Physics-based training of robots for manipulation of ropes and clothes

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https://structures.computer/roboticmanipulation

ABSTRACT This project enables collaborative robots to manipulate ropes and clothes in the real world using computer models without constant human monitoring. Seamless integration of robots, as aids to humans, into our daily life and manufacturing environments requires autonomous robotic manipulation of everyday objects. A broad class of these objects have one-dimensional (e.g. ropes) or two-dimensional (e.g. towels) geometry and are highly flexible. This flexibility and deformation can be seen in action everyday while tying shoelaces or folding clothes. Robots must be able to predict this deformation and act accordingly for successful manipulation of such objects. This project replaces training by demonstration with modeling in computer. The robots will employ numerical simulations to figure out the best policies for manipulation that are robust against uncertainties of the real world, e.g. friction and material defects. Areas of application for this framework include typing knots in ropes, securing rigid objects using knots, and folding of clothes.

CHALLENGE

Although abundant researches on robotic manipulation can be found, several problems still stay challenging and to be solved:

1) **Slender flexible objects, such as ropes, cables and clothes, are much more difficult to manipulate than rigid objects due to their deformable properties**. Robots should be capable of predicting the induced deformations in advance and furthermore avoid possible interference from surrounding environment and the flexible object itself.
2) **Some mechanic problems involved in the manipulation process maintain unsolved**. Contact with substrate or the deformable object itself need to be handled in developing the physics-based simulation model, in which the calculation of static and dynamic friction forces must be addressed.
3) In order to **minimize human intervention,** the physics-based training of manipulation is expected to be optimized and robust against various scenarios.

SCIENTIFIC IMPACT

This project is aimed at fundamentally understanding robotic manipulation of flexible objects (ropes & clothes) using model-based training. The work will contribute in the following aspects:

1) **The developed physics-based simulation model accounting for manipulation of flexible and deformable objects with self-contact considered, will be presented as an open-source package online**. All researchers in related fields will have free access to it.
2) **The trained neural network and optimized manipulation scheme will be available online**. It requires little time for users as the physics-based training can be translated to reality directly.
3) **The research approaches are proposed for robotic manipulation of rods and clothes, and can be adapted to other applications, such as suturing in medical surgery**.

TECHNICAL APPROACH

- Based on Discrete Elastic Rods (DER), a simulation model is developed simulating the deformation of elastic rods when the top end is manipulated.
- The optimal position that maximizes the normal force at contact point during manipulation are searched and a neural network is established to model the mapping relation from parameters (l_s, R_c) to the top end ($\mathbf{X}^*_{top}$).

Key innovations:

- The optimized policy obtained from simulation can be directly translated to real experiments.
- The proposed scheme is robust against different material properties of ropes and substrate.

New contributions:

- ❑ Distribution of normal force at contact point is revealed during manipulation of top end of elastic rods.
- ❑ Based on the optimal deployment policy, a trefoil know is tied with cooperative robots.

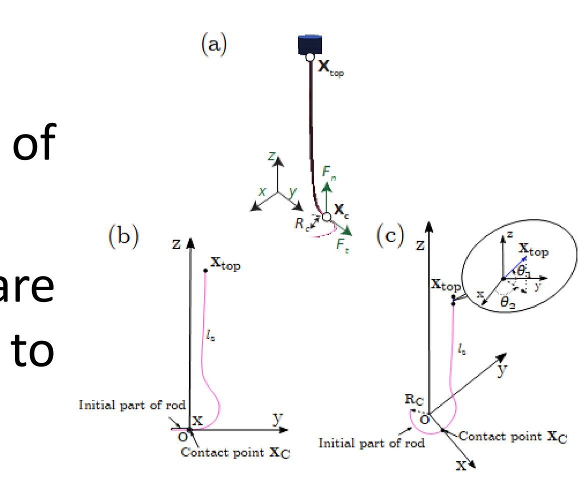


Fig. 1. (a) Schematic of the deployment process. Initial state of the clamping model for straight line (b) and circle (c)

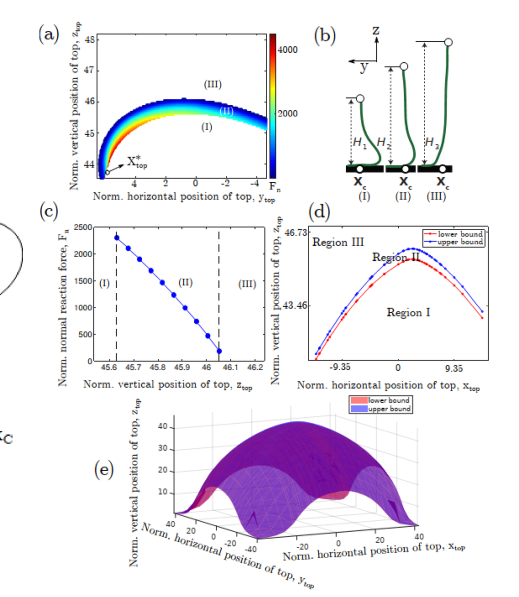


Fig. 2. (a) Distribution of F_n along horizontal y and vertical z coordinates of the top node (x=0) to deploy a rod along the y-axis. (b) Illustration of Region I~III. (c) Variation of normalized normal force F_n. (d) Upper and lower bounds of a slice from the acceptable region (e).

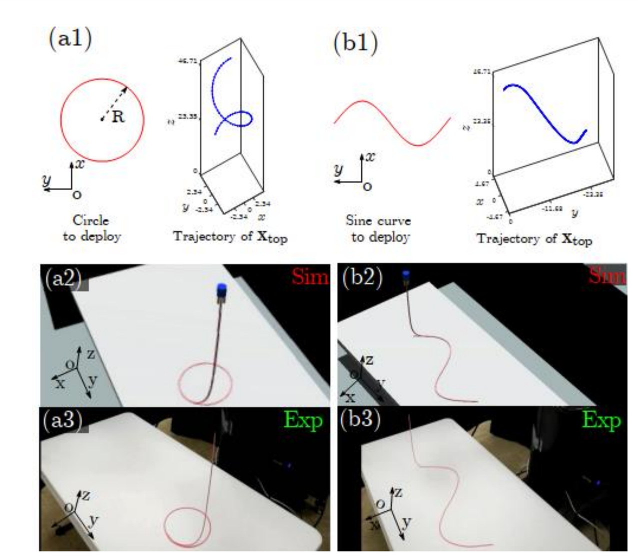
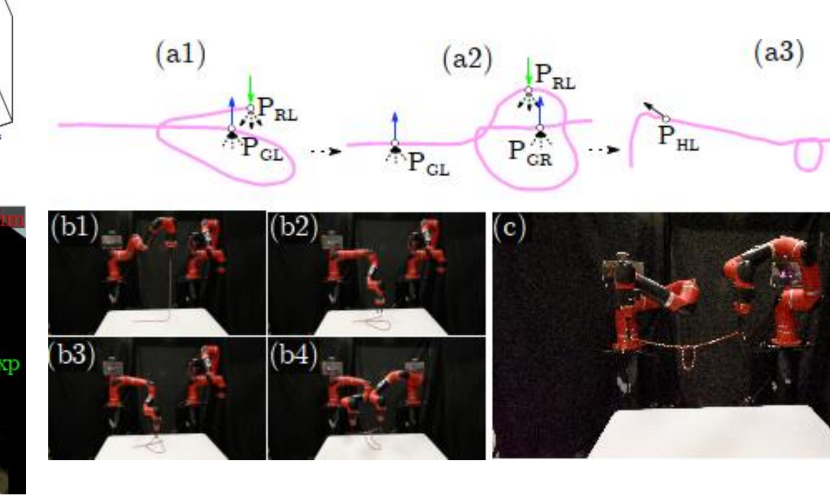


Fig. 3. Two prescribed patterns and the trajectory of X_{top} are shown in (a1) and (b1) to deploy a circle of R=3.2 and a sine wave, x=-4sin(0.1πy). (a2), (a3) and (b2), (b3) give the simulated and experimental results in (a1) and (b1).



(a1)~(a3) show the procedures to tie a knot with two robots that cooperate. (b1)~(b4) show four time instants during the knot-tying process. (c) presents the final knot and robotic setup.

BROADER IMPACT ON SOCIETY

1) The physics-based training of robotic manipulation facilitates robots to handle more complex tasks, such as securing a box, folding towels and clothes, etc.
2) The developed simulation model can simulate the manipulation of one end of slender deformable objects, which can be adapted and applied to suturing in medical surgery.

BROADER IMPACT ON EDUCATION

1) Training of 1 postdoctoral scholar and 2 graduate students.
2) New graduate level course on physics-based simulations that uses this project as a case study.

QUANTIFIABLE IMPACT

1) Publications under review with *Physical Review Applied*, *Extreme Mechanics Letters*, and *Structural and Multidisciplinary Optimization*.
2) Conference presentation at American Physical Society March Meeting and Society of Engineering Science Annual Meeting.
3) Open-source software repository (in progress).

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