12-21-2022

Physical Model of Cilia Motion

Toby Utterback
Washington University in St. Louis

Follow this and additional works at: https://openscholarship.wustl.edu/mems500

Physical Model of Cilia Motion

MEMS 400: Independent Study

Toby Utterback

Lab Instructor: Dr. Philip Bayly

December 21st, 2022

Mechanical Engineering and Materials Science - McKelvey School of Engineering

Washington University in St. Louis

1 Brookings Drive, MSC 1185-208-125 St. Louis, Missouri 63130

ABSTRACT:

The motion of cilia could be further understood by creating and analysing a large scale model with similar stiffness and property values. Varying amounts of vibrating HEXBUG robots, representing motion and active particles, were placed in series with different segment lengths connecting them. The oscillating motion of a ciliium was able to be replicated and analyzed using autotracing and autotracking programs. The amplitude of the model increased with increasing length, while increasing length had an inconclusive effect on period. Furthermore, the visual path of a marked end segment repeated with each oscillation recorded.

INTRODUCTION

Motile cilia are hairlike structures found on the surface of cells. The beating nature of cilia moves fluid and aids in general development within the body. The motion and structure of cilia including different types of imaging have highlighted a "9+2 axoneme comprising nine outer doublet microtubules and a central apparatus" [1]. The physical model created will be used to learn more about how the axoneme moves and the importance of its movement. Scaling up from realistically sized cilia allows properties and theories about cilia movement to be tested.

Hexbug Properties. To introduce vibrations and motion into the model, HEXBUG nano® robots were used to simulate active particles. The HEXBUG can move due to a combination of a rotating motor and twelve bent rubber legs. The motor "rotates a counterweight that causes forces up and down" [2]. The rotation of this counterweight is believed to only be in one direction. When the force is downwards the legs are pressed down. On the reverse, when the force from the weight is up, the legs are uncompressed. This leg motion produces the movement and bouncing of the HEXBUG. The direction of the bugs is random and the power is dependent on the battery power [3].

Stiffness Calculations. A nylon rod was used to calculate the force produced by the HEXBUG. The properties of the nylon rod were found by using length, added weight, and difference in height of a tube. Young's modulus was calculated using the following beam displacement equation.

$$EI = \frac{F_m * L^3}{3 * \delta * 1000^3}$$

(1)

1

where E is the Young's modulus [Pa], F_m is the weight [N], L is the length of rod [m], and δ is the difference in height [m].

To find the Young's modulus, the area of inertia for a solid cylinder is calculated with eqn. 2

$$I = \frac{\pi * d^4}{64} \tag{2}$$

where I is the calculated area moment of inertia for solid cylinder $[m^4]$, and d is the diameter of the rod [m].

Force Calculations. To measure the force produced by a HEXBUG, a nylon rod was connected to the HEXBUG and the displacement was measured. To find the force eqn. 3 was used.

$$F_{hexbug} = \frac{\delta * 3 * E_{rod} * 1000^2}{L_{rod}^3} \tag{3}$$

where F_{hexbug} is the force produced by a HEXBUG [N], δ is the displacement [m], E_{rod} is the Young's modulus of the rod [GPa], L_{rod} is the length of the rod [m].

Scaling of Physical Model. The scale of the physical model was based on previous experiments done by Zheng and coauthors. The experiment conducted by Zheng et al. used seven HEXBUGs in series to represent active particles. The HEXBUGSs were connected by a laser-cut rubber chain with slots for each HEXBUG. For the physical model discussed in this paper, rubber tubing was used to connect 3d printed HEXBUG casings. For the laser cut model, the width and height of the segments were constant with a varied length between segments. The different segment lengths varied the motion of the HEXBUG chain [4]. Using the dimensions of rubber segments that produce an oscillating motion and rubber tubing with a set Young's modulus and cross-sectional area, estimates the length of the rubber tubing needed to produce oscillations. This relation is done by calculating the stiffness of the rubber segments (eqn. 4) and setting it equal to the stiffness of the rubber tubing as shown in eqn 5.

$$K_s = \frac{\frac{W_s * H_s^3}{12} * E_s}{L_s} \tag{4}$$

where K_s is the stiffness [N*m], W_s is the width [m], H_s is the height [m], E_s is the Young's modulus [Pa], L_s is the length [m].

$$K_s = K_t \qquad (5)$$

The K_t is the stiffness of the rubber tubing [N*m]. The s is used to indicate rubber segments and the t indicates the rubber tubing. With the stiffness known, the estimated length needed for oscillations using rubber tubing is found using eqn. 6.

$$l_t = \frac{\frac{\pi * (d_t^4 - d_i^4) * 1000}{64} * E_t}{K_t} \qquad (6)$$

where l_t is the length [mm], d_t is the outer diameter [m], d_i is the inner diameter [m], E_t is the Young's modulus [Pa]. This length value is the starting point for creating a range of length values that could produce oscillations.

METHODS

Stiffness Properties. Initially, a nylon rod was going to be used in between the HEXBUGs to add stiffness to the model. The properties of the nylon rod available were unknown. To find the properties, a set length of the rod was placed over the side of a table with the other end taped down. The pre-weight free end height was measured from the ground to the middle of the rod cross-section. A 10 g weight was taped with a string on the free end of the rod. The post-weight height was measured to find the height difference. This was repeated with a 20 g and 50 g weight. The length of the rod was changed two more times for a total of nine trials. The length and weight values used were set to prevent too much bending. This rod material was not considered for the segments between the HEXBUGs because the average Young's modulus was too large and would have required large segments lengths. Instead, this tubing was used to find the force produced by a HEXBUG because its properties were known.

Force Properties. Three different types of robots were considered to act as active particles due to their force values. Each robot had a rotating motor and rubber legs. The rod previously used was measured at a set length and one end was tabled down on the table. The free end was placed so that the rod was linear and the distance from the tip to the side of the table was measured. A bug was

taped to the end of the free end perpendicular to the rod. After the bug turned on and stabilized in one bend rod position, the distance from the middle of the bug to the side of the table was measured. The distance was the only unknown property needed to find the force values.

Scaling Model. The MATLAB file lengthcalculator.m uses the known property values from the Zheng et al. paper and user inputs [4]. When run, a popup tab appears asking for the outer diameter of the rod (mm), inner diameter of the rod (mm), and Young's modulus of material (DURO). This allows the user to use different materials in the tube shape. Once input, the script uses the known properties to find stiffness, as shown in eqn. 4. That is set as the stiffness of the new material, eqn. 5. The final output is $Length_{needed mm}$, which is the length needed to keep the same stiffness as the material known to oscillate.

Creating Hexbug Casing. The HEXBUG required a casing that was able to hold it in motion and connect to other casings. A SolidWorks model of a HEXBUG was found online. This model was used to cut out the shape on an extruded rectangle. This rectangle was cut down to replicate the shape of the HEXBUG. The size of the connection part of the casing had to be adjusted due to the material for the in-between segments. A rubber tubing was chosen because it had a low enough Young's modulus to allow smaller connecting segments between casings. The connection part was a hollow cylinder. Midway down the cylinder, a hole was made. This hole allowed for a pin to go through the rubber tubing and secure the segments together. The pin was also important because it allowed chains with varying amounts of HEXBUGS to be experimented with.

Experiment. Once all of the parts of the chain's properties had been made and analyzed, the experiment could be run. The experiment was run on a smooth, white table to allow for contrast and optimal movement. The first rubber tubing segment was weighed down on one side and pinned to the first HEXBUG casing. The HEXBUG casings were all pinned in series with the rubber tubing in between. There were a total of eight casings. A camera was set up overhead of the experiment to record the motion of the series. For the first set of trials, 10/16" segments were used. Once all eight of the HEXBUGS were pinned and turned on, time was given to let the oscillation start. Once the oscillations started, three to four full oscillations were recorded with the camera. Then the end HEXBUG was unpinned, shortening the series to seven. Time was given for the oscillations to adjust

and then the model was recorded. This was repeated until there were three HEXBUGS left, for a total of six trials. This process was also repeated for 11/16" and 12/16" segments.

Video modificaiton. Before the videos were traced, different video modifications had to be performed. The video camera used recorded at 29.87 fps. The number of frames collected per video was too much to efficiently trace. videoDOWNsample.m is a MATLAB script created by Dr. Louis Woodhams of Washington University in St. Louis. This program reduces the number of frames in a video by a set number. For this experiment, the videos were all reduced so only one of every ten frames are saved in a new video. shape.m is a Matlab script that replaces a set area with a white rectangle in each frame. The tracing program relies on contrast, so a dark object not part of the waveform could distract the program. The output of this program is a new video with the white rectangle added.

Tracing. The tracing MATLAB script, $autotracefunhexbugs.m$, was created by Dr. Woodhams. The input of this program is the video being traced, the spatial resolution, and the frames per second. When the program is run, the user is given the first frame of the video and roughly traces the cilium. Once traced, the program will use the contrast to trace the rest of the frames. To get the program to trace correctly for each video, different tracing factors such as the number of segments along the length and number of theta values had to be adjusted. The relevant output of this program was the length, period, and amplitude. plotThetaArray.m, another MATLAB script created by Dr. Woodhams, takes the output from the autotrace program and makes a GIF of the movement of the cilium.

Autotrack. autotrack.m, made by Dr. Woodhams, is another tracing program that tracks the body motion of a focused shape in a video. In this case, the user is able to circle one of the HEXBUGS. The output is a visual trace of where the HEXBUG was in all of the frames on one image. This was done with each of the HEXBUG videos.

RESULTS AND DISCUSSION

Stiffness and Force Results. The average calculated Young's modulus value for the rod was 2.19 GPa. This is similar to the known Young's modulus value for nylon of 2.7 GPa. Table 1 shows the force values of three different types of robotic bugs.

Table 1   Force Values of Different Robot Bugs

	Average Force Value (N)
Nanoflash Large	0.0169
Nanoflash Small	0.0171
Nano Nitro	0.0229

The Nano Nitro had the largest force, but it also bounced back and forth at the max displacement. For the final model, the Nanoflash small was chosen.

Scaling Model. The dimensions and properties of the rubber segments and the rubber tubing are shown in Table 2 and Table 3. The rubber segments are from the Zheng el al. paper [4]. The rubber tubing is the material used as segments for this model.

Table 2   Properties of Rubber Segments

Width (m)	Height (m)	Length (m)	Youngs Modulus (Pa)
4.25E-03	4.25E-03	8.50E-03	2.39E+05

Table 3   Properties of Rubber Tubing

Outer Diameter(m)	Inner Diameter(m)	Young's Modulus (Pa)
3.20E-03	1.60E-03	1.00E+06

Using lengthcalculator.m the length needed was found to be **6.31mm**. This length does not include the 6.7 mm of the HEXBUG casing. The total length of each segment needed to be around 19.71 mm (~ 12/16 in). The length of segments used in this experiment were 10/16 in, 11/16 in, 12/16 in.

Hexbug Casing. Figure 1 and 2 show the Solidworks model for the HEXBUG casing.

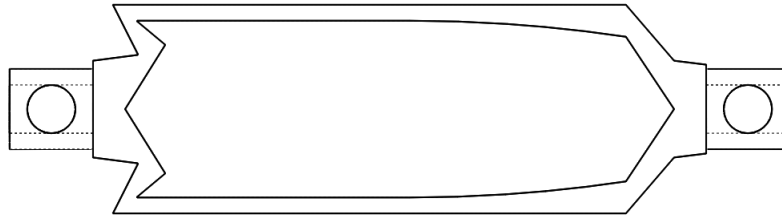**Figure 1   Top View of HEXBUG Casing**

The shape of the HEXBUG was cut out so that the HEXBUG has a snug fit. The dotted lines are hollowed cylinders.
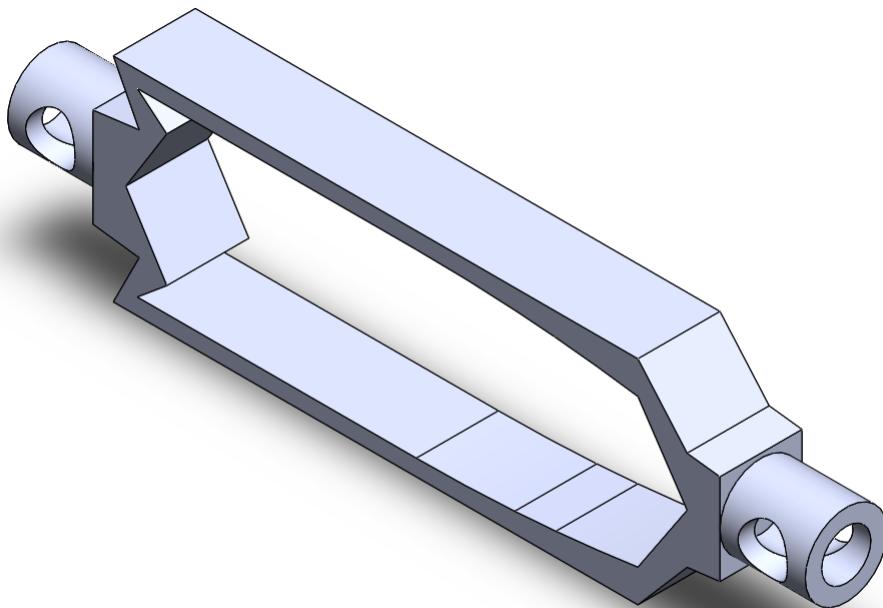

Figure 2   Rotated View of HEXBUG Casing

The holes in the connection parts are for inserting a pin to hold the rubber segments.

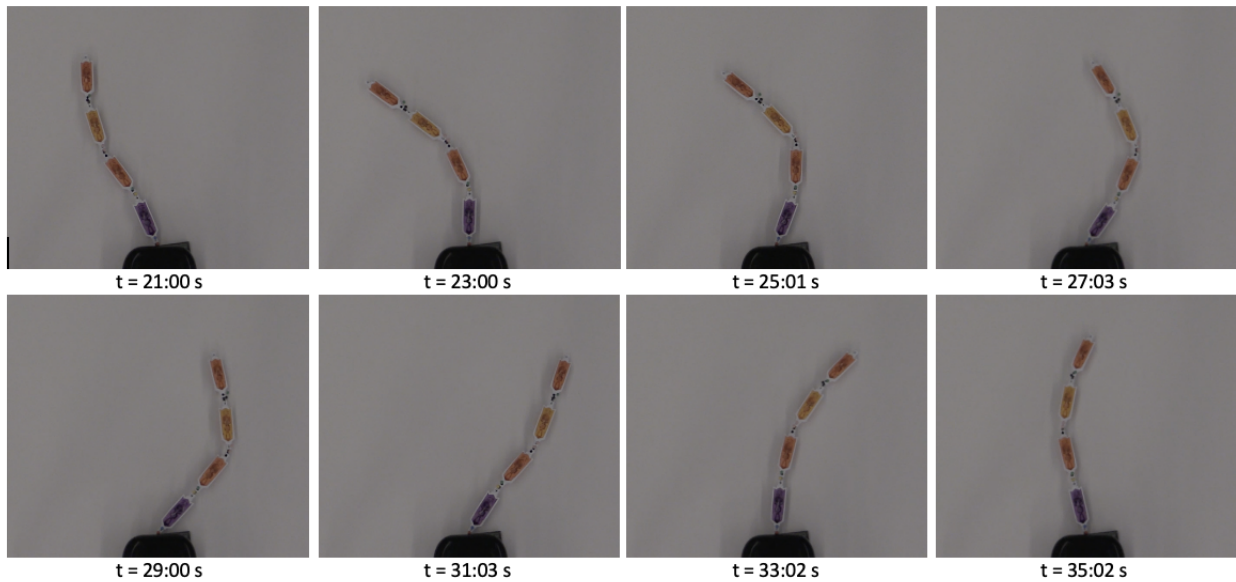**Autotrace Results.** Figure 3 shows eight frames from the trial with 12/16 in segments and four HEXBUGS.

Figure 3   Frames from Trial with Four HEXBUGS

Figure 4 shows eight frames from the trial with 12/16 in segments and eight HEXBUGS.
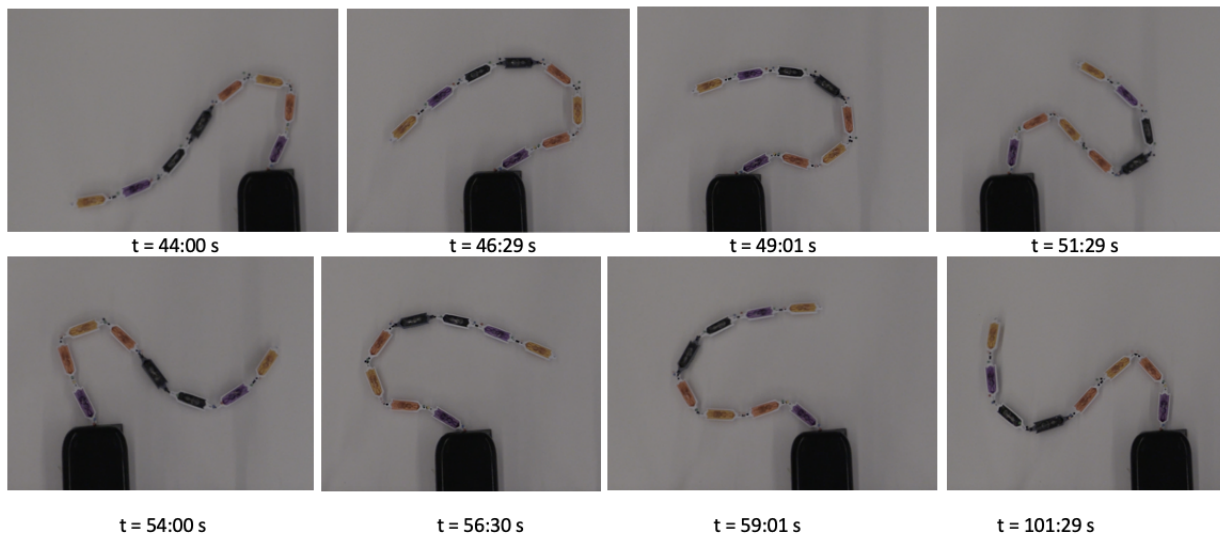

Figure 4   Frames from Trial with Eight HEXBUGS

Figure 5 shows four frames from a .Gif of the traced motion. This trace is from the trial with 11/16 in segments and six HEXBUGS.
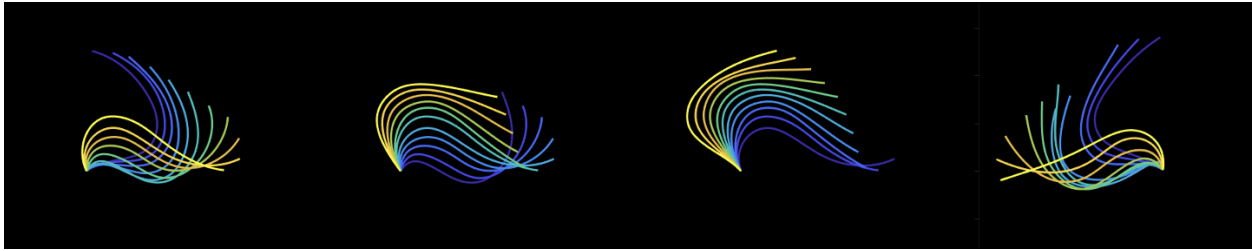
Figure 5   Frames from Autotrace Tracing

There will be a link to all of the Gifs of the traces in the Appendix. The most important values from Autotrace were period and amplitude. Figure 6 shows the period vs. calculated length of the cilia model in mm.
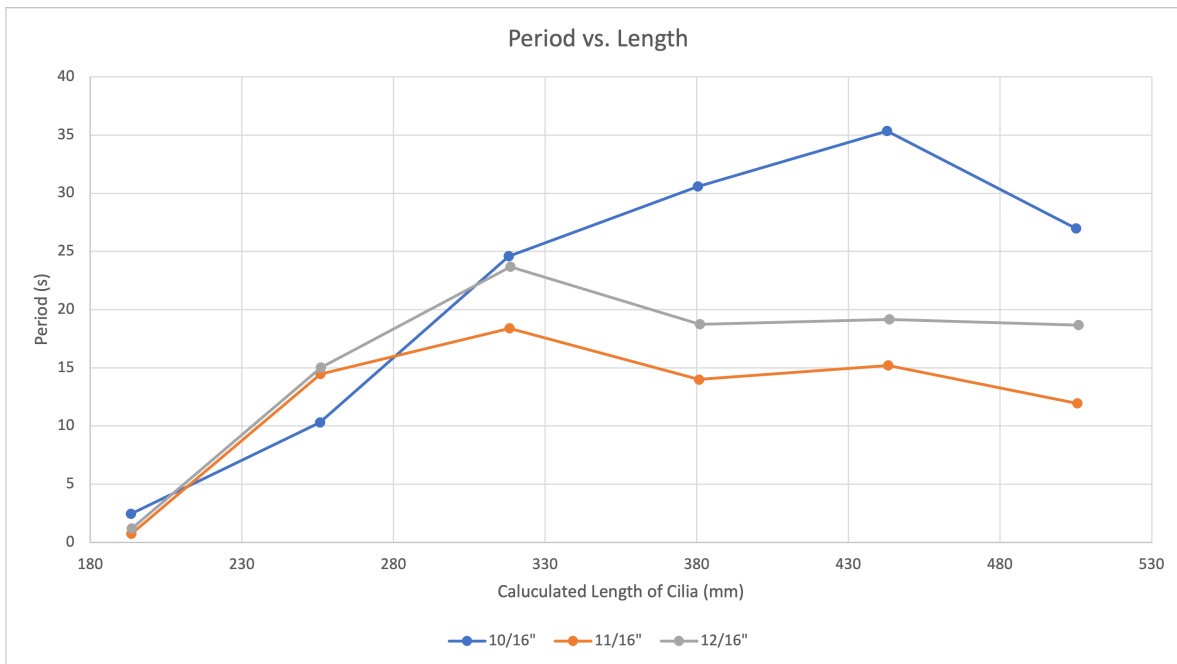

Figure 6   Period vs. Calculated Length of Cilia Model

The calculated length of cilia was found by the length of the HEXBUG casings and the length of the segments in between the casings. Each point signifies the amount of HEXBUGs included starting with three HEXBUGs on the left to eight HEXBUGs on the right. For all of the different segment lengths, from three to five HEXBUGS, the period increased with the length of the cilia model. This means that as the cilia model increased the time in-between cycles increased. The 11/16" and 12/16" segment experiment's periods peaked at five HEXBUGs and then slightly decreased. The largest period of the 11/16" segment trials and the 12/16" segment trials were respectively, 18.4 s

and 23.7 s. The increasing length of the cilia model did not seem to increase the period of 11/16"
and 12/16" segment trials for over five HEXBUGs. The 10/16" segment trial's period continued to
increase with the length of cilia until peaking at seven HEXBUGs. This means that as the length of
the cilia model increased, the period also increased until over seven HEXBUGs. The 10/16" segment
trials largest period of 35.4 s was at a length of 442.72 mm (7 HEXBUGs). Figure 7 shows the
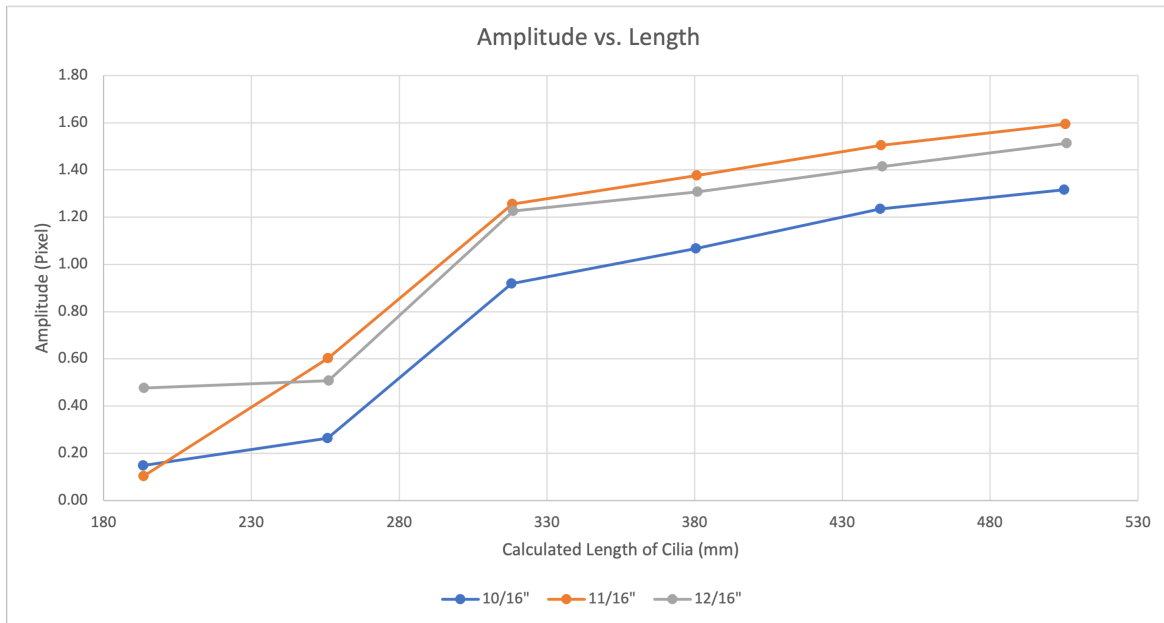amplitude vs. calculated length of the cilia model.

Figure 7   Amplitude vs. Calculated Length of Cilia Model

For each of the experiments, as the calculated length of the cilia model increased, the amplitude
increased. The amplitude is the deviation from the median, indicating more bending. Overall, the
11/16" segment trials consistently have higher amplitudes at each different HEXBUG amount, followed
by 12/16" and 10/16" segment trials.

Autotrack Results. Figure 8 shows the tracing of the end HEXBUG from three to eight HEXBUGS with 12/16" segments.
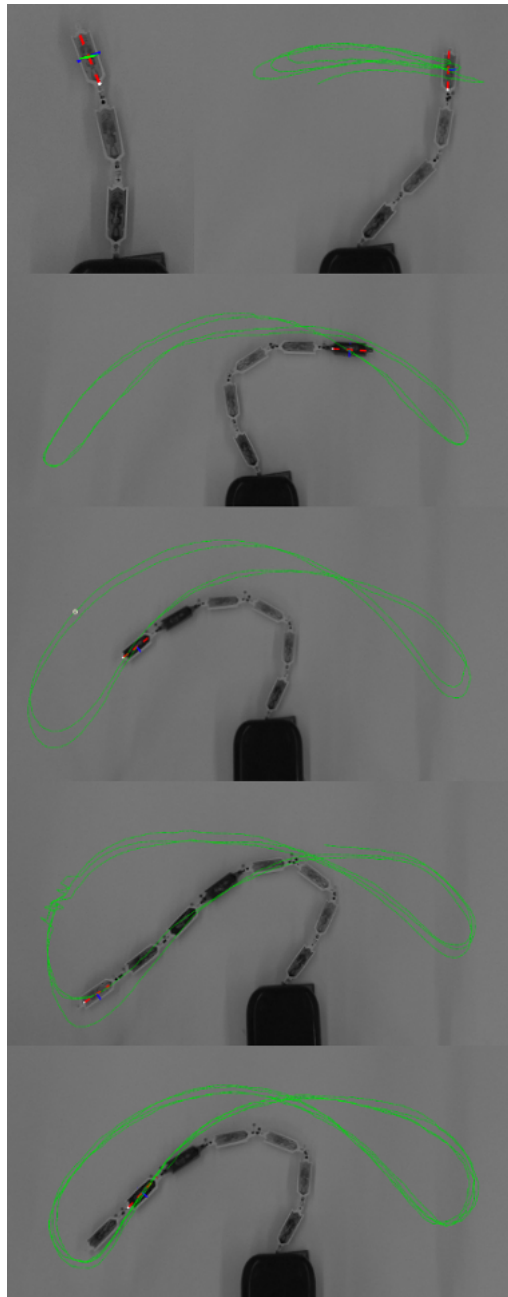

Figure 8   End Movement of Three to Seven HEXBUGs

Each frame shows the end movement with a different amount of HEXBUGs. The first two frames show the light sway of the chain back and forth, while the longer chains demonstrate a figure eight motion. The larger section on the left motion is consistent throughout all of the experiments. The reason is unknown, but could be connected with the direction of the motor inside the HEXBUGs.

CONCLUSION

The motion of cilia can be physically modeled on a large scale by using forces from vibration and calculated stiffness from set segments. Using known material properties, the forces of vibrating HEXBUGs and the stiffness of the rubber tubing were found and connected with 3d printed casings. The motion of the 3D model was able to be recorded and analyzed visually with tracing software; the software allowed the period and amplitude of the motion to be compared between trials with differing segment lengths and number of HEXBUGs. These findings highlight that is possible to replicate and analyze the motion of a large-scale cilia model. The future of this work involves using the techniques and values discovered in this model to create coupled models. Coupled models will contribute to understanding the synchronization of a phase and the general motion of the flagellum.

References

[1] Rasagnya Viswanadha, W. S. S. and Porter, M. E., 2017, "Ciliary Motility: Regulation of Axonemal Dynein Motors," Tech. rep., Cold Spring Harb Perspect Biol.

[2] Robotics, "HEXBUG Nano How it Works," accessed November 13, 2011, https://www.youtube.com/watch?v=dhRoqUkhbdU

[3] Suphona, T., 2021, "Collective behaviors of automous robots in complex enviroment," Master's thesis, Chambers University of Technology, Gothenburg, Sweden.

[4] Zheng, E., Brandenbourger, M., Robinet, L., Schall, P., Lerner, E., and Coulais, C., 2021, "Self-oscillation and Synchronisation Transitions in Elasto-Active Structures," doi: 10.48550/ARXIV.2106.05721, https://arxiv.org/abs/2106.05721

A   Additional Figures

Autotrace GIF. Click here to be able to see the all of the GIF from Autotrace.
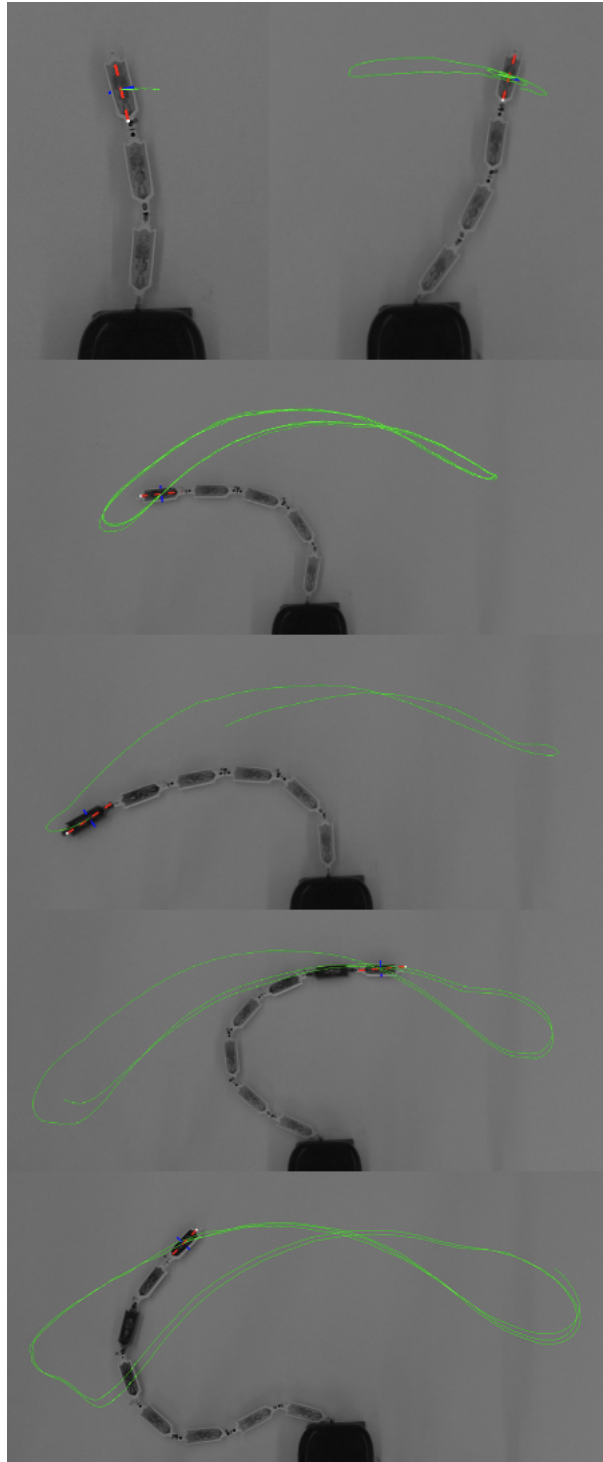
Autotrack Results. :

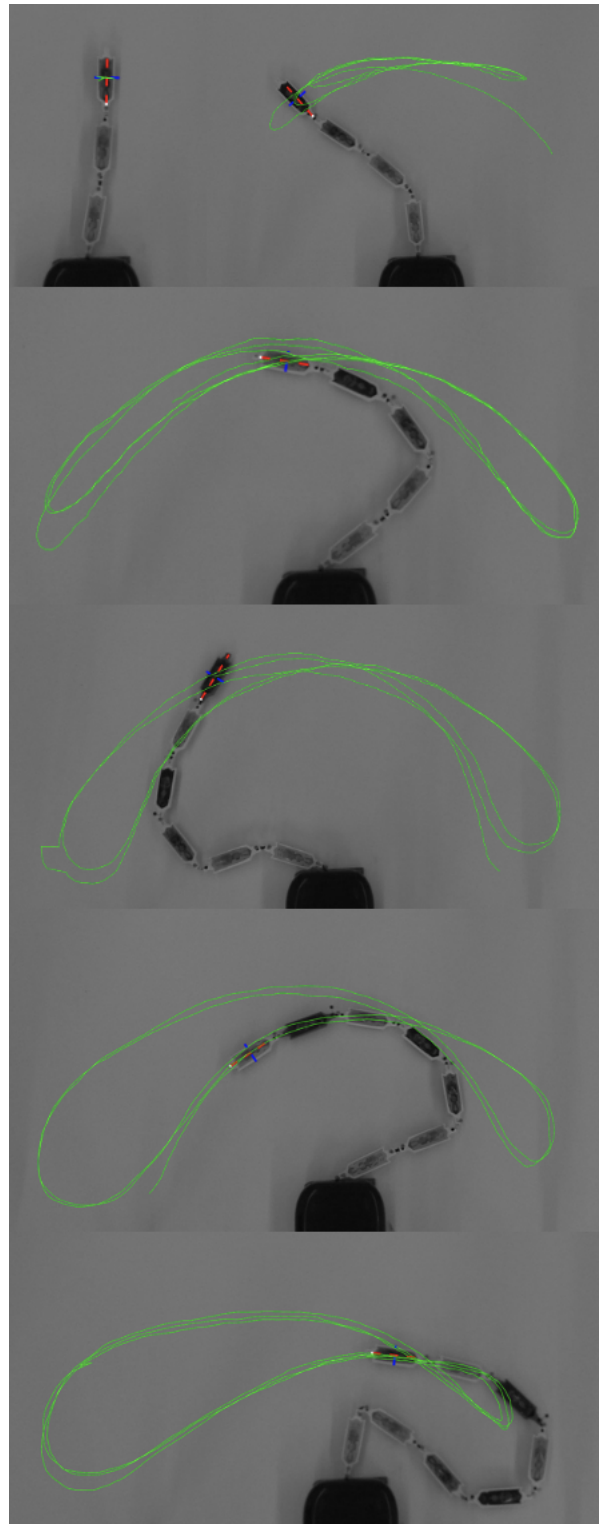**Figure A.1   End Movement of HEXBUGs (10/16")**

Figure A.2   End Movement of HEXBUGs (11/16")

1 MATLAB Code

```matlab
%Bug Length Calculator
%TLU with variables from Zheng et al.
%Paper Variables
W_p = 4.25e-3; %m (p.1 fig 1)
L_p = W_p*2; % m ( based on fig 1c)
H_p = W_p; % m (based on fig 1c)
G_p = 0.239e6; %Pa %youngs modulus (p.7)

% %Variables
% d_t = 3.175; %mm %diameter of rod
% E_r = 2.185 %GPa % Measured Young's Modulus
% I_r = 4.988E-12 %m^4

prompt = {'Enter Outer Diameter of Rod (mm)','Enter Inter Diameter of ...
    Rod(mm)','Enter Youngs Molulus of Materal(DURO)',};
dlgtitle = 'Input';
dims = [1 40];
definput = {'0','0', '0'};
answer = inputdlg(prompt,dlgtitle,dims,definput)

%d_t = str2num(cell2mat(answer(1,1)))/1000
%d_i = str2num(cell2mat(answer(2,1)))/1000
%E = str2num(cell2mat(answer(3,1)))

d_t = .0032
d_i = .0016
E = 60

%E_r = exp(E*0.02750-0.6403)*10^6; %Pa
%E_r = exp((E+50)*0.02750-0.6403)*10^6
E_r = 1e6 %

% if cylinder
I_r = (pi * ((d_t)^4 - (d_i)^4))/64; %m^4

```

```matlab
35  %Paper Torsional Constsant --> torsion is twisting
36  w_p = W_p/2; %m
37  l_p = L_p/2; %m
38  h_p = H_p/2; %m
39  J_p = w_p^3*h_p*((16/3) - 3.36*(w_p/h_p)*(1-(w_p^4/(12*h_p^4)))); %m^4 (p.7)
40  C = (G_p*J_p)/L_p; %N*m/rad %torsional stiffness (p.7)
41
42  %Paper Bending Stiffness
43  I_p = (W_p * H_p^3)/(12); %m^4
44  C_p  = (I_p * G_p)/L_p; % N*m
45  C_b = C_p/C;
46
47  %Model Stiffness
48  K_t = C_p; %N*m
49  Length_needed_mm = (E_r * I_r *1000) / K_t %mm
50  Length_needed_c = Length_needed_mm/10 %cm
```