# DER Simulation of the World Highest Jumping Robot Midterm Report

Junlin Chen[1] and Sanskar Nalkande[2]

## I. INTRODUCTION

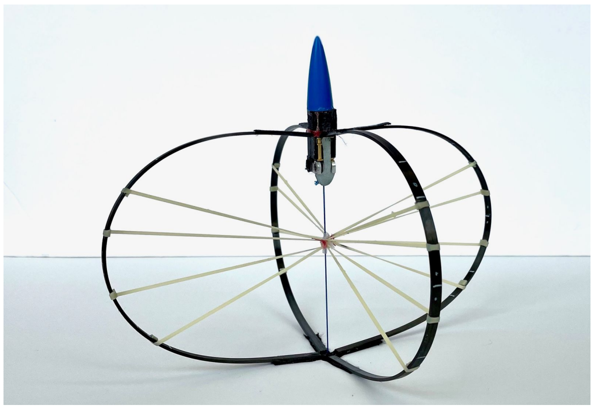

Fig. 1. The presented jumper with the hybrid spring in a stable pre-jump configuration [2]

Recall that this project focuses on the world's highest jumping robot that can soar 31 meters above the ground with a body less than half a meter. To achieve a jump of this height, this robot utilized an engineered drive system along with the novel hybrid tension-compression structure to best improve the specific elastic energy stored by the system.[1] The use of a new elastic structure and the success of the robot incentivize the digital simulation of such robots for future parametric study and preliminary design. If proven successful, this project can act as the foundation stone for future research on high-performing jumping robots or hybrid tension-compression structure analysis.

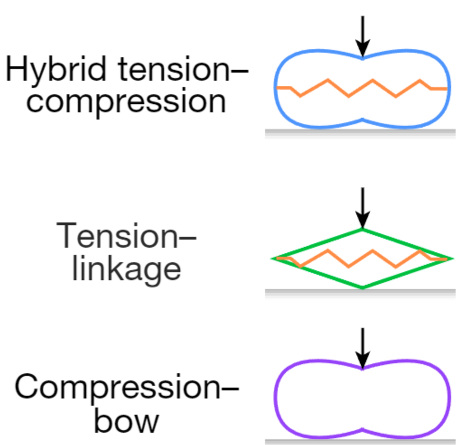


Fig. 2. Hyrbid Tension Compression Structure Design Layout from Hawkes et al.[2]

## II. SIMULATION BACKBONE

### A. Discrete Elastic Rods

The backbone of simulation is the DER theory introduced by Mikl Bergou et al. in 2010. The rod is divided into a number of edges and vertices that partition the rod. The state of each edge and node is predicted based on the equation of motion at each time step.

$$M\ddot{q} + \frac{dE_{elastic}}{dq} = f_{external} \tag{1}$$

where

1) $M = mass of the system$
2) $q = the position of the system$
3) $E_{elastic} = the elastic energy of the system$
4) $f_{external} = external force experienced by the system$

The equation of motion is solved numerically at each time step and each edge or node to obtain the respective position of nodes and edges. The numerical method utilized in the project is the Newtonian method. At each iteration, the predicted solution($x_{n+1}$) is updated using the following formula:[3]

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \tag{2}$$

The numerical process continues to reduce the error until the error meets the corresponding threshold. To facilitate the Newtonian method calculation, the equation of motion can be rearranged and discretized to:

$$0 = \frac{m_i}{\Delta t}\left(\frac{q_i(t_{k+1}) - q_i(t_k))}{\Delta t} - \dot{q}_i(t_k)\right) + \frac{dE_{elastic}}{dq_i} - F_{i,external} \tag{3}$$

By using the Newtonian method to solve for the $q_i(t_{k+1})$ either implicitly or explicitly, the system can be simulated throughout time.

### B. DisMech Simulation

DisMech is a physical simulation built specifically for soft robots and structures. Thanks to the members of the Structures-Computer Interaction Lab at UCLA, the simulation can be done on a user-friendly interface. DisMech offers functions that allow users to easily create geometry through limb() and joint() commands. DisMech also carries other functions that enforce force application, edge fixture, data logging, and other packages that facilitate the simulation of rod-based structures. All commands and parameters are specified inside the robotDescription.cpp file and an OpenGL-based graphical representation of the simulation will automatically pop up for easy visualization.

## III. Modeling Progress

### A. Material Updates

After a deeper dive into the material selection of the original robot, it was found that the carbon fiber bows used by the UCSB team come from ACP Composites. The exact properties of the carbon fiber they used are obtained from the specification sheet published by ACP Composite.[2]

TABLE I
ACP Composites Carbon Fiber Properties

| | |
|---|---|
| Tensile Strength | 1.72 GPa |
| Tensile Modulus | 138 GPa |
| Flexural Modulus | 131 GPa |
| Density | $1.5g/cm^3$ |
| Ultimate Tensile Strain | 1.50% |
| Composite Type | 0° unidirectional orientation carbon fiber |

The above properties will be applied to the DisMech simulation for each carbon fiber bow and the crosses.

### B. Structural Updates

The hybrid tension-compression structure is constructed on DisMech, here is a screenshot of its current form:

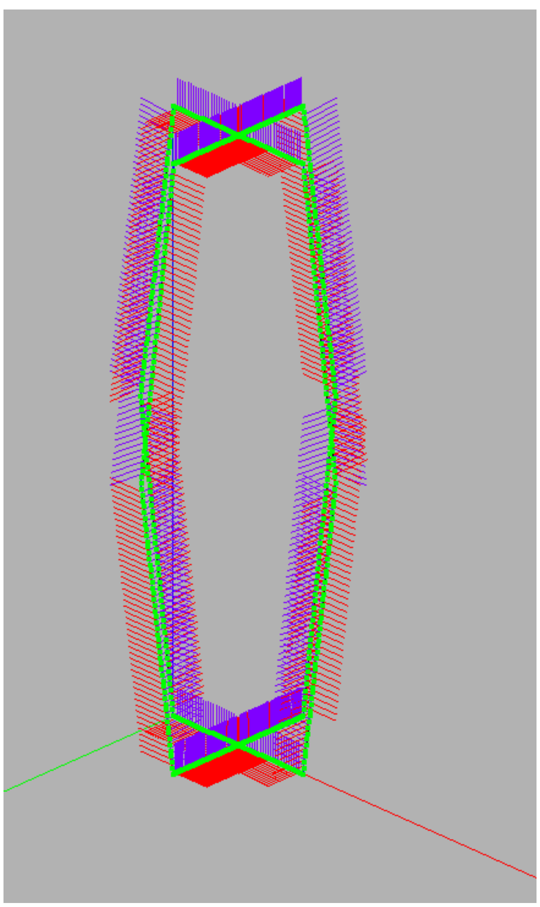

Fig. 3. Current structure of the robot at the natural condition

The four bows are connected to two crosses located at the top and bottom of the system. When force is acted on the top of the system, the bows will compress and store elastic energy. The tension linkage system is vacant in the first iteration of the model but will be added to the system and will be connected to a central rod fixed to the middle of the bottom cross. The linkage rubber bands will have drastically different material properties compared to carbon fiber. Thanks to the interface of DisMech, such problems can be addressed easily by setting different parameters when constructing the corresponding limbs.

### C. Simulation Progress

We have got a basic DisMech simulation working. We have fixed the middle node at the bottom cross and added a force at the top cross so that the robot can actually compress and store energy needed for jumping. The following image shows the compressed shape of our robot.

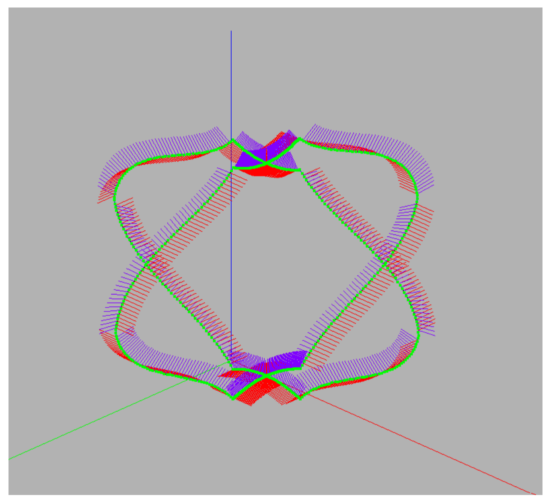

Fig. 4. Structure of the robot at the compressed condition

Now coming to the methodology of the simulation, we have used backward Euler method with a time step of $10^{-5}$ seconds. The backward Euler integration method can be visually understood by the figure below.

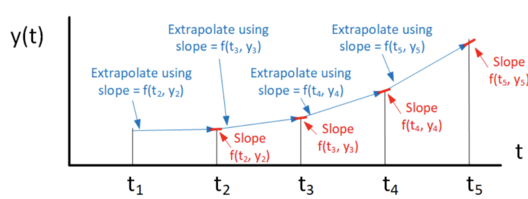


Fig. 5. Visualisation of Backward Euler Integration Method

## IV. Work in Progress & Challenges

### A. Z component force issue

A test involving 2000N of force acting on the top of the cross was conducted. However, instead of bow deformation, oscillation occurs.

## B. Elastic bands addition

As mentioned, the elastic bands will be added to the system for the next iteration of the model. The material properties of rubber bands are determined from K. McLaughlin's research[4].

## C. Ground contact

Even though the current boundary condition of the model involves a cantilevered edge at the middle of the bottom cross, the real-world robot does not rely on ground fixtures. Instead, the real-world robot is able to maintain its position and orientation through ground contact. However, using the example code from the spyder robot example on DisMech, the behavior of the system is abnormal. Further studies and discussions with Structures-Computer Interaction Lab members are necessary to provide correct boundary conditions to the system.

## D. Compute the total elastic energy stored

One most the key parameters focused on by the UCSB team is the amount of specific elastic energy produced by the system. Since the goal of the robot is to do vertical movement across a gravity field, the height attainable by the robot is dominated by the amount of energy convertible to the gravitation potential of the system. Thus, by obtaining the total elastic energy of the system, one will be able to predict the final jump height with a few real-world adjustments to the value.

## E. Actuation

In the original paper, the robot is actuated by the release of the wire that joins the bottom cross to the mass at the top cross. This actuating condition may be implemented using a simple conditional:

$$l_{rope} = \begin{cases} \frac{l_{natural}}{2}, & \text{if } t \leq t_{trig} \\ l_{natural}, & \text{otherwise} \end{cases}$$

The wire is in tension in the compressed position and applying a downward force on the top part. When this wire is released, the tension in the wire essentially becomes zero and all the stored energy is released in a very short amount of time. While it is better to do it using the method mentioned above, we are currently planning to trigger the condition by making the compressive force acting on the robot disappear almost immediately. This will cause the sudden release of the stored energy in the bows. Although this method is not the same as the one used for the robot originally, we believe it will produce almost the same results.

## F. Recurve bows

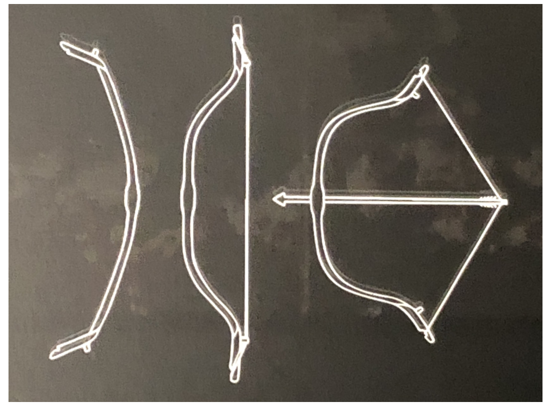

Fig. 6. Illustration of Recurve Bow Before and After Pulled

# V. TIMELINE COMPLIANCE

TABLE II
TIMELINE TABLE

| Date | Challenge to be done |
|---|---|
| Nov.5 | Presentation and proposal write up |
| Nov.13 | Simulation for a single bow ready |
| Nov.19 | Two bow system simulated, mid-term presentation ready |
| Nov.27 | Rubber band implementation and actuation |
| Dec.4 | Visualization and final presentation ready |
| Dec.7 | Final report due |

# REFERENCES


[1] E. W. Hawkes et al., "Engineered Jumpers Overcome Biological Limits via Work Multiplication," Nature News, Apr. 27, 2022.

[2] ACP Composites, "Solid Carbon Rod All Series PDS," No.49881, Oct.2019.

[3] M. Khalid Jawed, Class Lecture, Topic: "Networks of Beams." Module 17, University of California, Los Angeles. Oct, 2023.

[4] K. McLaughlin, A. Titus, "Elasticity of Thera-Band Resistance Band," High Point University., High Point N.C., 2014.

[5] Ethnographica, "The unstoppable horde: How the Mongolian recurve bow created the greatest empire ever," July 23, 2018. https://ethnographica.net/2018/07/23/the-unstoppable-horde-how-the-mongolian-recurve-bow-created-the-greatest-empire-ever/

[6] "1.3: Backward Euler method," Mathematics LibreTexts, Jul. 17, 2022. https://math.libretexts.org/Bookshelves