Predictive Modeling of Drop Impact Force on a Concave Substrate Using Machine Learning

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Abstract

Fluid-structure interactions are an important consideration in the construction of IoT sensors all around the world. Manufacturers are now easily capable of using 3D printers to construct sensors that can detect falling water droplets. However, it is difficult to describe fluid interactions with a surface using theoretical models. This study explores the advent of machine learning in the study of fluid dynamics to better predict a drop's impact force on a concave substrate. A system is constructed in which the impact force of a falling water droplet can be measured when it hits a 3D printed concave surface. A droplet's impact force on a surface may depend on a variety of key factors. In the experiments, the focus is on six input variables: drop velocity, drop diameter, displacement of a drop from the center of a surface, wettability, drop height, and radius of curvature. The experimental data is used to train and test an ensemble of machine learning algorithms. The ensemble consists of three algorithms: gradient boosting regressor(GBR), random forest regressor(RFR), and a k-nearest neighbors regressor(KNN). The ensemble model will be analyzed to determine feature significance and the model's accuracy in predicting a droplet's impact force.

Methods

- In total, we conducted 480 trials and saved videos and images using the Phototron FastCam Viewer software
- For each trial, we adjusted the nozzle, drop height, surface, and wettability
- We measured drop impact force using the MESUR® gauge Plus software
- Tracker video analysis software was used to analyze the first 60 trials and estimate a drop's velocity, diameter, offset from the center of the surface, and mass
- For the remaining 420 trials, we used a MATLAB program that we used to analyze a series of 3 images for each trial

Experimental Setup

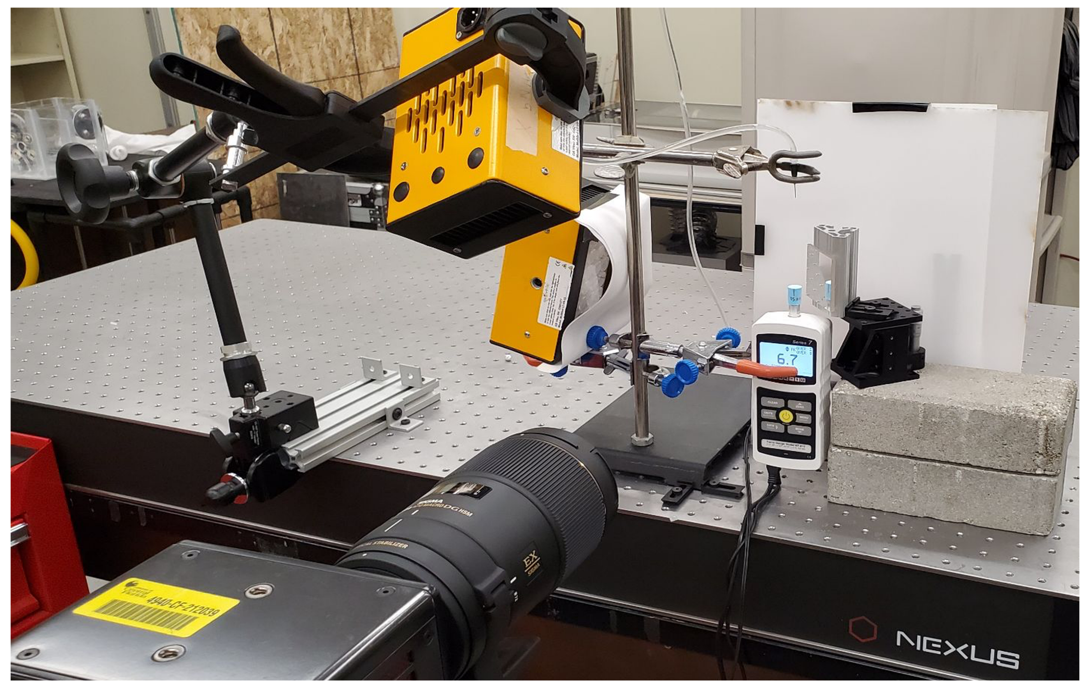

Figure 1*: A photo of the experimental setup*

- A Mark-10 Series 7 force gauge that sends force data to MESUR® gauge Plus
- Adjustable clamp secures the nozzle and can be used to change drop height
- Concave surface printed using a Flashforge Creator Pro 3D printer
- Three GS Vitec LED lights
- Fastcam Mini AX 100 high-speed camera
- New Era Pump Systems Inc. syringe pump

Data Analysis and Results

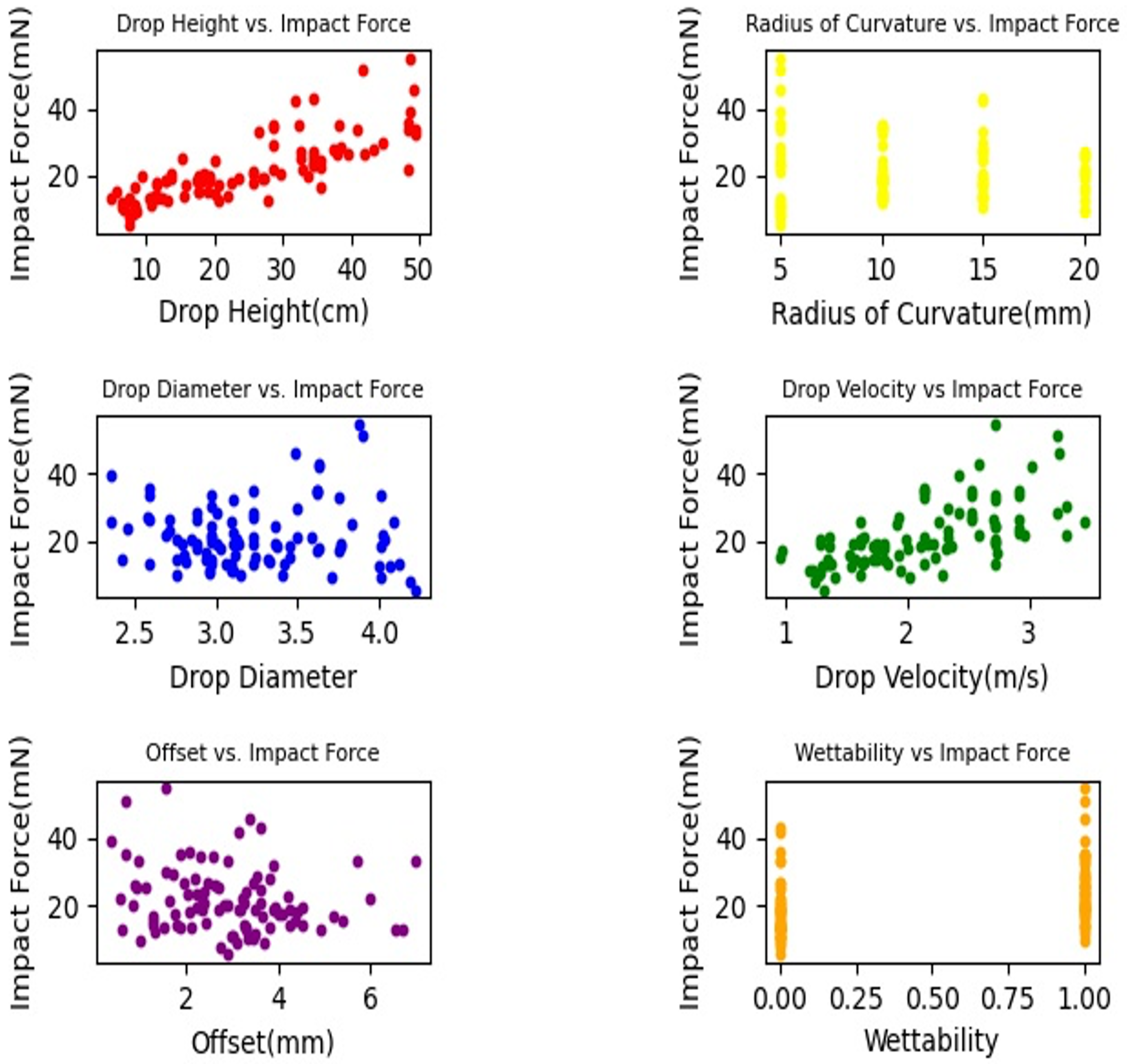

Figure 2: *Graphs visualizing the relationship between each feature and Impact Force*

Features:

- Wettability (W)
  - 1 indicates a hydrophobic surface and 0 indicates a hydrophilic surface
- Offset (O)
- Drop Diameter (D)
- Drop Velocity (V)
- Drop Height (H)
- Radius of Curvature (RC)

Ensemble Metrics:

- R^2: 0.72
- RMSE: 6.4
- MAE: 4.76

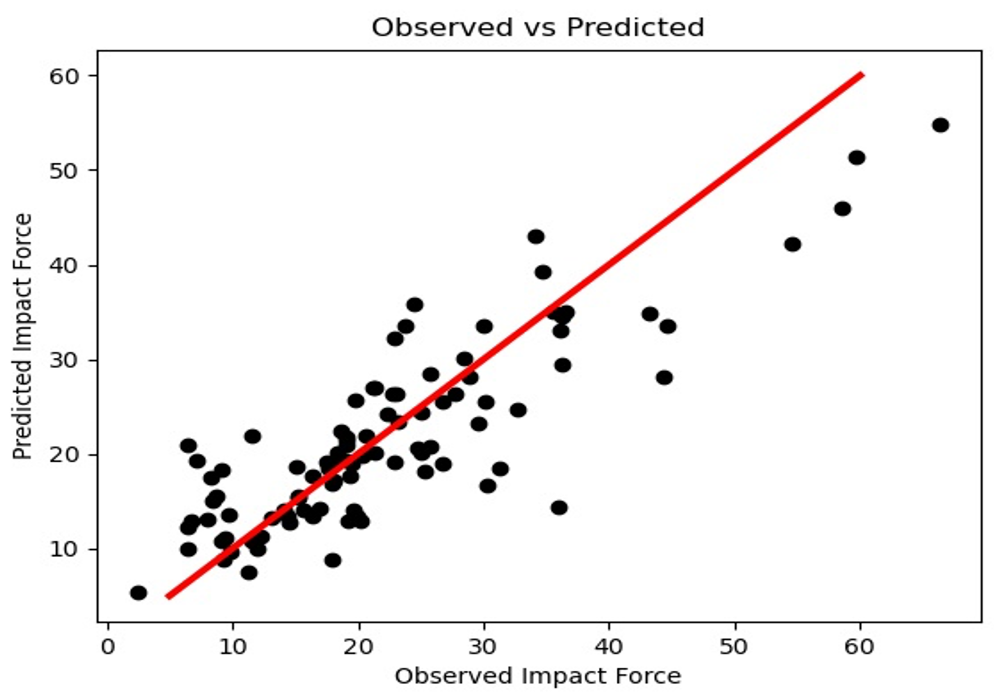

Figure 3: *Observed vs Predicted Impact Force values*

Results (Cont.)

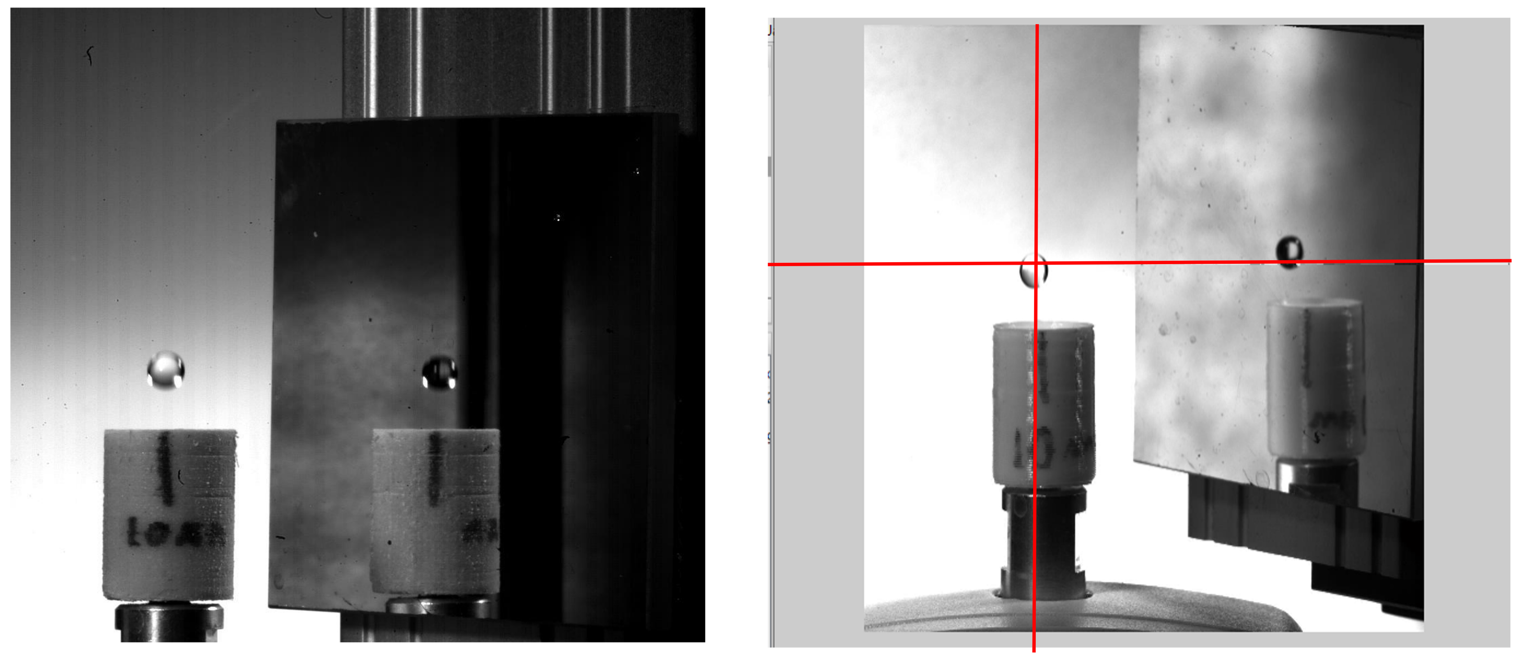

Figure 4: *A water droplet falls onto a concave surface with a radius of curvature of 10 mm(left). An image of the MATLAB analysis interface(right)*

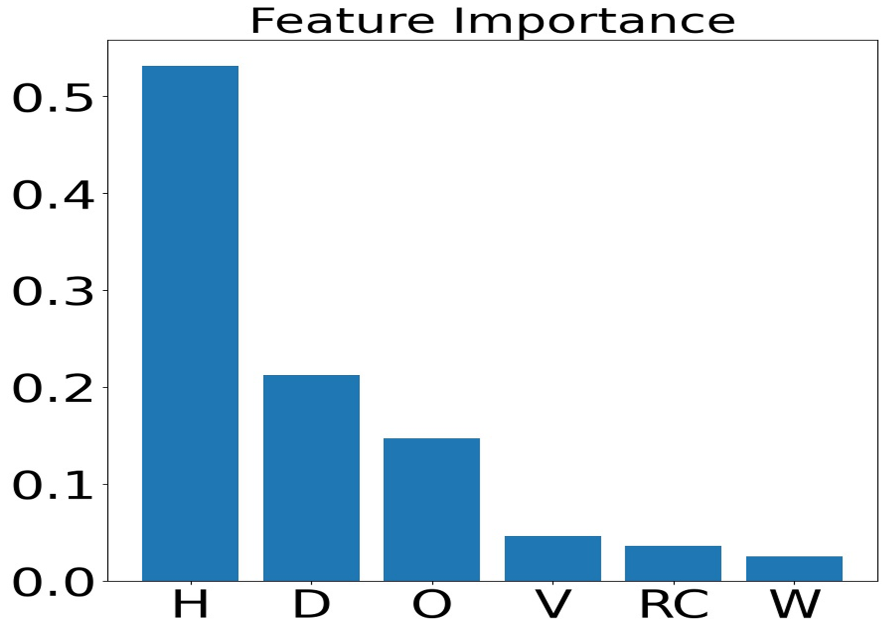

Figure 5: *The significance of each feature in affecting impact force predictions*

Conclusion

- Drop height is the most significant factor in influencing the impact force of water droplets on a concave substrate
- Drop height and drop velocity have positive correlations with drop impact force
- Radius of curvature has a slight negative correlation with drop impact force
- Simple linear models such as linear regression and linear support vector regression are not as accurate as non-linear models(GBR, RFR, KNN) in predicting impact force

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