Applying a bead and spring framework to light-driven deformation

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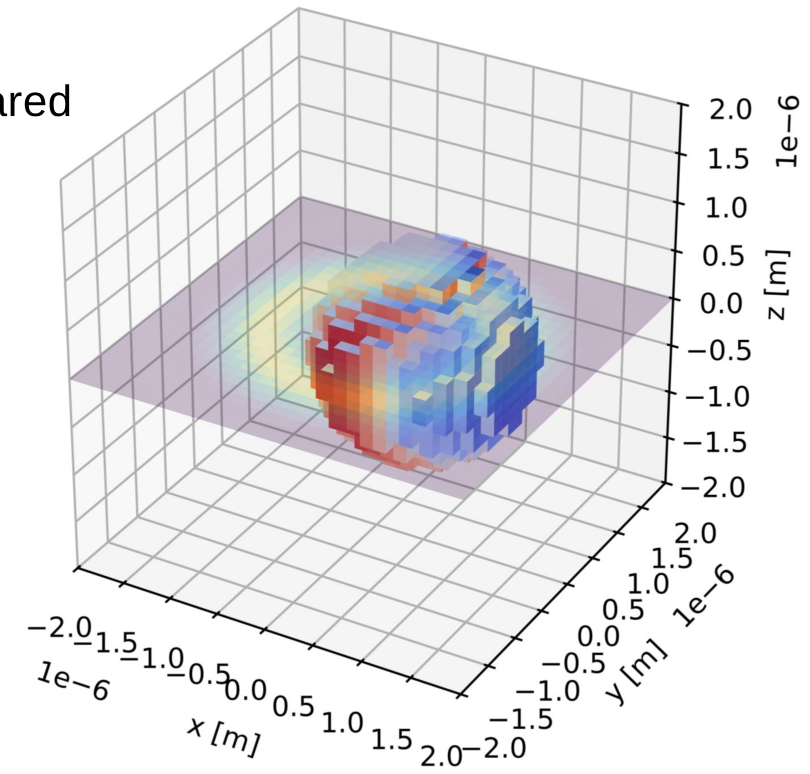
Introduction

The optical forces from a laser beam can be used to manipulate microscopic particles. These are used as optical tweezers to control flexible biological cells and have medical applications which could be researched efficiently through the simulation of optically dense, deformable objects.

The force on a set of rigid particles can be calculated using existing methods such as the discrete dipole approximation (DDA). However, the Abraham-Minkowski Controversy only guarantees the accuracy of the total force on the object, not the force densities. This experiment simulated the forces as a flexible object was divided into rigid spheres to validate the bead and spring model.

Then, the simulation's predictions were compared to experimental results.



Visualisation of the stresses exerted on a spherical particle in a Laguerre-Gaussian beam.

Experimental Methods

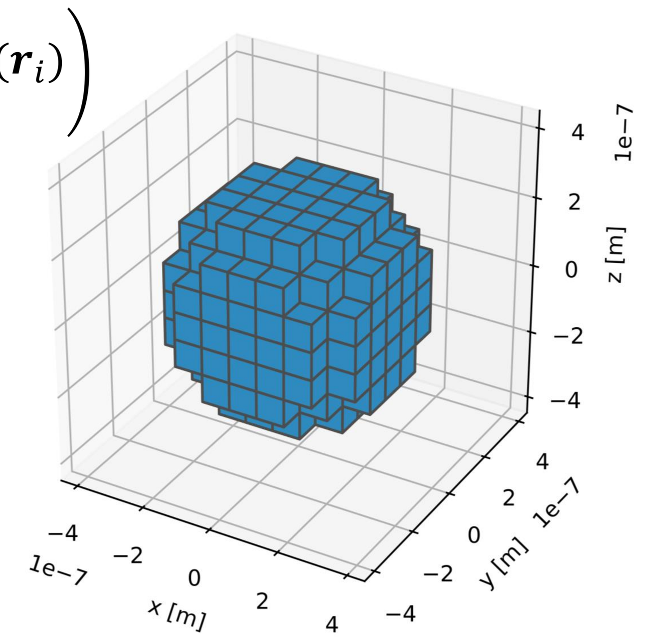
The discrete dipole approximation was used to calculate the force on each particle. This method considers the particles as a collection of many point dipoles, as shown in the figure below. The following system of equations is solved for the polarisation.

$$\boldsymbol{E}(\boldsymbol{r}_i) = \boldsymbol{E}^{\text{inc}}(\boldsymbol{r}_i) + \sum_{i \neq j} \overline{\boldsymbol{G}}(\boldsymbol{r}_i, \boldsymbol{r}_j)\boldsymbol{P}(\boldsymbol{r}_j)$$

$\boldsymbol{E}$ and $\boldsymbol{E}^{\text{inc}}$ are the total and incident electric fields respectively and are evaluated at the position of each dipole. $\overline{\boldsymbol{G}}$ is the free space Green's tensor and $\boldsymbol{P}$ is the polarization. Then, the force at each dipole found using the following equation.

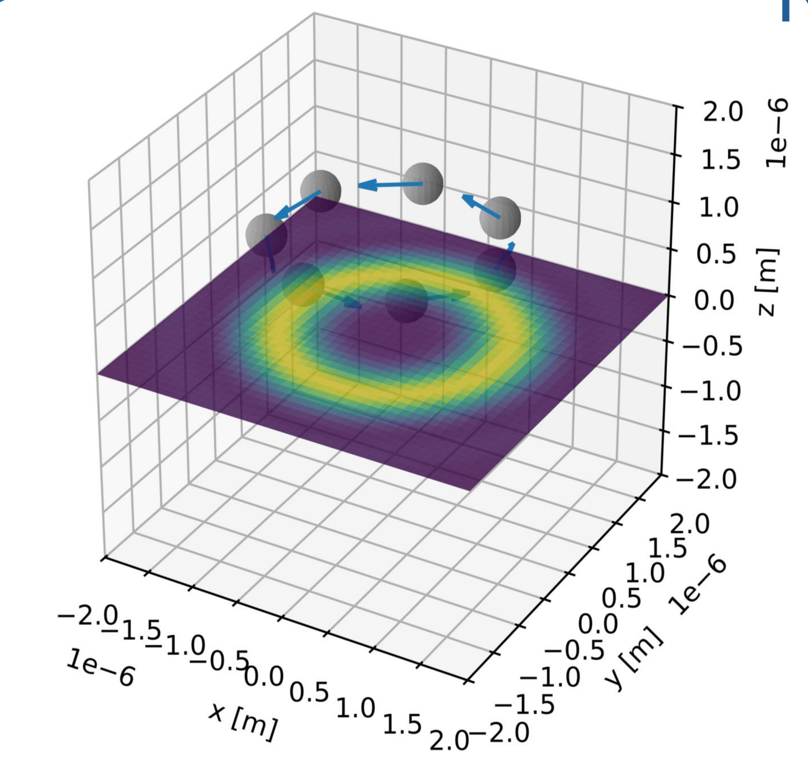
$$\langle F_u(\boldsymbol{r}_i)\rangle = \frac{1}{2}\, Re\left(\sum_{v=x,y,z} P_v(\boldsymbol{r}_i)\frac{\partial E_v^*}{\partial u}(\boldsymbol{r}_i)\right)$$

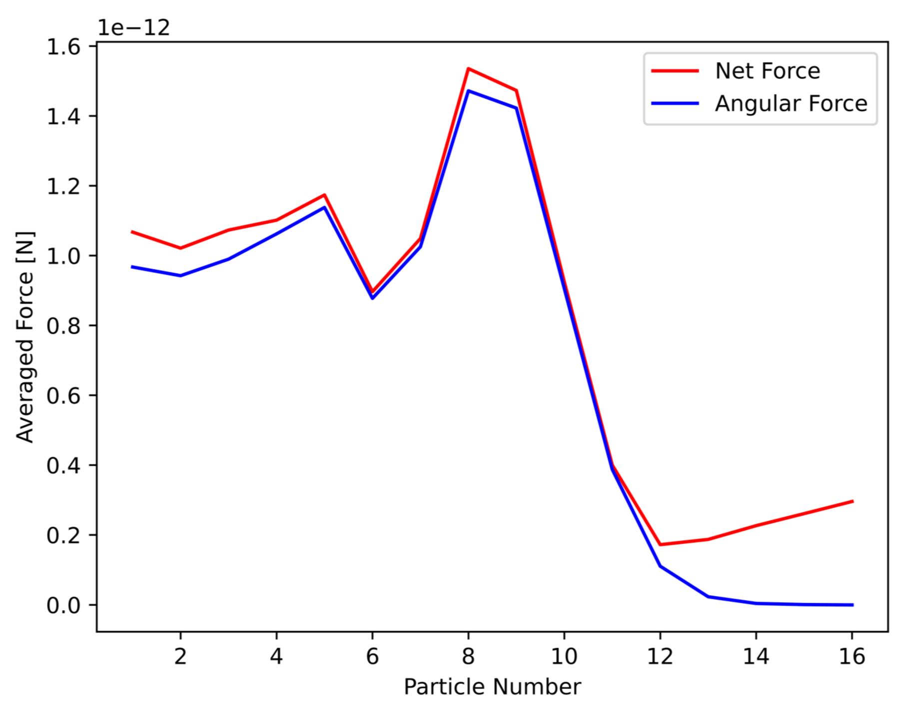
F is the force evaluated at one of the dipoles. The subscripts u and v give the components of the vector, with values of x, y and z.



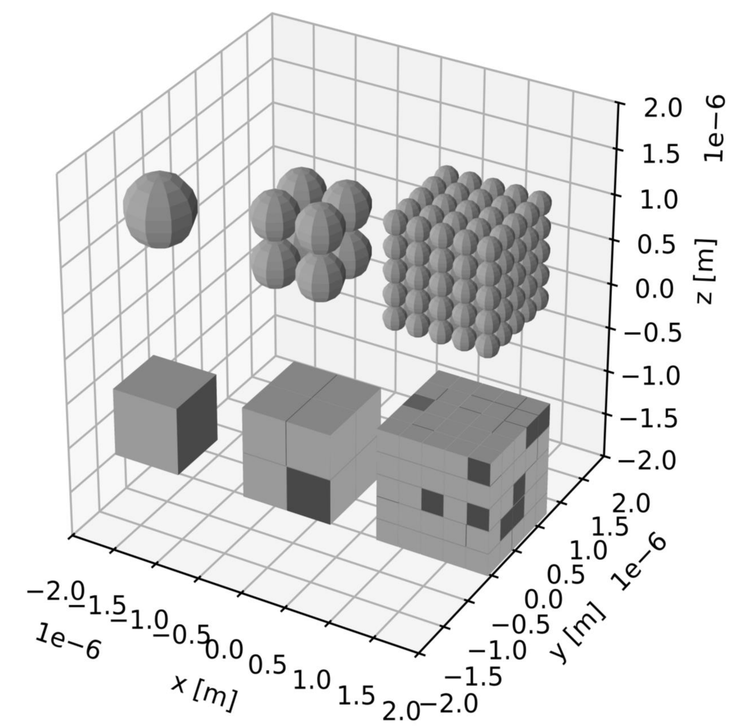
In a low Reynolds number regime, the system's force can be equated to a zero inertial term. The net force is zero, which is the sum of the optical, spring, bending, drag and Buckingham components. The system is time stepped using the resulting differential equation.

Results – model validation

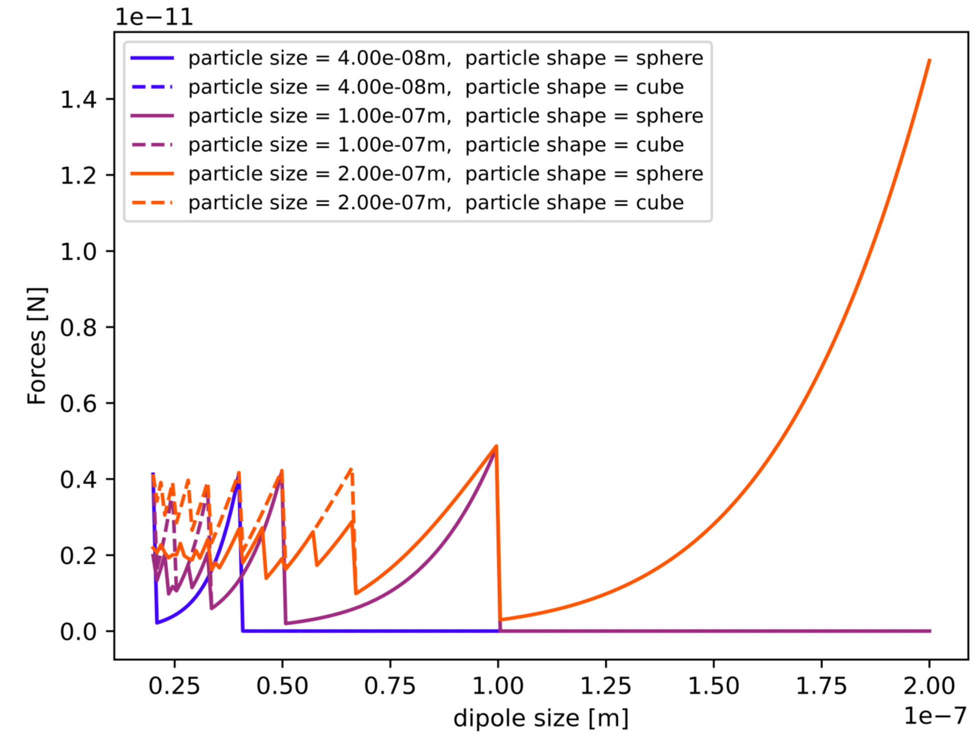




Total and angular force on spherical particles as more are added in a ring formation near the high intensity annulus of a Laguerre-Gaussian beam.

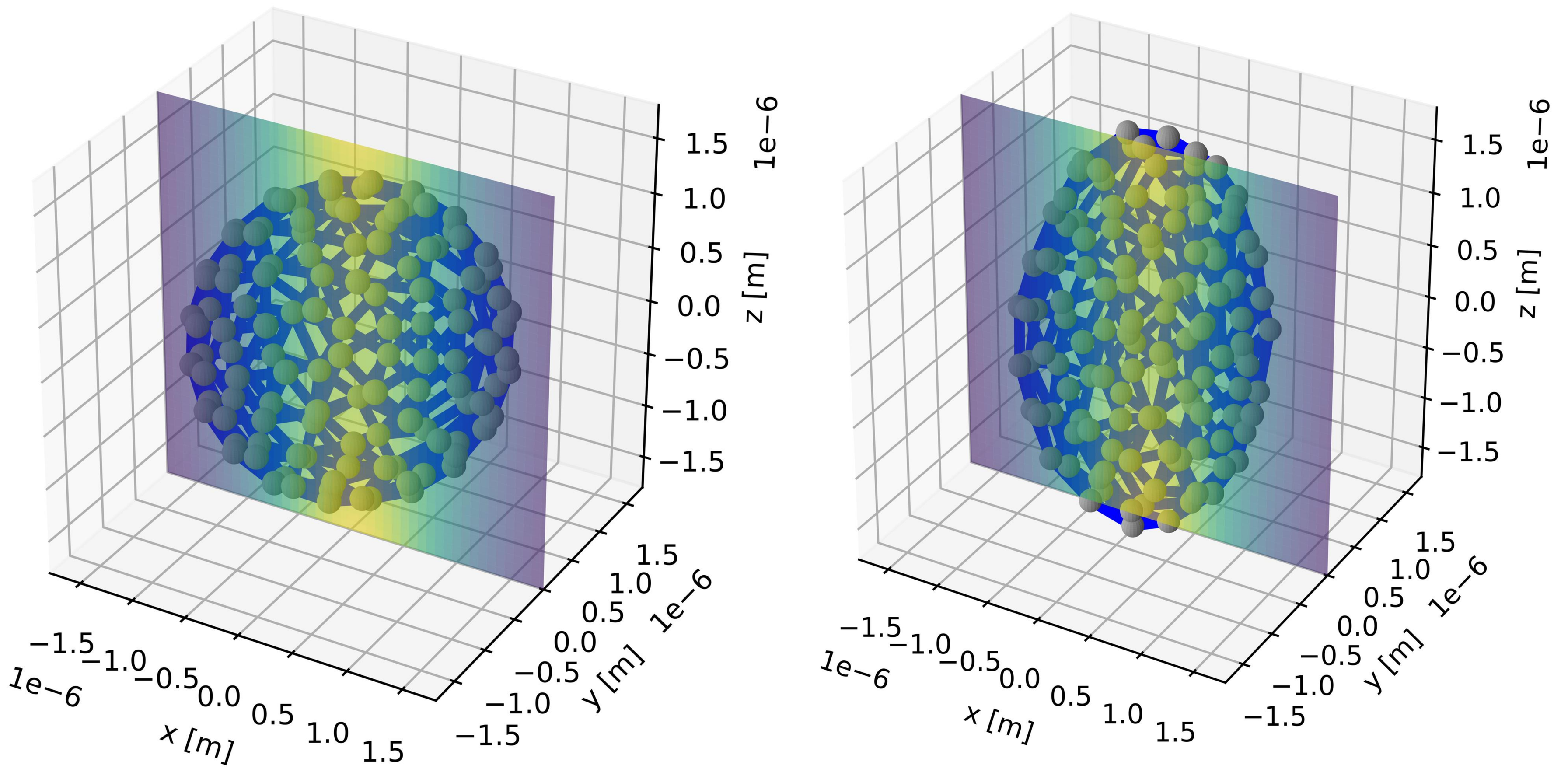


Cube object approximated by spherical or cubic particles. The model is refined by using more particles and dipoles.



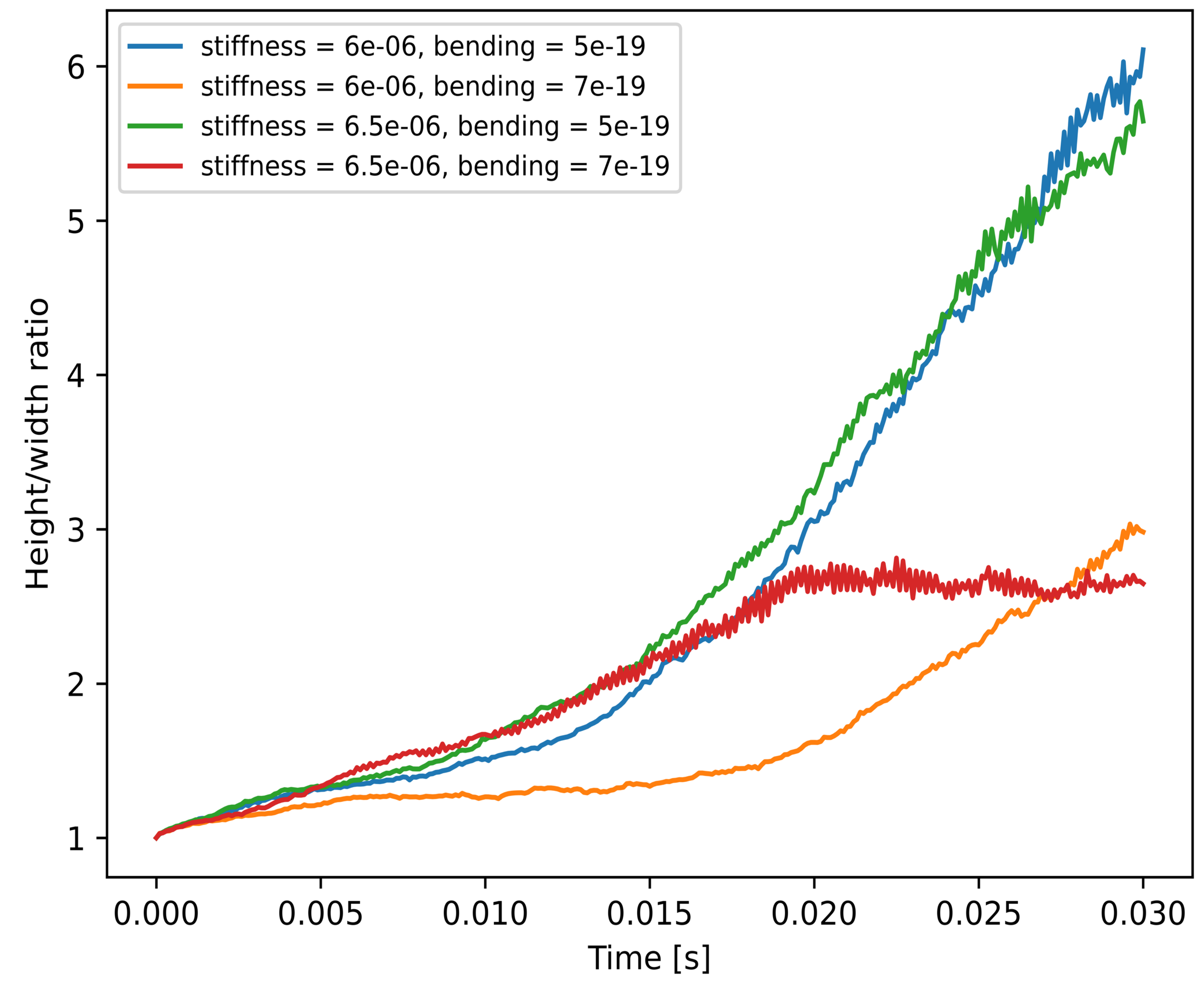
Total force exerted on the object as the dipole size is refined for various particles sizes and shapes.

Results – optical stretcher



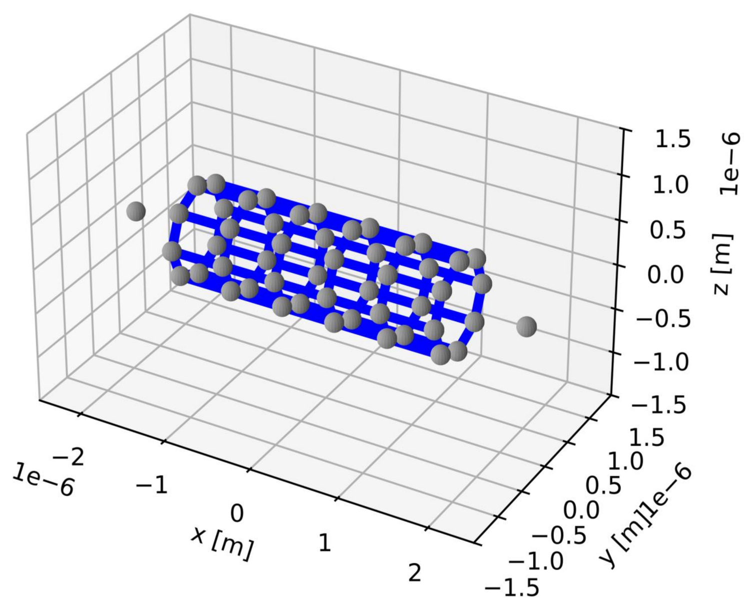
Spherical shell stretched by two counter-propagating Gaussian beams in a dynamics simulation.

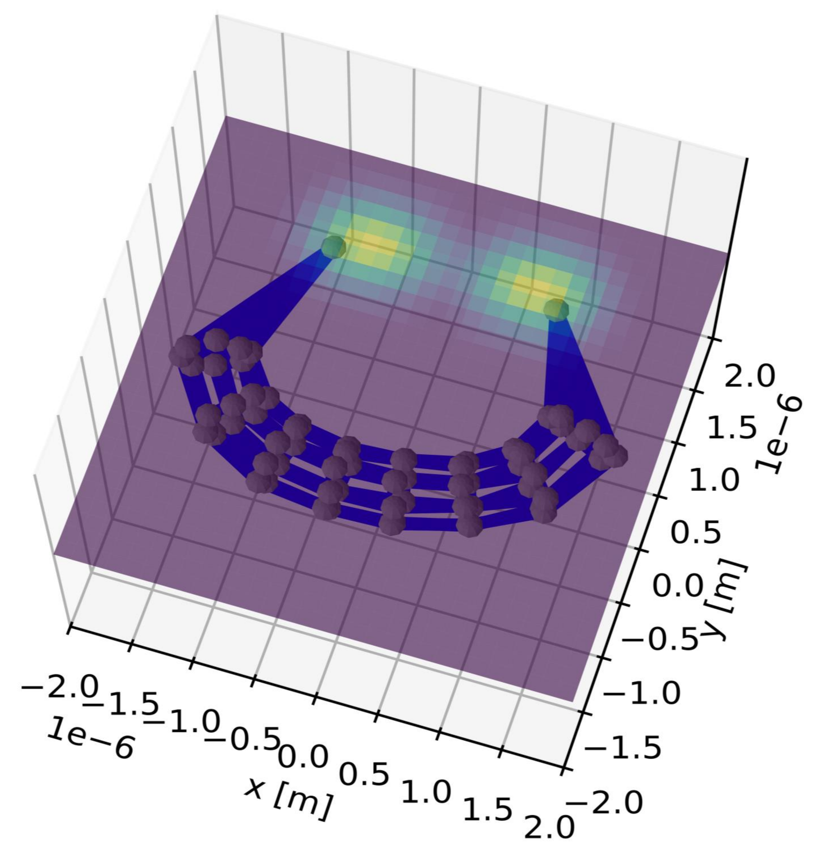
Height-width ratio of the sphere, stretched along the z-axis, against time for various spring and bending force constants. Changing these parameters results in stable and unstable deformations. The former is seen in the red line.



Results – general dynamics

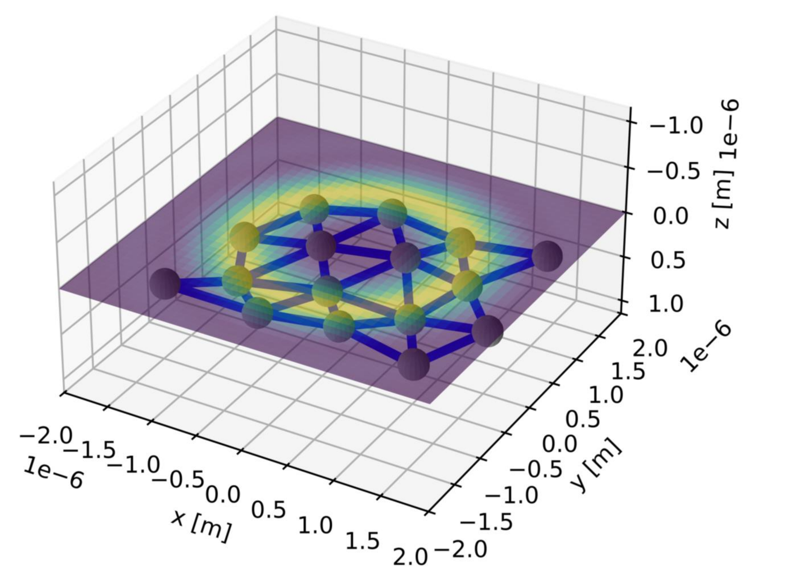
Flexible rod modelled through a hollow tube, connected to two outer silica beads with unique spring constants.





Silica beads connected to the ends of a flexible, hollow rod. Translating two Gaussian beams, each trapping a bead, causes the rod to bend in a dynamics simulation.

A thin layer of particles in a 2D triangular lattice. Blue links represent particles connected by a spring and bending force.



Conclusions

- Verified that a bead-spring framework can accurately model a larger object through the sum of its constituent spherical particles in a DDA system of high refinement, despite Abraham-Minkowski concerns.
- Considered various configurations of structural connections, deformation coefficients and optical manipulation tools to reproduce experimentally found deformation characteristics, in order to assess the accuracy of the simulation.

NOTES

- (D) Introduction
  - *(Maybe put in traffic beads figure cited, if spare room)*
- Experimental methods
  - DDA ***(*Graph -> General voxels)***
- Results
  - Verifying bead and spring
    - (D) (LG) Torque goes to zero with many spheres ***(*Line plot focus)(*Graph-> Spheres in ring)***
    - (J) Cubes and spheres tend to same total force ***(*Line plot focus)***
  - Applying bead and spring
    - (J) Dynamics ***(*Graph-> rod)***
    - (D) Optical stretcher, compared to Guck **(*Graph -> stretched sphere)**
- (J) Conclusion

! Think what we're gonna talk about, what they will ask

TODO:
Think what we will be asked
Is there anything we've included that they will catch us out on.

Assessment of poster presentations

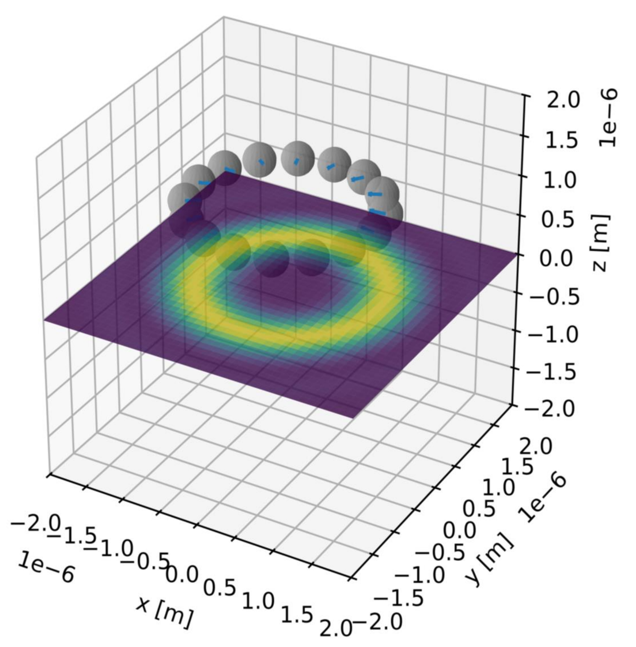
1. **Visual Impact:** Is this a poster that would stand out (in a good way) at a conference and make you want to read it?

2. **Content:** Does the poster convey the results of the project well? Are the Graphs and diagrams clear? Is all displayed material relevant/necessary? Does it contain appropriate references? Are the conclusions sensible? Does the poster and presenters demonstrate a good command of the relevant physics?

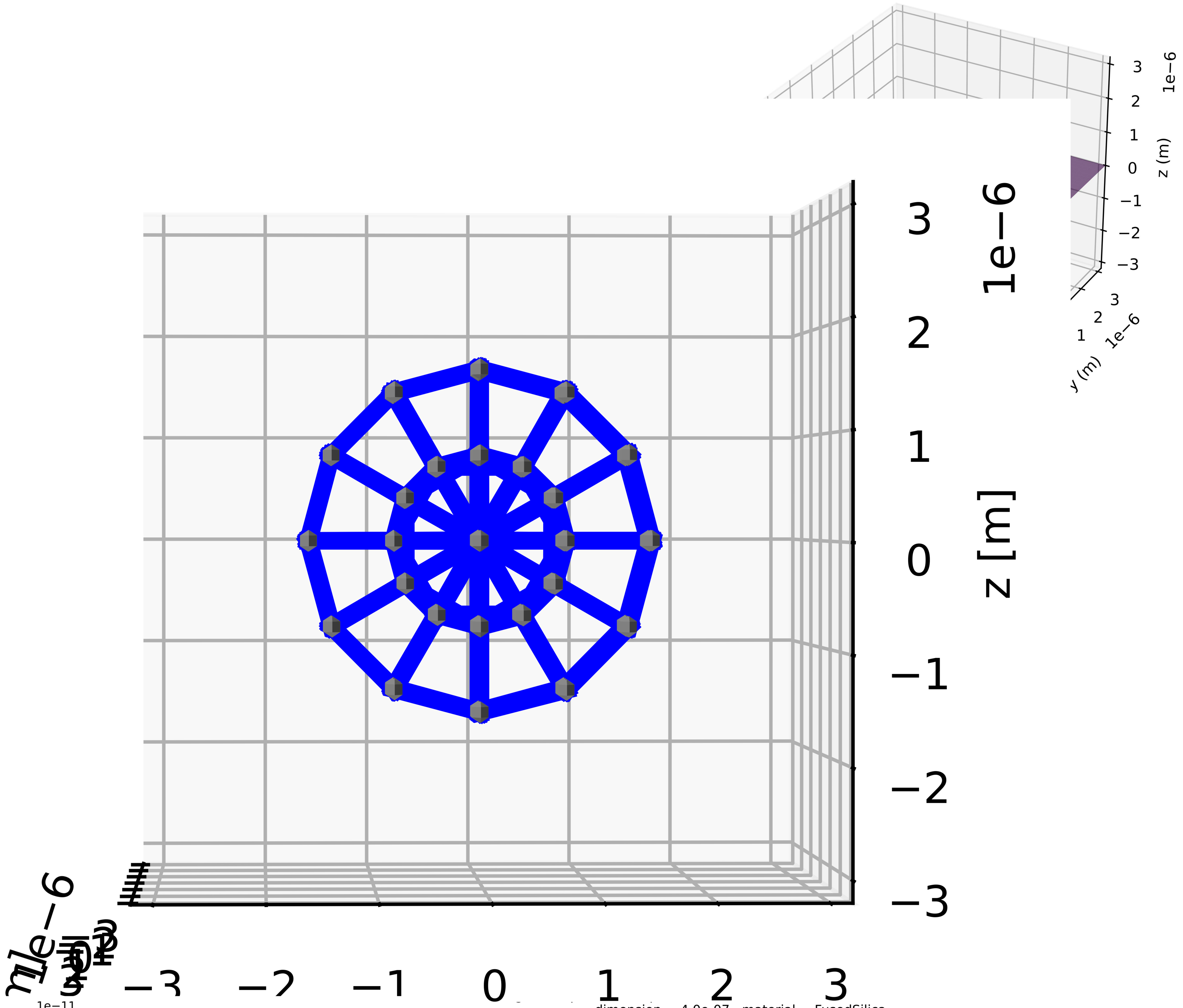
3. **Poster Presentation:** Was the poster presented well by the students? Can they identify and communicate what is new and important? Are they able to answer questions?

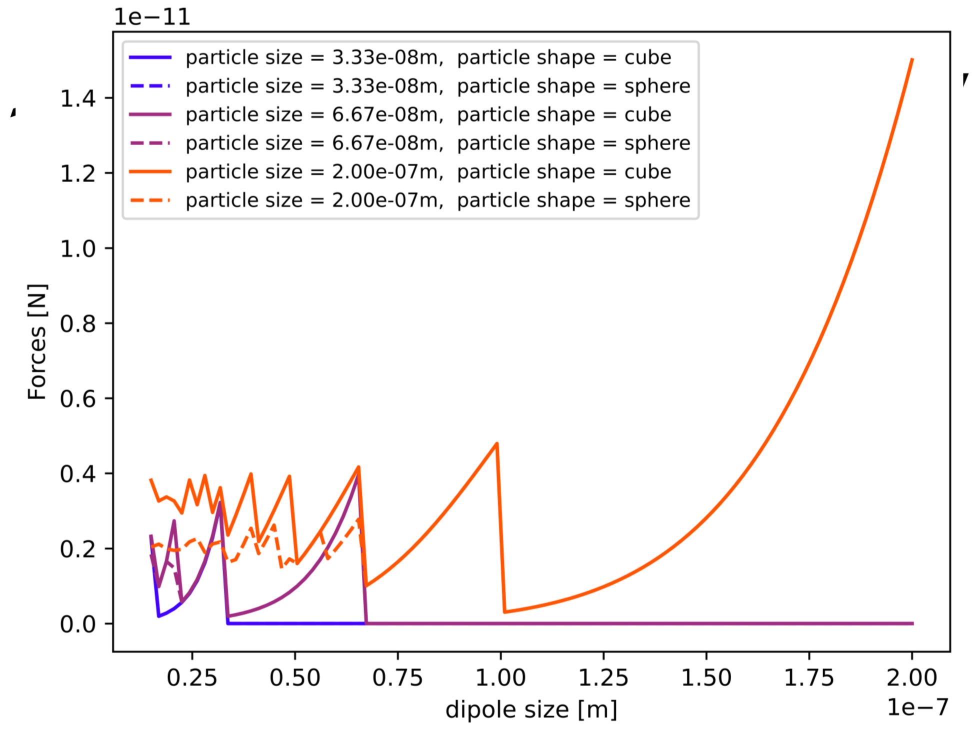
Unused graphs

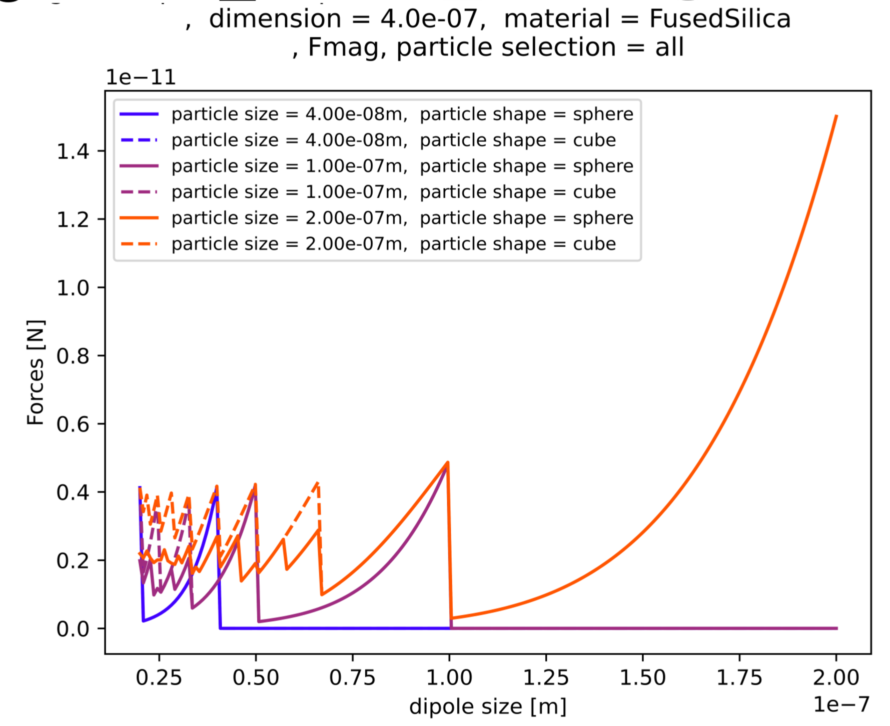
Note, voxel sphere has 1736 dipoles – 40nm each so it is quite a large sphere



(used the 7 particle graph as the arrows are more visible, then we say torque -> 0_







Slightly better convergence seen,
Also sampled at higher res