(s) \right]^2 \right\rangle = L_p^2 \left[2\frac{s}{L_p} + \frac{16}{3}\exp\left(-\frac{s}{2L_p} \right) - \frac{1}{3}\exp\left(-\frac{s}{2L_p} \right) - 5 \right] \quad \text{(S1)}$$

The average transverse fluctuations were determined as a function of arc length from the filament configurational distributions. Figure S2 illustrates equation S1 fit to the transverse fluctuations from the 6-hb configurational distribution.

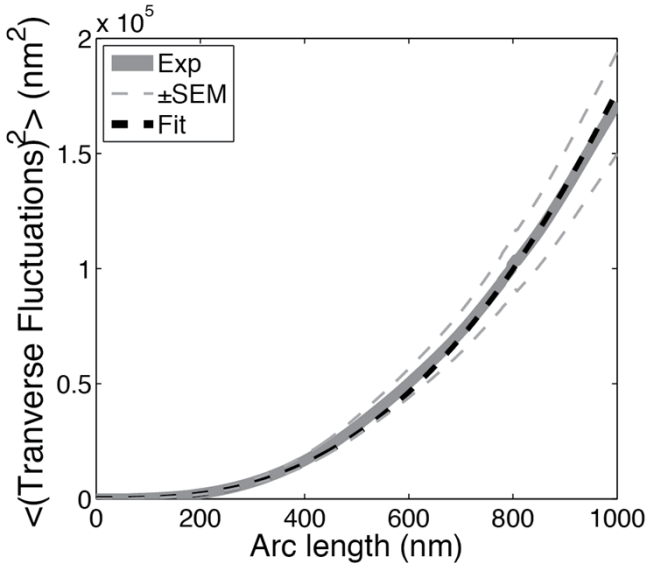

Figure S2: Fitting transverse fluctuations to determine persistence length. The gray shows the experimental data ± the standard error on the mean (dashed gray lines). The dashed black line shows the fit of equation 2 used to determine a persistence length of 1.4 μm.

Calculation of persistence length for rigidly coupled DNA origami bundles

The persistence length, L_P, of a biopolymer can be written in terms of its bending stiffness, EI, with the following equation:

$$L_P = EI / k_B T \qquad \text{(S2)}$$

The bending stiffness is the product of the elastic modulus, E, and the second area moment of inertia, I, which for a cylinder is $I_{cyl} = \pi d^4 / 64$. In equation S2, $k_B T$ is Boltzmann's constant times the absolute temperature, which at room temperature is 4.1 pN·nm. The E of DNA can be calculated based on the persistence length of 50 nm (taken from literature[4]) using equation S2. Assuming double stranded DNA (dsDNA) behaves effectively like a cylinder with diameter of 2.0 nm, equation S2 gives E_{dsDNA} = 261 MPa.

To calculate an upper limit to the bending stiffness of DNA origami bundles, we assume the dsDNA helices in the bundle exhibit E_{dsDNA} = 261 MPa, and that all of the helices in the bundle act like cylinders that are rigidly coupled. Therefore, the area moment of inertia for the bundle, I_{hb}, can be calculated from the parallel axis theorem:

$$I_{hb} = \sum_{i=1}^{N} \left(I_{dsDNA} + \frac{\pi}{4} d_{dsDNA}^2 h_i^2 \right) \qquad \text{(S3)}$$

In this equation, I_{dsDNA}, is the area moment of inertia for a dsDNA helix, which we calculated assuming a helix behaves effectively like a cylinder with a diameter of d_{dsDNA} = 2.0 nm. N is the total number of helices, and h_i is the distance from the centroid of the ith helix to the neutral bending axis. Douglas et al. observed that dsDNA helices in honeycomb cross-sections swell exhibiting an inter-helix gap of 0.1-0.4nm[5]. Therefore, we used a helix center-to-center distance of 2.4 nm for the DNA origami cross-section to calculate the upper limit. An example for a 6 helix bundle (hb) is shown in figure S3, which gives I_{6hb} = 59 nm^4. Using equation S2 then gives an upper limit for the persistence length of a 6 hb of $L_{P,6hb}$ = 3.8 μm.

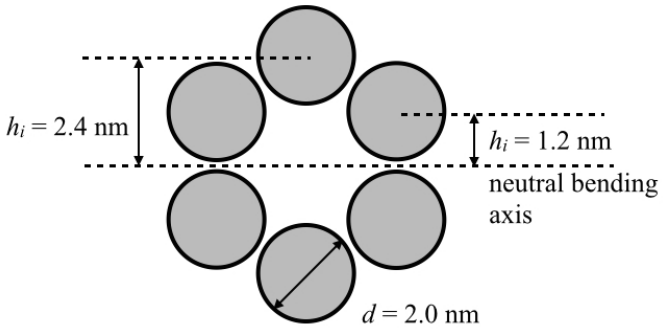

Figure S3: Schematic demonstrating the calculation of the area moment of inertia for a DNA origami 6-helix bundle.

Stochastic simulations of conformational distribution

Filament conformations were simulated following a stochastic approach with a wormlike chain model. For this simulation, filaments were discretized as a chain of rigid links. The length of each link, s_{link}, was set to 0.2 nm. Although simulations are not sensitive to the selection of s_{link} as long as it is much smaller than the overall contour length, L_c (the total path length of the filament). The incremental change in tangent angle, $\Delta\theta$, between consecutive links in the chain was defined according to a wormlike chain equation as:

$$\Delta\theta = r\left\{\text{acos}\left[\exp\left(-\frac{s_{link}}{2L_p}\right)\right]\right\} \quad \text{(S4)}$$

The stochastic variable, r, was randomly assigned as either -1 or 1 to give either an upward (positive) or downward (negative) change in the tangent angle. Figure S3a demonstrates this approach to construct a single filament. The inset shows a zoomed in view of a few links in the chain illustrating the change in tangent angle.

We validated this simulation approach by confirming that simulated trajectories reproduced the expected 2D wormlike chain root-mean-squared (RMS) end-to-end distance, $\left\langle r_{ee}^2\right\rangle^{\frac{1}{2}}$, as a function of persistence length given in equation 3:

$$\left\langle r_{ee}^2\right\rangle^{\frac{1}{2}} = 4L_P L_C - 8L_P^2\left[1-\exp\left(-L_C/2L_P\right)\right] \quad \text{(S5)}$$

As shown in Figure S3b, the RMS end-to-end distance calculated from simulated trajectories for a range of different persistence lengths (open circles) closely follows the wormlike chain prediction from equation S5 (dashed line).

Conformational distributions of DNA origami bundles were constructed by running many filament simulations. Figure S3c shows three examples of conformational distributions constructed for the 6hb. Similar simulation approaches have previously been used to compare to 2D conformational distributions of DNA[6].

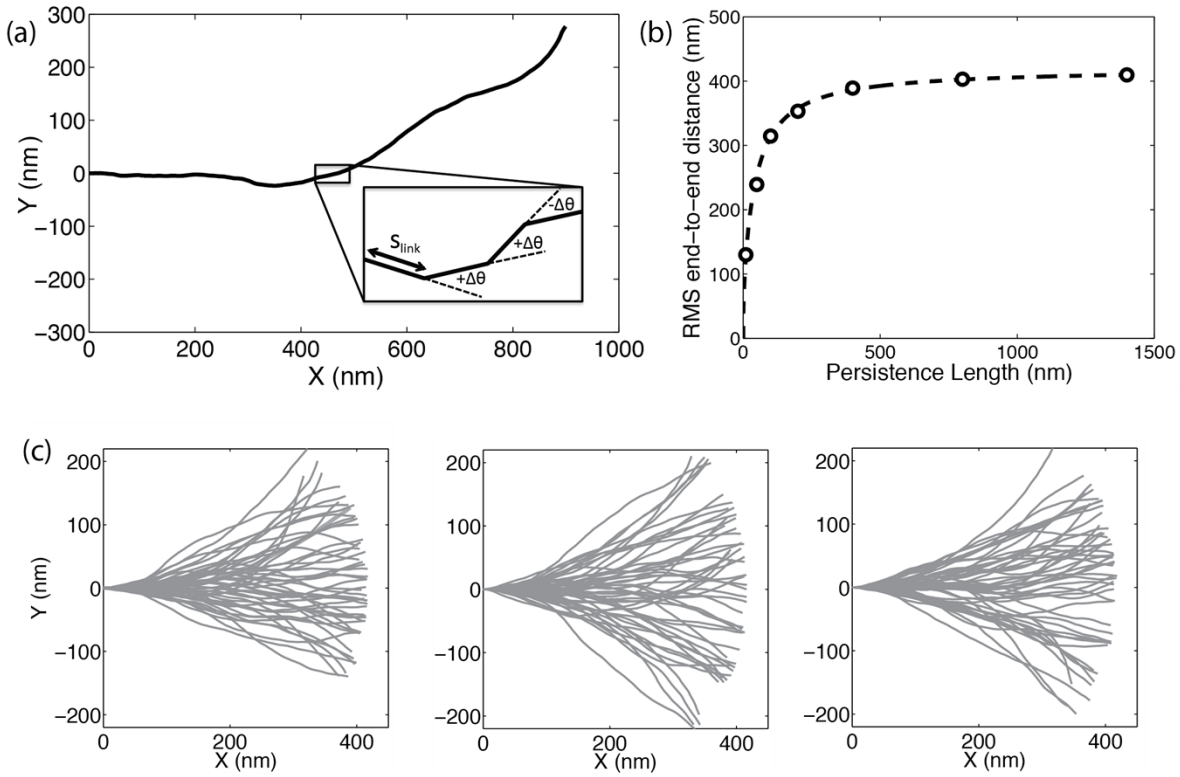

Figure S4: (a) Example of stochastic simulation to construct a single filament. The inset shows a zoomed in view of a few links in the filament. (b) Simulated trajectories (open circles) closely follow the expected wormlike chain behavior for root-mean-squared (RMS) end-to-end distance as a function of persistence length. (c) Three examples are shown of a 6 hb conformational distribution (L_P = 1.4 μm).

Cadnano square lattice[7] design of universal joint (p7560 scaffold)

Figure S5: cadnano design of universal joint on square lattice.

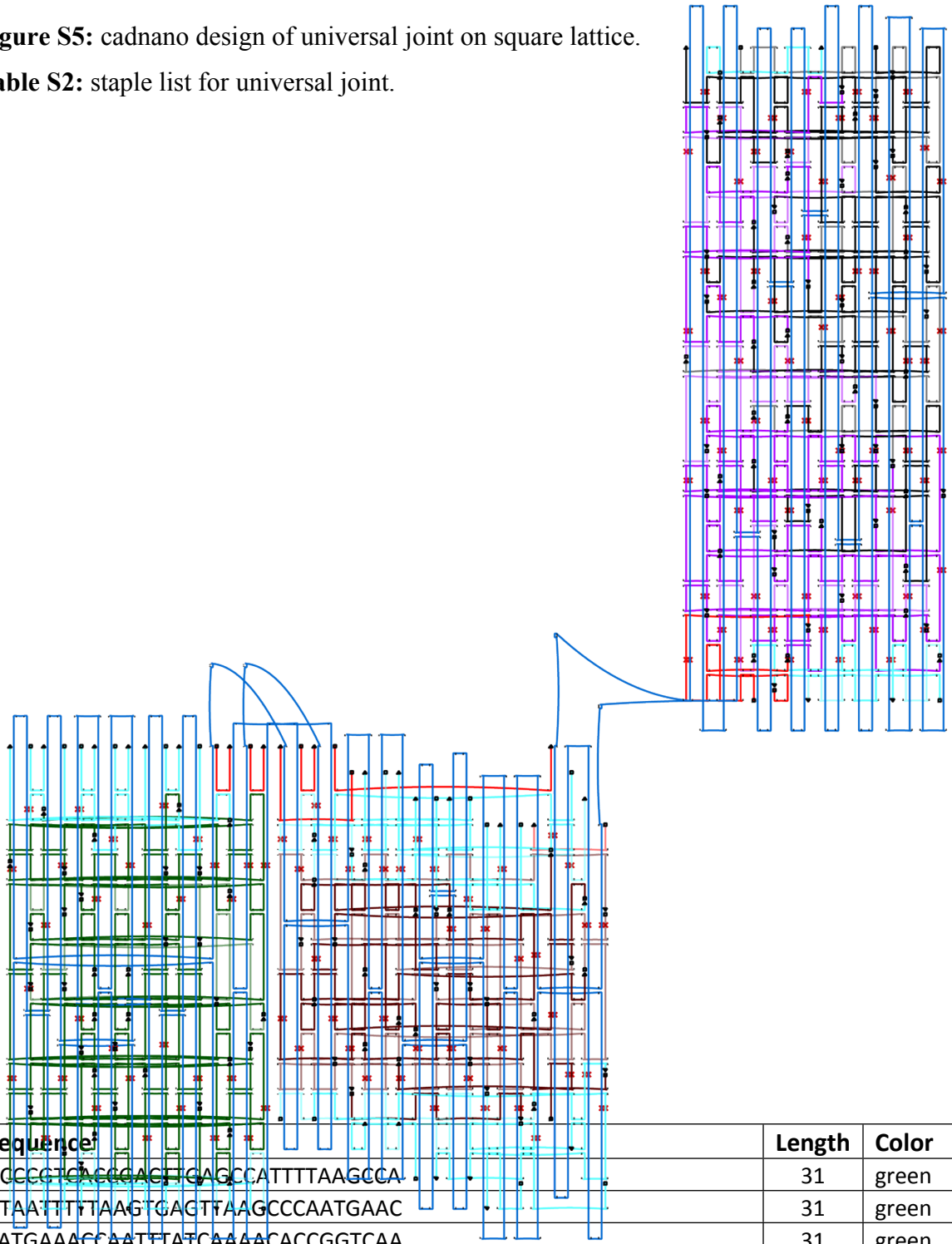

Table S2: staple list for universal joint.

Sequence	Length	Color
ACCCGTCACCGACTTGAGCCATTTTAAGCCA	31	green
ATAATTTTTAAGTCAGTTAAGCCCAATGAAC	31	green
TATGAAACCAATTTATCAAAACACCGGTCAA	31	green
CCACGCAGTATGTTAGCAAATAATCAAAGACT	32	green
TAAACAGTAGCGACAGAGACTTACCAGCTTTA	32	green
TTCATACAATAGCAATAGCTATCTTACAATAC	32	green

CAGCCCTGCCTATTTCGGAACCTATTAACACTGATTA	37	green
TATTGCATGTATTTGCACCCTAATTTGCCAGTTATAGCA	39	green
AATTGAGAAGTAATAAAAGTCCTGTCCAGAGCCAGCTACA	40	green
AGCACCATAAGGTGAATGAGGGAGACAAGAATAAAAGTAA	40	green
GTAGGCAGGTCGGAAAGCGCAGTCTCGAGTGTACTCACCAGT	42	green
AAGCAAGAAACAATGACAACGCTAACGCAGGGAAGGAGGCATT	43	green
ATTTTATCCAAGCAAAAGGAATCATTACCGCGTAAGACTAAAA	43	green
TTAAAAGAACTGGCATGATCCCAATAGCTGAATCTTATATATC	43	green
ATTGACAGCAGAGCCGCGTTTGCCATCTTTTCACGTAGAACGGA	44	green
CATAAAAAAGCGTCTTAACAAGAAAAATAGGTCGTGTGATATTT	44	green
CCATCCTATTAATGGTGCCAACCTCCGGCTTAGGTTGGGTTTTT	44	green
TGGCCTTGTCAGAACCGGAACCAGAGCCACCACCGGAACCTTGA	44	green
CGCCACCCATATTCACACCATCAAGTTTGCCTATCAATAGCCTTA	45	green
ACATTAGCGTCAATCACCGCCACCCTCAGAGCCACCACCCTGAGGT	46	green
CATACCGAGGAAACGCAATAATAACGGCGAAGCCCGTTTATTGCGA	46	green
AACAGAGTAACAGTGCCCGTATAAACAGAACGCCTGCGTTAAAACCT	47	green
CATTATAGCAGCCAGCAAAATGGTAATAAGTTTTAACGGGGTCTCAT	47	green
CCATCTTAAATCAAGATTATATTCTAAGAGAACAAGCAAGCCGTATA	47	green
TAATTATTTTAGCTATATGTTTTATCAAAATCATAGGTCTGAGACGA	47	green
AAATATTTACGATTCATCGTTCAGATATAGAAGGCTTATCCGGGTTGC	48	green
GGCACGCATTAGACGGGAGAATTAACTAATAAGAGACAAAAGGTTGTC	48	green
CCTTACGCCAACATGGGGAATTAGAGCACCGTAATGCCAGAATAGACGAT	50	green
GCCAAAGTACCGACAAAAGCCAACGCAATCATAAGTTTCGTCGTCGTCTT	50	green
TAATTAATTTCAAAGTTTTACCAGTACAAACTACTTAATGCCTAGGGCTT	50	green
TGAGCGCGTTTACCATCGCAACCGATTTATCACCTGAACAAAGTCAGAGG	50	green
AATAAAACAGCCCTCATAGTTAGCGTAAGACTACCTTTTTTCCCTCAGAGC	51	green
TCTATCTTCTGTAAGAATACAATAGATGAGAATATTTTACAGAGAGAATAA	51	green
TTCGAGCCATCGCCATAAATAAGGTAGCATTCCACAGCAAATAAATCCAGTG	52	green
GCAAAGCGGATTGCATAACGAGACATGAGG	30	brown
AAATTAATATCATCGCCAGTTTGCGGAACAAA	32	brown
GCTTTTCATAAATATTCATTGCAAATATCCTCAGTAC	37	brown
TCGCCCACGACCAACTCCATGTTCTGACGAGATCATTG	38	brown
ATACAGTCGAGATTAAGAGGAAGCCCGAAAGACTTAATCC	40	brown
CCGCCACCTAAGTGCCGTAACAGTTCAAATGCGACGATAA	40	brown
GAAACCACGCTATTAAACAATTTCGAGAATAGCTCAGAGC	40	brown
TGAACGGTTGCGCCGACGGGATCGAATAATAACCTCAGAA	40	brown
CAGGCGGACTCAGAAACAAACATCAAGACCCTCAGCAGAAT	41	brown
CAGGCATTCAATCAATATCTGGTCAGTTAGAGCCGGAAACAA	42	brown
GGCTGACCTAGTAAATTTGTGTCGACCCCCAGCGATTATATTTT	44	brown
AGTACTGAAAAAGAAGGAAACAATGGGTTTTGGCGTTTTAATTCGAGC	48	brown
CAGTTTAATAAAACGAACTAATTTAATTTATCTTTGAAATCCGCCGCT	48	brown
TTTGCAATGACATCGGTTTATCAGCTTGCTTTCGGAATTGCGTCAAAACA	50	brown
AACTAAAGAGGTGAATTTCTTATTTTCCCTTAGAATCCTTGCGGAGTATTT	51	brown
GAATCCTGAGCTTGTTTGGACGTAAAACAACAGTTAAAGCATCACCTTGCT	51	brown

TAAATGGACATTTGAGGATTTAGAAGTATAACATTATCATGCGCATAGGCT	51	brown
ACAATTTAACGTTACCAGACTTTAAACAGTTCAGAACAAAAAGAGGGTTGAT	52	brown
AGATTTGTTACATTTATTAAAACAGCTTGATACCGATAGTGTACAGACCTGA	52	brown
TAAACGGAAACACTCCAACTTTAAAACACCAGAACGAGTTCATCAAGGACAGA	53	brown
CCCACCTTTTATGCGTAGACCAAGCGCTCAATAGATAATGCTTGAGATGGCGGA	54	brown
GAACCTCATAGCGAAAAGAAATCATCGGGAATGATGAACCGCCACCAAAGGAAC	54	brown
AAGTTATGCGAAAGACACCGCCACTTTTTTCACGTTGAATTAATTGTAACAACCA	55	brown
ATAAGTATGGTTTAGTAGCATCGGTAAAGGCGACCTGCTTTGAAAGAGAGTAATC	55	brown
AAACCAAAAAATATCAAACCCTATTACAGGTAGAAAGATTCCCTCGTTCAGTCCAT	56	brown
CCCACGACGTTACGTGGCAGCAGATTCGTAG	31	purple
CCAGTACCTACACTACAGGGGTCACGCTCCGA	32	purple
TAAGCAAAGTCTGGAGTAAATGCAATGCCTGGCGC	35	purple
ATAAATCACTTTATTTTATTTTTGGTACCCCGGCTTGACG	40	purple
GGAGAAGCTACAGGCATCTGAAATTCAAACTACAGGAGGC	40	purple
GCTTAGACAGGCATCACTTGCCTGAGTTTTGCGGAACATCCA	42	purple
GTGAGACGGGGATTTGCAAGGCGTTACATTGCAGACAACAAC	42	purple
TCAGAAAATAATCGTAGGATAAAAATTTTTAAATAGTAACCA	42	purple
TGGGCCAGTTTGAGGGGAGTCTGTCCTGCAACTAATATTTTC	42	purple
AAAGTCGCACTCGGGCGCATCGTAACCTTCCATATCATTTCGC	43	purple
GAAAAACAATATTTTCCTCGTTAGAATCCTGAGAGCTGTTTGA	43	purple
GCAAAAACTAGCATGTCAATCATTAACACCGCCTGCTTTTGCG	43	purple
GGGAAAGCGAAAAACCGTCTATCAGGGCGATGGCCCACTAGCC	43	purple
GGACATGAAAAGGTGTAGCTCAACATGTTTTAAATAATCACGCA	44	purple
TTTTGTTAATCTACAAAGATTCAAAAGGGTGAAATAACCTCTCCG	45	purple
CTTCTCAATCGAGGCAAAGTGCTCCTTTTGATAAGAGGTCATTAGAA	47	purple
GATCGTGGACTCCAACGTCAAAGGGCCGGCGAACACCACCACTTAGT	47	purple
AAAATTAATATGACCGAACTGAAGATAAAAAAAGGAAGGGAAGAATTAA	49	purple
AAATCGCGCTTAGAGCTAAATCGGCCTTGCTGGTACCTTTAATAATTAGC	50	purple
CGATTAAAGGCAACAGCTGATTGCCCTTCACCGCCTGGCCAGAGCGGATGC	51	purple
ACCCCATCAACAGTAGGTAAAGGCTATCAGGTCATTGCCTGAGATATTTAAA	52	purple
ATGCTGGCATCAATTCTACTGAACCCTCCTGAAAGCAAACAGGATCGGAACC	52	purple
CGCCGTAATAACTTCTGACATATATTTCAAACAAGAGAATCGATGAACGGGCCC	54	purple
CTTTGTCGGATTGTTTAGCTAAGTACGGTGTCTGGAAGTTTCAGTGCATCTGAA	54	purple
ACAGAGAGGGTAGCTATTTTTGAGAGAAATTCGCTCCTGTAGTTGTGAATAGGCT	55	purple
GCCGTTTTGACGTAATGCGCCTGTAATACAACAGTGCCACGCTGAGAGCCACCAG	55	purple
CATTATGGCTTAGAGCTTAATTGCTGAATTTGATTACACGACCAAGCTGGCGACGG	56	purple
TGGTGGTAGAATAGCGCGCGTAGTGGCGAGCAGAGGTGAGGCGGTCAGTATATAAT	56	purple
CCAGTGCCTAATGAGTGAGCCGAACTCACGAC	32	black
TTTACGCTACTCGTCCTGGTTGGTGTAATGAAAGT	35	black
CGCTCACACCTCGATGCCAAGCGCACTAAAAGATTGTA	38	black
TCATAGCTCGAGCTCCCCAGTCGATTTAGAGTTGATAA	38	black
AAATGGTCGAAAGGCCTCTGGCCTATTAAATCTAATCTA	39	black
AAGCATAGTAAACAGATGTTCTTAGTGACTCCGTTAATA	39	black

GAGCTTCTGGCCGAGCGAGTCGATCGGTAGGGTGGGGCT	39	black
AATTAACCTATAATCAGTGAGGCCGCGCGGGGCGAGCCGG	40	black
GTAACAACTGTTAAAGACGACGACAGTATCGGCCTTCGTG	40	black
ATTTGGGAGTAATGTTTAAATGTAACAGAGGAGAAGCCGCGG	42	black
TTACCCGCTTTTTTGTTAAATCAGCTTAATGCCGGTCAAATC	42	black
CTAAAGGGACGTGAACGAGGATCCCCGGGTACGTTTCCTATGT	43	black
GAACGGATTATATTAAGTTGGGTACGCCGGCAAAAAATCATGG	43	black
GTCAGTAATAAAACGGTACGCCAGAATCCAGGGTGTTGTTATC	43	black
GTCCCGCCGAATCGGCCACATAAATCATTTCTCTAACTCAGGC	43	black
GCCACAACATAAGAGGCGGTTTGCGTATTGGGCGCCTGAGAAATTA	46	black
TAAGGTGCGGCCCTGCCATCTGTAAGCACGCCCTGGCTAAGTGGCCAG	48	black
AACAGTGTCCCAAAAATATGACCGTATTAGATAAACAGTTGATTCCCAA	49	black
GGCTAACCACGCCAGGGTTTTGAATTCGTTCCCTTATAAATCAAATCCG	49	black
TTGTAAATATGATACCGGAGGTGCCGTAAATTTCTCAGATAGAACCAAG	49	black
CCAGTCGGGAAACCTGCAGGAAGACGCCATTCGGCGGATATTCGCGGGAG	50	black
CAAGTAAGAATGTAAAACGAAAGGGGGGTGTGAAAGTTTTTCTTTTCACCA	51	black
CCAGTAAAGACGCATCACCCAAATCAAGTTTTTTGGGGTCACACTACGTGG	51	black
TGCTTGTTAATTCCACTCTTCGCTGTGTTTTGTTGTAGCAATACTTCTATA	51	black
GCGAGCCTGGGGCTGCATTAATGAATCGGCCAACACCGAGTAGGGAAGGGAACA	54	black
CAAACGCCATTCTCATGCGCTGACCTCGGTGGGCACGAATATAGGGGCCTTAAAAT	56	black
TGATAAATCATTTTTTAACGCCATTTAGTGCTCGGAAACCACATTAATCCCGCTTT	56	black
ATCAAAATTGCTTTGAATACC	21	light blue
TGATGGCTTTAATGGAAACAG	21	light blue
GCAGATAGGAAGGAAACATAAAGG	24	light blue
AACCAAGTACCGCTTTCCTTATCATT	26	light blue
CATGTTCAGCTAAAATTCTGTCCAGA	26	light blue
CGAGAAAACTTTTAAAAGCCTGTTTA	26	light blue
GAGGTTTTGAAGCATTATTTATCCCA	26	light blue
GTCCACTAAGCGAAAGGCTGGCAAAAAC	28	light blue
ATAAGGGAACCGAACTGCATAACCGAGGCTTG	32	light blue
AATCGTCCAGAAGGAAATATAATACAAACAATTCGAC	37	light blue
TCCAGACGATAGTGAAAAATGCTGATGCAAATCCAAT	37	light blue
TGAATTACAAGAAAACGTAATGCTAGTAAGAAAATCAAA	39	light blue
ACCATCAATTTGACCAATGGGATAGTGTAGATCAGCCAGC	40	light blue
ATTCATTATACCATTAAAACGTCACCGTTCCACCGCCAGC	40	light blue
ATTTTAAGCTCATTCAGTGAATAATATTCATTACCCAAAT	40	light blue
CGTTATTAATTTTAAAAGTTTGAGTTAGACTTTCCAACGG	40	light blue
ACAAATTCTTACCAGTATAAAGGTAAAGTTGCAGAACACAG	41	light blue
ACTGGATAGCGTCCCGAACCAGCAAGAGAAGGATTAGTCAT	41	light blue
TTTCTTCAATTATACCTTTAATTCATCGCGGAATTATCATC	41	light blue
TAGGAGCACTAACAACTAATAGATTGGCAAATCAGAAATGAG	42	light blue
ACGTGAGATTTAGGAATACCACATTCAACGAGGCACACTACGA	43	light blue
TTCAAAGAATACTGCTCGCCTGATTATTTGCATTATACTTCTGAAT	46	light blue
ATTTTTTGTTTAACGTCAAAAATGAAAACAAAATAAGCGCCTGTCAA	47	light blue

ACTAATGCCAGTCAGGACGTTGGGCTTATGCGCGAAAGAGGGAACGAG	48	light blue
CTAGATCAAATACGGCTGTCACTCATCGAACGCGAGGCGTTTTAGCGA	48	light blue
ACTCAGGAAGCCCGGAGACTTTTTATGACCATGCAACACTATCATAACAT	50	light blue
CAGATAGCCCTAGTGTAGCGCGCGTACCGAAAATCAGTTGCAGCAAGCGG	50	light blue
AGAAAGGGTTGAGTGTTGTTCCAGCAGGTATGGTTGTAACGTGCTACCGCCA	52	light blue
AGGAGCCTAATCTCCACAGGGAGTAACGAGGGATACACTAGTAAAATAATCT	52	light blue
GCTTTTGATGATACAGTGAATTTACCAATGAATCATCGGCAGACACCAAATA	52	light blue
GGCGAATTATTCATAGGGATAACTTTCAACAGTTTCAGAAAACACTTCTGTA	52	light blue
CACCACCCGATTAGCGAACGGATGGAATCGTGCAAAAGAAGTTTTGCCAGAGG	53	light blue
TTGACAAGAACCGGAGGCTTGCCACTTAGCCGCAAAAGATAGCAACGGGACTAAA	55	light blue
GTAATTGAGATAACCCGGAAGGTAAAACGCAAATTTTCGGCTTATTAGCCACCAGA	56	light blue
AAAAATCTGAAAGGAA	16	red
ACCCATGTACCGTATTCTGAAACATG	26	red
ATTTTGCTAAACAGCAAGCCCAATAG	26	red
CTGAGAAGAGTCATTAGTAAATGAAT	26	red
GGCTGAGACTCCTACCGGAAGCAAAC	26	red
AGTGAATAACCTTGTAGCGATAGCTTAGATTAAGA	35	red
ACGAACCAGCAGCAAAGTTGTACCAAAAACATGCAATAAAATG	43	red
ATCGAAACGCTCGCCTCAGACAACAGGTCAGGATTAGAGAGTAATAT	47	red

Cadnano design for scissor mechanism (p8064 scaffold)

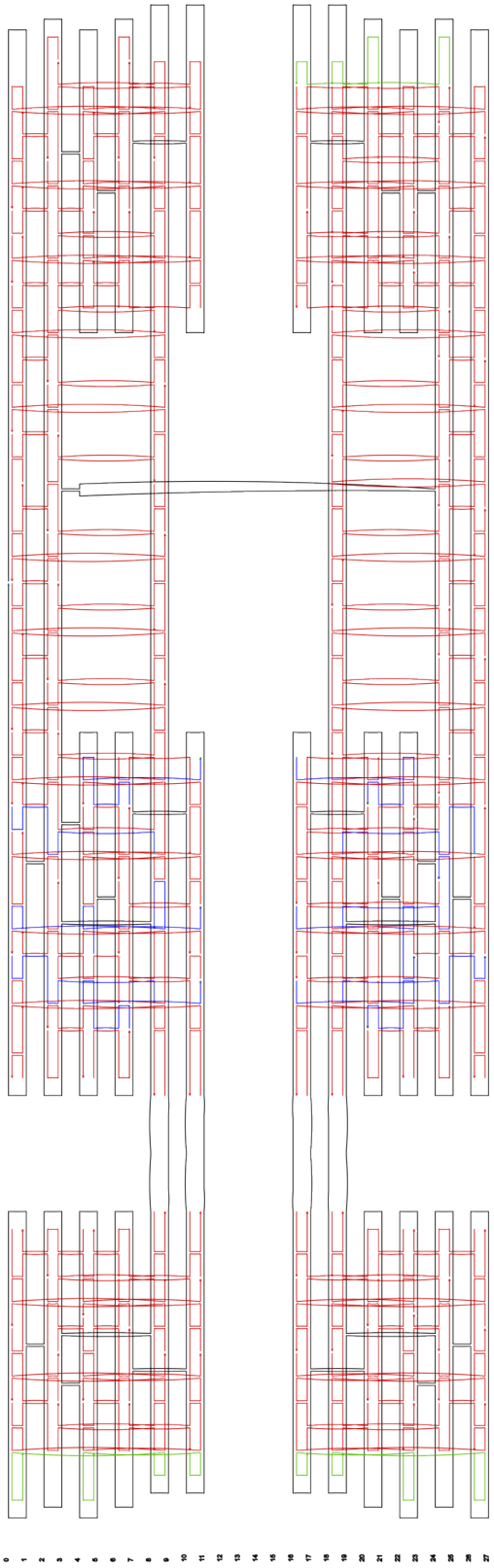

Figure S6: cadnano design of scissor-mechanism.

Table S3: staple list for scissor-mechanism. Staples not shown in cadnano diagram were used to polymerize the scissor-mechanism

Sequence	Length	Color
AGCGAAAAGAAAGG	14	red
TTACCCTAATCAAA	14	red
TGCATCAGCGGGATACCAAAA	21	red
TTGACCGAAAAACAAACGTTA	21	red
ATTTAGGCAGAGAAGCAAATCAGA	24	red
GAGGACTAAAGAAGGCATAGTAAG	24	red
GCCAGCAAAATCTTGACAGGAGGT	24	red
TAATCAGTGAGGTAGAAGTATTAG	24	red
AAAAATCCAATACTGTAATAACAGAACA	28	red
AGGCGAATTATTCATTTAACGATAAATC	28	red
CAGCCATTGCAACATAATATCCATCACT	28	red
GGAAGAAGATTCATTTAGGAAGCCTGAT	28	red
GTAGAAAAAATCTACTCATTATACCAGT	28	red
TAGTTAGCGTAACGGTGCCAAGGGTAGC	28	red
AAATCCTCATTAAAATGGCTTTCGGAACCTATACA	35	red
AATCGGAACAAAGAAACCACCAGAAGGAGCCGTAA	35	red
AGAGAGTATCCCTTTCAGATGAATATACCGCGCAG	35	red
ATTAATGATTTTCAGCTGTAGCTCAACACGTTGAA	35	red
CCTTAAAAAAGCCAAAGCCTGTTTAGTAATCCAAA	35	red
CTCTTCGCTATTAACCGGAAACCAGGCAATCGCAC	35	red
GACTTGCGGCTTAACGGAATCATAATTATAATTTC	35	red
GGGAGGTCTACCTTAGGCCGACGCCGCTTAGCGGT	35	red
TAAGATATTTTAGTCTAGAAAACGCTCAACAGTAG	35	red
TACATAAAGTAAGCGTCATACGCCAGAAGGAGGGA	35	red
TGCTTTAAAATATTGAGAGGCGTCGAGATATTGAC	35	red
AACCACGCAAGTAGAAGAACTCGAGATAGAAAATCAAT	38	red
AGGCAGGTCAGACGATTGGAATTATCACCGTCACCGAC	38	red
CAACACTATCATAACCCTCACAGCATCGGAACGAGGGT	38	red
CGGTACCATTCCACCAGAGCCGCCCCTCAGACACCGGA	38	red
CTCGTATTAAATCCTTTGCGAATCCTGAGAAGTGTTTT	38	red
TCTAAGAACGCGAGGCGTTATTTAACAACGCCAACATG	38	red
TTTCGTGCATTCGGCCTCAGGAAGAAGCGCCTGCGGGC	38	red
ACCGATATTAATTCAAATCGGTTGTACCCAAGGATACAA	39	red
AGAACGCAATTCTGCGAGCCAGTAATAAATCATTAGCTG	39	red
CGCAGTCCCGTTCCAGGTGGCAACATATACGCAGTAATA	39	red
GATTATAGCTGCTCATCGGAACAACATTAATGCAGACAA	39	red
TGAGAATTTCCATAGATTTAGTTTGACCAGGTCATTAGC	39	red
AAAAAAAATATAATTTTGGGGCGCGAGCGTTCTAGACGGGAA	42	red
AAAAAGCCCGCCAGAGAATGCCAACGGCACGTGCCGGACTTG	42	red
AAAAGAAACCGCCTTTCTGCCAGCACGCACGGAAATACCTGA	42	red
AAAAGAACTTCATCTACCCAAATCAACGGCCCTGACTTTAAT	42	red

AAAATAAAGAGCCTTACCAACGCTAACGCACCCAGAAACAGG	42	red
AAACTCCGCGCCGATCATTTTCAGGGATATAGCTAAGTAATG	42	red
AACATCATGCACGTCAGTTTGGAACAAGTTTCTTTCTCACAG	42	red
AACATCCGCCTCCGGCCAGGGCGCGGTTCTTTGCTGCAAATC	42	red
AATAAGATGTACCGAGGTGAATTTCTTAACCTTTAAAATCAT	42	red
AATCCGCCCACGCAGCCCCCTGCATCAAGTGTTCACGTCATA	42	red
AATTATTAGAAAACAGATAGACTTTCTCGAGCCTCTCACCAG	42	red
ACAAAATAGTAACACCGAAATCGGCAAATGCAGCATTTCACG	42	red
ACAGGCAAAAGATTACAATGAAATAGCAAGCAAGCTGATACC	42	red
ACCCTGACATACGAGCCCGCTTTCCAGTCCCAAATTGATTAT	42	red
ACCGCCTGCGACCTTATCATCTACCACAAATTACGCTTTTTC	42	red
AGCGCGTAAGTTTGAATGAAACCATCGAGTGTACAATAAGGG	42	red
AGTTTCAAGAAAGGTTAGTAAATGAATTGTAAAACTGCCTGA	42	red
AGTTTTAACGGGGTAGTAACAGTGCCCGTCCTCAAGAGAAGG	42	red
ATAGGTGCTCAGGATAAAGGCCGCTTTTAAAAGATCCTCAAA	42	red
ATATTTTGCTCATTGCCAGCTTTCCGCTTCTGGTGTTTTTGT	42	red
ATGAGGAGAACTGGCGTTAATAAAACGAACTAATCTTATGCG	42	red
ATGCGTCCCCTTCTGACATTCTGGCCAACCTACATATTAGAG	42	red
ATTTTAAAGTTTCCATAACGCCAAAAGGTTCAACTATTACAG	42	red
CAAACGTAGAAAATTATAAGTATAGCAGGATTGAGTGGAAAG	42	red
CAAATCAACTAATATCATTTTTGCGGATATTGTATGTACAAA	42	red
CAATAGCGCATTTTTCCAGACGACGACATGTTCAGAGAGCCA	42	red
CAATTCTCCATCAAGGAAACAATCGGCGGTCACCACGGTTTA	42	red
CAATTTATCTGAATGGCGACATTCAACCGAAACGCATGTTAG	42	red
CACACAAACAAAGTCTTGCTTCTGTAAAATATTCCCAAGTTT	42	red
CACGCTGGGTGGTTGTACCTTTTACATCTTGAATACACTGCG	42	red
CAGAATCTTTCATCTTGCCATCTTTTCAGTCAATCGACCAGG	42	red
CAGAGCACCCTCATGAAAAGTAAGCAGAAGAACCGACGCATA	42	red
CAGAGCCTTTTTAAATATTTTAAATGCAAAGCAATCGGAAGC	42	red
CAGATGAGAATAACCAGAGGGTAATTGATCCGCTCCCTGTCG	42	red
CAGCAGCTCAGCGTCAAACGCGGTCCGTAGTTAAACCCGTAA	42	red
CATAGCTCCCACAATAATGGAAACAGTACTGATTGTCTATCA	42	red
CATTGTGATACGTAAAACACTCATCTTTGACCCACATTAAAC	42	red
CCAGTAAGTCTGAAAGGAGCACTAACAAGTTGAAAGTCTTTA	42	red
CCAGTATTCAAGATCAAAATCATAGGTCTAAACGATTTTTTG	42	red
CCGGAAAGCGCGAAACGAGGCGCAGACGTAATCAAAGACTGT	42	red
CCGGAATTCCCCGGGCGCCAGGGTGGTTAGTCCACATATCAA	42	red
CCGTCAACCGTCAGTTGGCAAATCAACACTAATAGTTTGACG	42	red
CCTGTAATACTTCCTAAGAGGAAGCCCGAGGGAGTGGTTTAG	42	red
CGAGAATGACCATAGACTATTATAGTCAGCGAAAGGTTTACC	42	red
CGCATAACGTCACCCCTTTAGCGCCACCAGAACCAAGCAAGG	42	red
CGCCTGTGTGCTGCGGCCAGAATGCGGCGCAGTGTCCAAGTT	42	red
CGGATAAGCCTGTAAAAAGGAGCCTTTAGGCTTAGGTGGCAT	42	red
CGTAGGAGAGAATATAAAGCCTTATCATGTTTTTACCCGAAC	42	red

CGTCTTTTATGTACCTACAAAGGCTATCATTAGATGTCTGGA	42	red
CTACAACCCTCACCTATGATATTCAACCTGAAAAGAGCTTAA	42	red
CTCAATCTAAAAGGGACCTGAAAGCGTAGCTATTAGGAATTG	42	red
CTTTGACGAGCACGTTTCCTCGTTAGAAGGTTATATAACTAT	42	red
CTTTTGAGCTTTCGTAACACTGAGTTTCAAACGTAAGACAGT	42	red
GAAATCCCCCTCAGCTCAGAACCGCCACGCCAGCAACCAGTA	42	red
GAACCCAGCAAGAACAAAAGGGTGAGAAATCCAATATTGCTC	42	red
GAACGTGGTATTGGGTACCGAGCTCGAACATGTTTTTTCATT	42	red
GAAGCCCACCACCCCAATGACAACAACCACCAGACAAAGCCT	42	red
GAAGCTGTCAAAAATATTATTTATCCCATCATATGCGTTACG	42	red
GAGATAAGTTTCCTATGAATCGGCCAACAAAACCGTTTGGAT	42	red
GAGGATTCCACCGAGTTGTAGTAAAGCACACGCTGCTAATGC	42	red
GATAAAACCTAAAAAGAACAAGCAAGCCTCCAAGAATAATCG	42	red
GATAGTTAACAGGTGAATTAGCAAAATTATGCCTGTCTTACC	42	red
GCAAAAGAAGATGAAAGGGATGCGGTTGAAAAAATCGATGCT	42	red
GCAAATGGAGAGATCCAAACGACGGCCAATCTAAATAATAAT	42	red
GCACCATAGATTTGGCTCCATGTTACTTGAGCCACGCCACCA	42	red
GCCCCCTGCCTATTTTGATGATACAGGAAACAAATGGAAATT	42	red
GCGTTGCTCGAGGTGCGGAATTATCATCTCGTCGCACTGAAC	42	red
GCTGGCACTCTTTAGTGATGAAGGGTAATTTTTCGTCTCGTC	42	red
GCTGTCTAAGTCCTGAGGCGGTCAGTATATCAAACTTTTCAT	42	red
GGAAATACAAAACTATCGGCCTTGCTGGGGAAAAATACATTT	42	red
GGAAGGGCTGCAAGTAACGCCGAGGTGGGCCCTCAAATCTCC	42	red
GGATGTGCGATCGGATTCGCCATTCAGGGACAGTACTGCCAG	42	red
GGCGCTGGGAAAGCTTATTAATTTTAAAAGTTTGATTAGAGC	42	red
GGCTGACTACACTAATGCCACTACGAAGATTTCAACGAGAAA	42	red
GGGCGATTGCATTAGTGTGAAATTGTTAGCGCTAACAATATA	42	red
GGGTAAAAATTACCAGTGAATAAGGCTTTAACAAACCAGGCT	42	red
GGTTTGCGACTCCAACGTCAAAGGGCGAGCGCGGGTCATGGT	42	red
GTAAAGTGCCTGTTGCCTGCAACAGTGCTCACCTTCCGCGCC	42	red
GTCACTGGCTGGTAATGGGTAAAGGTTTGCGGTATCGCACTC	42	red
GTCATACCAGCGGATCAGACGATCCAGCGGGCCGTAGCGGTC	42	red
GTTAACGTGCCGGTACCAGCTTACGGCTGCGCTTTGAGCCGG	42	red
GTTGAGTGGCAACATTCTTCGCGTCCGTCGTGGTGTGAAACA	42	red
TAAATCAGTTAAAATTCGCATTAACGCCAGCTGGCCACGACG	42	red
TAACGGAAGCACCGTTTCTGCGCAGAAACGGGGGTGGCCCTG	42	red
TAATTTTCCCTTAGAGGCATTAGACGGGGTGTAAAATTAATT	42	red
TACGCCACCGAACGCGGCGAACGTGGCGGGAGCGGGCGCTAG	42	red
TATACTTCCTTTTTGAATTGAGTTAAGCTTCGTAAGAGAGGC	42	red
TATTTTTGTCAATAAATATGCAACTAAATTGCGAAGTTTTGT	42	red
TCAGCTTTAAGAGGGTAGTAGCATTAACAGGCCGGCACCAAT	42	red
TCCAGCCAGCTTTCCGGCACAATAGGTCACGTTGGGTTGATA	42	red
TCGCGTTTATTCGGTCGCTGAGGCTTGCAAAGACTTCAAATA	42	red
TGAATTACTGAATAATGGAAGGGTTAGATTAACAAACCAGTC	42	red

TGAGAAGATACACCCGCCGCGCTTAATGTTAGATTAAGACGC	42	red
TGAGACGGTTGTTCAAAACAGAAATAAAGAAATTGAGATAGG	42	red
TGATAGCCAGAGGTGAACAAGAAAAATACCAATCAACGGGTA	42	red
TGATGCAAATCCAAGGTTTGAAATACCGAAATAAGGCGTTAA	42	red
TGCCAGCGGCCCACTCATCAATATAATCCATAAATTATCAGA	42	red
TGCCTGAATTAACCGTAAAAGAGTCTGTTAGATAACGCTCAT	42	red
TGTAGGTAGGCAAACAGGATTAGAGAGTAACAGCTCCAATAG	42	red
TGTGAGTTGGCAATTACGTGAACCATCACGGGAAAACAATTC	42	red
TTGAGGATTGTGAGAAAATTAATTACATACCTACCTATTAAA	42	red
TTGCTGAAGGCTCCGCATTCCACAGACAAGCCGCCCTGATAA	42	red
TTGTACGTGTAGATGGGCGCATCGTAACTCCCAGTGAAAGGG	42	red
TTTAACGAATTTATTAGTTGCTATTTTGAGTACAAATTCTTA	42	red
TTTAGAATAAAGCTGAGCTTCAAAGCGAATCGCCCCCACCCT	42	red
TTTGGGGGCTCACTGCCGGAAGCATAAAAGAATTATATTAAT	42	red
TTTTGCAGATAAAACGTCACCCTCAGCAGAAGCAACAGAAAA	42	red
AGTACGGAATACAAAAGCAATAGAAAATTCAAGTTTATACGCAAA	45	red
ATATACCAGAACCCTCAGAACCGCCACCCTCTAGCCGAAAAAATT	45	red
ATGAAGCCCCTAATGGGTCAACATTAAATGTTCCTGTATTTTAAC	45	red
TTTTTCATGTTTTAACCTGTTTAGCTATCCGGAGAGCTTTCAAGGG	46	red
AGGGATTTTAGACAAAACAGGTTTAACCACGCGAGATCTTCTGACCTAA	49	red
ATCAGAATCAATCACCAGACGAACAACTAAAGGAAGTACGGTACATTTC	49	red
ATCTGATCTCAAATTAACACCTATCAACAATAGATTTTACCGACAAAAG	49	red
CCCTCAGAGCCGTCAATCACCGGAACCAAGCCGGAACAAAGTATCCAGC	49	red
GAAAACATTGCGGAACCCTAAAGGGAGCCGCGTAACCACCGAGTGAGCT	49	red
GCGGCTACACTGGTACTTAAATCGGTGGTGCCATCCGAGCACATCCTCA	49	red
GCGGGGTTTTGCTCAGAGGGGGTAATAGAGACTGGATAGCGTCCAATAC	49	red
TAAACACTTGAGAATCGCCATTTAGCGATAGGTTGTCAGAGCATGGTTG	49	red
TAGAACGAACCGCACAGTTGGAGCTCTCGTGCCTGGCTGATTGCCCTTC	49	red
TAGCCCGCGTAGATTTTCAGGTTTCAATAAGAGACTCATTTGCGCACAG	49	red
TTTTGCCAGTACCAAAAGGTGCCTTGATATTCACAGTGTACTAGTTAAT	49	red
AAGAGTAATCTTGACATACCTGCAGCCAGCGGGCATCAG	42	not shown
ACGAGTATAACAGTTGATTCCCATACGAGCATGTAGAAA	42	not shown
ATATCCCATCCTAATTAACTTTCAACAGTTTCTGGGATT	42	not shown
ATTGCAGGGAGGTGTCCAGCATCAGAACCGGATATTCAT	42	not shown
GATTGCTGGGAGAAACAATAACGGCCCCCTTATTAGCGT	42	not shown
GGAAGATTGTATAAGCACAATATTTTTGAATGAGAATAC	42	not shown
GGCATTTTCGGTCATAGAAAATCCTGTTTGATGTTTGCC	42	not shown
TTGGCAATAATCAAATAAAATTATCAAATATTTAAATTGTA	42	not shown
GTGGCACAGTCTCCGTGGGAACAAATAACAACCCGTCGGATAGATT	42	not shown
ATGCCGGGTAACGACCTAACTGCGTTGCCTTGGGGTAAAAGCGGGGTC	42	not shown
CCAGCAGGCAATCAACCGTCTGTGGCACTGAAAGACTTTGATTCGCCT	42	not shown
TTGCTAAACGAACGATACCGAATCCAAGACCGCAAAGTAATTCTGCGA	42	not shown
AACCGAACTGACCAAGGACAGATGAACGTAGCAGCGTAGCGA	42	green
AGGAAGGTATCTTTATGGATTATTTACACACCAGTCACACGA	42	green

CAATAGGAACGCCATTCGCGTCTGGCCTGAGCGAGCGGCGGA	42	green
CACCAGAACGAGTACTTGAGATGGTTTAGCACCAAAAGAGGC	42	green
GAGTCTGGAGCAAAGATGAACGGTAATCTTCTGTAAGCGGAG	42	green
TTAAACCCTCATCGCATCGCCATTAAAAAACCACCAGCAGAA	42	green
GCCAAAGACCCAAATAAGACTCCTTATTAAAAGAATTTGTCA	42	blue
TCTTTCCACAGCCATGAAAATAGCAGCCAACATAACTACAAT	42	blue
AGCACTAAACTCACGCCTGGGGTGCCTAAGTCAATAATCCTT	42	blue
TACCGCCAGGAAACCCTTTATTTCAACGAAAAACATTATGAC	42	blue
CACGCTGCCCCGATGTAACATTATCATTTAGCGATAGCTTAA	42	blue
TACCGTATATCAGCCATTGAATCTTGCGGGAGAAGCGCCGGA	42	blue
AAAACTTTTTCAAATGAGAGATTTGAAG	28	blue
AGACGACAAAGAAGTGCGGAATCGTCATAACAGTTAGCGGAT	42	blue
AGGTAAAGGGTTGATATTCTGAAACATGAAAGTATAAGTGCC	42	blue
ATAAGAAATTTAATTCGCAAGACAAAGATCCGGCTACCTCCC	42	blue
ATTCATTGGCGGATTAAGAGGCTGAGACTATAAACGGTAATA	42	blue
TTGACGGGCAAGTGACAGGGCGCGTACTGGGAGCTGGAACGG	42	blue

Design and assembly of universal joint and scissor-mechanism structures

The universal joint and the scissor-mechanism structures were designed using the DNA origami custom design software, cadnano[1]. The universal joint and scissor mechanism respectively utilize 7,560 and 8,064 nucelotide (nt) long single stranded DNA (ssDNA) scaffolds derived from the M13MP18 bacteriophage genome[5] (Tilibit Nanosystems, Munich, Germany). The universal joint was designed on a square lattice. The cadnano design is shown in Figure S4 and the solid model design is depicted in Figure 4 (main text). It consists of 3 dsDNA bundle modules. The two outer modules both comprise bundles of 16 dsDNA helices in a 4 by 4 cross-section. The central module comprises a bundle of 20 dsDNA helices arranged in a 5 by 4 cross-section. The hinges connecting modules consist of two ssDNA scaffold connections that are each 2 nt long. For each hinge the two ssDNA connections are arranged on a line to form the hinge axis.

The scissor mechanism cadnano design is depicted in Figure S5 and the solid model design is depicted in Figure 4 (main text). It consists of two bundles of 12 dsDNA helices that form the "arms" of the scissor mechanism. Along each arm, there exists one hinge and one pin joint. The hinges consist of 4 ssDNA scaffold connections. Two of the connections, which form the hinge axis are 2 nt long, and the other two connections are 21 nt long. The two additional longer connections are required to complete the closed loop scaffold routing. The hinge connections are made along the length of a single arm and facilitate angular motion. Further along the mechanism, the two arms are connected together by two ssDNA scaffold connections, each 2 nt long, that cross-over from one arm to the other at a single point forming a pin joint. Where the pin joint is formed, the 12-helix cross-section is reduced to a 6-helix cross-section effectively leaving slots where the two arms can fit together (see Figure 4, main text).

Both structures were folded, purified, and imaged by transmission electron microscopy following protocols detailed in Castro et al.[2]. The scissor mechanism was polymerized by adding additional staples (Table S3) in a second self-assembly reaction carried out at room temperature for 1-3 hours in 0.5xTBE buffer with 14 mM $MgCl_2$ with polymerization staples at 10-fold excess relative to the structure.

Gel and TEM characterization of universal joint and scissor mechanism

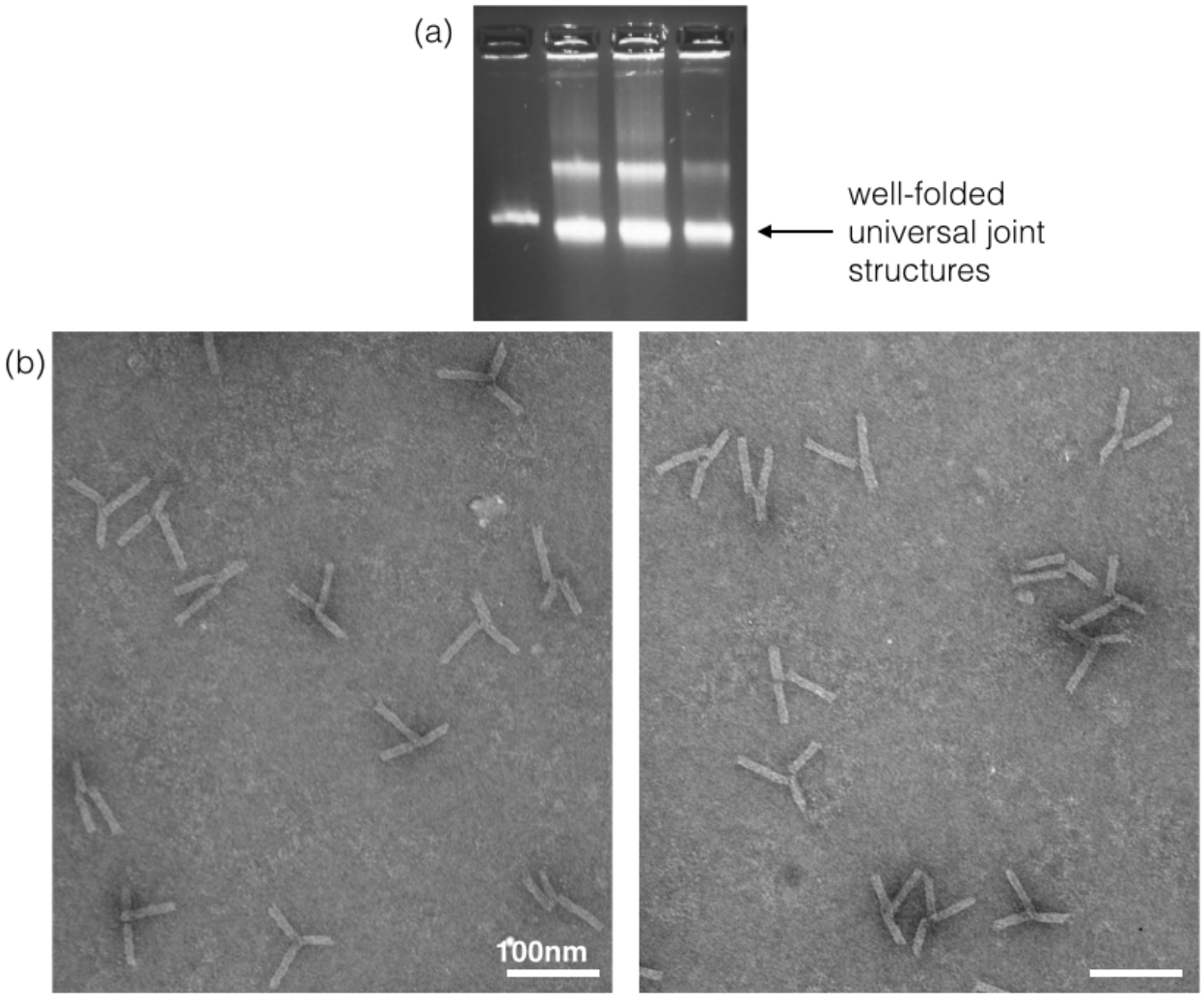

Figure S7: (a) Agarose gel electrophoresis of the universal joint. From left to right, the lanes contain the ssDNA p7560 scaffold, and three lanes of the universal joint folded at 14 mM $MgCl_2$. (b) Additional TEM images of the universal joint.

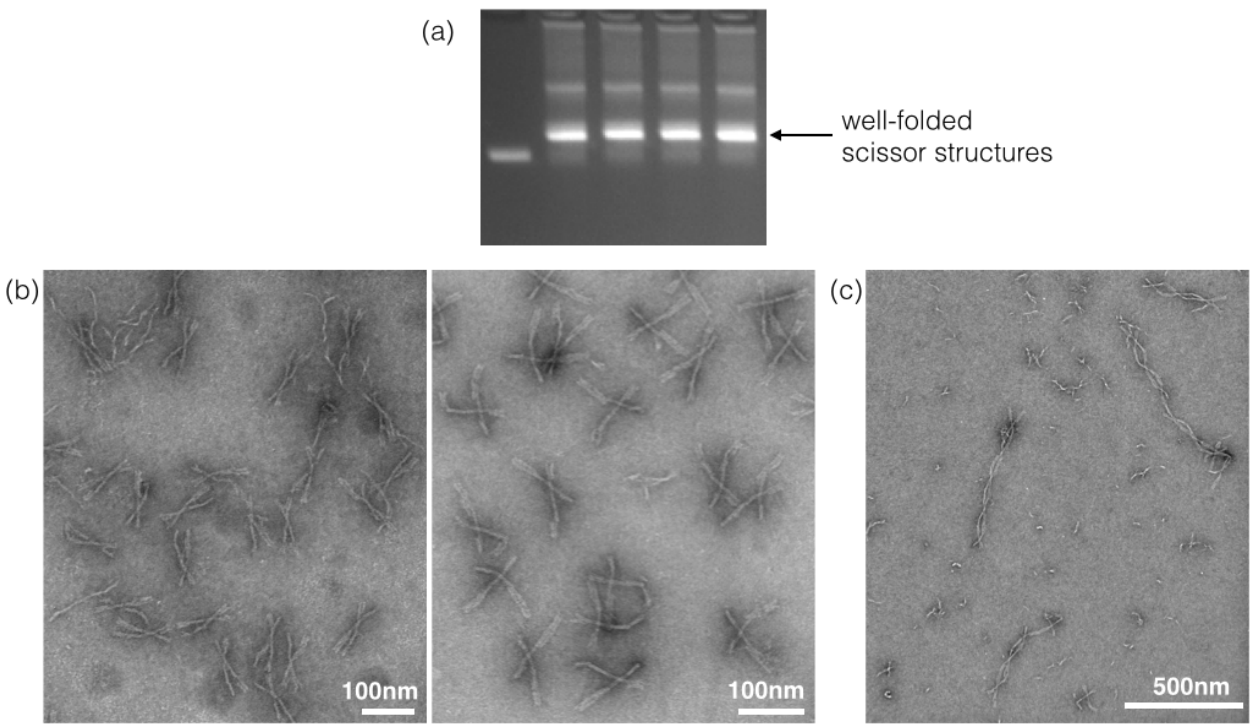

Figure S8: (a) Agarose gel electrophoresis of the scissor mechanism structure. From left to right, the lanes contain the ssDNA p8064 scaffold, and four lanes of the scissor mechanism structure folded at 14 mM $MgCl_2$. (b) Additional TEM images of the scissor mechanism structure. (c) Additional TEM image of the polymerized scissor mechanism.

References:

1. S. M. Douglas, A. H. Marblestone, S. Teerapittayanon, A. Vazquez, G. M. Church and W. M. Shih, *Nucleic Acids Res*, 2009, 37, 5001-5006.
2. C. E. Castro, F. Kilchherr, D. N. Kim, E. L. Shiao, T. Wauer, P. Wortmann, M. Bathe and H. Dietz, *Nat Methods*, 2011, 8, 221-229.
3. H. Isambert, P. Venier, A. C. Maggs, A. Fattoum, R. Kassab, D. Pantaloni and M. F. Carlier, *J Biol Chem*, 1995, 270, 11437-11444.
4. M. D. Wang, H. Yin, R. Landick, J. Gelles and S. M. Block, *Biophys J*, 1997, 72, 1335-1346.
5. S. M. Douglas, H. Dietz, T. Liedl, B. Hogberg, F. Graf and W. M. Shih, *Nature*, 2009, 459, 1154-1154.
6. K. C. Wolfe, W. A. Hastings, S. Dutta, A. Long, B. A. Shapiro, T. B. Woolf, M. Guthold and G. S. Chirikjian, *The Journal of Physical Chemistry B*, 2012, 116, 8556-8572.
7. Y. Ke, S. M. Douglas, M. Liu, J. Sharma, A. Cheng, A. Leung, Y. Liu, W. M. Shih and H. Yan, *J Am Chem Soc*, 2009, 131, 15903-15908.