Predicting force feedback of cutting interactions for haptic bilateral teleoperation

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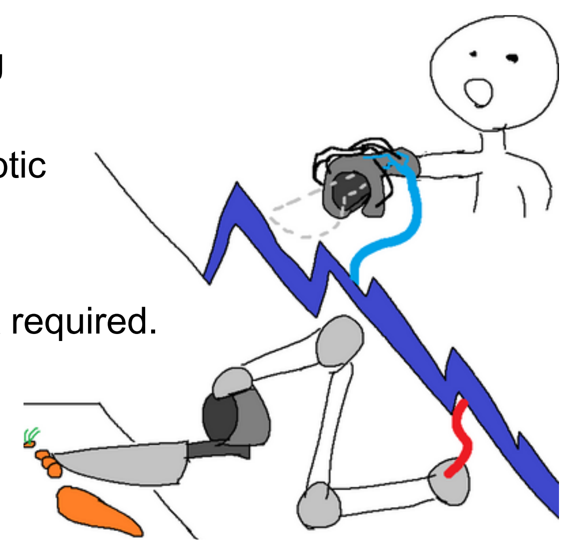
1. Background

Haptic bilateral teleoperation

Goal:
- Human-like precision without being physically present.
- Makes use of robotic arms and haptic controllers.

Problem:
- Instant feedback from environment required.
- Network latency too high.

Solution:
- Simulate forces locally.
- Use delayed vision information.



How to approximate cutting interactions to get convincing force feedback for haptic bilateral teleoperation?

2. Methodology

2.1 Cutting physics

- Anthony G. Atkins' *The science and engineering of cutting* used as baseline [1].
- Slice-push ratio.
- Friction models based on normal force and surface area of knife in material.

$$Vdv + Hdh = Rwdv + \mu V dh + \nu A(dh + dv)$$

$$A = w \cdot \min\{l, L\}$$

V, H - vertical and horizontal force. • *dv, dh* - vertical and horizontal *displacement*. • *R* - material's fracture toughness. *w* - cut width. *μ* - coefficient for normal force friction. *ν - friction constant between side of the knife and the material. l* - cut depth. *L* - knife height.

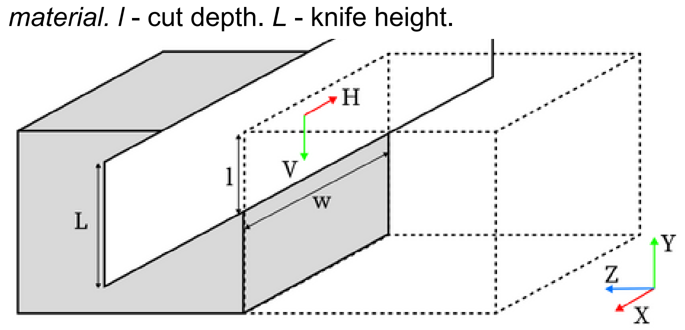


Figure 1: Diagram of a flat plane knife cutting into an object corresponding to the cutting model.

2.2 Simulation environment

Force feedback generation with proxy and pointer model. Pointer corresponds to controller position, proxy to robot arm (knife) position.

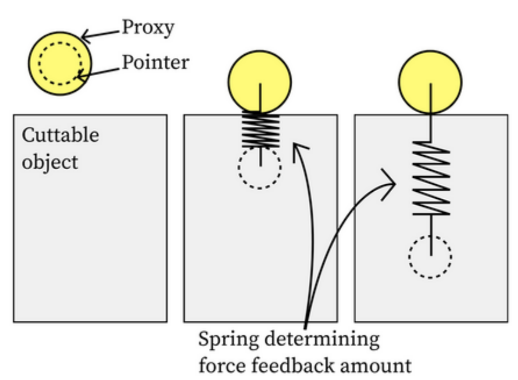


Figure 2: Force feedback is generated with a spring between proxy and pointer.

3. Implementation

Implementation was done in steps to verify correctness of the model.
The following plots show the forces present in the simulation for specific knife movements.
It is possible to see the effect of different fracture toughnesses and object shapes, knife paths, and friction amounts on the resulting force feedback generated.

1. Vertical cutting

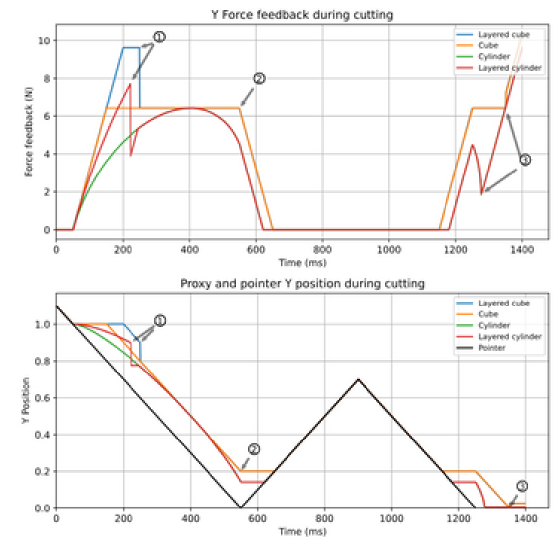


Figure 3: Forces and positions during vertical cutting. Resistance shown to depend on fracture toughness and cut width.

2. Horizontal forces

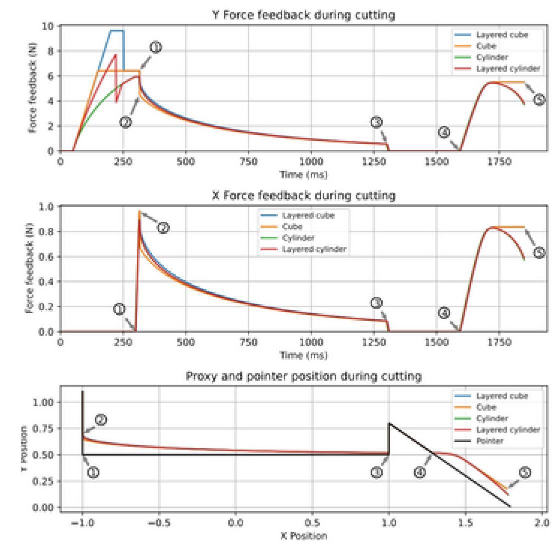


Figure 4: Forces and positions during a complex cutting motion. Applying horizontal force is shown to reduce vertical load.

3. Friction

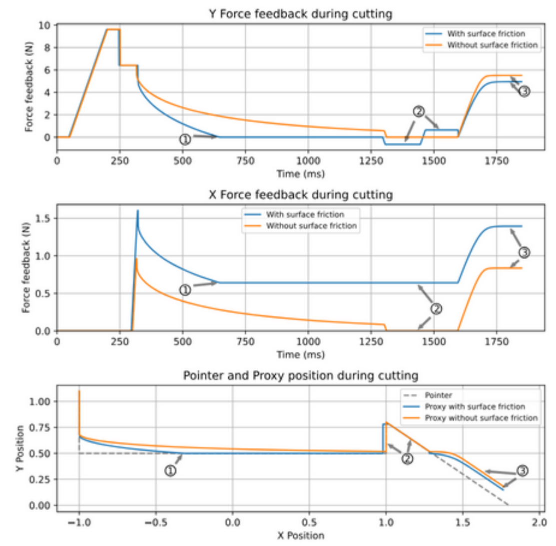


Figure 5: Forces and positions comparing cutting with different frictions. Surface friction shown to generate additional resistance.

4. Results

4.1 Experiment setup

- User study using the simulation environment and Novint Falcon controller.
- Assess baseline system immersion and controllability
- Assess impact of visual latency.

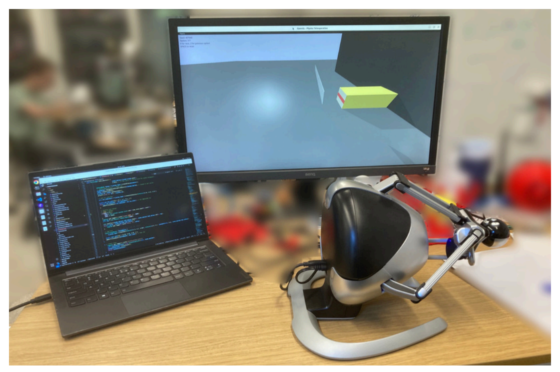


Figure 6: Experiment setup with the simulation environment and a Novint Falcon.

4.2 Baseline application

- Great control and confidence over their actions in the system.
- Immersion scored lower.
- No negative responses to any of the questions.

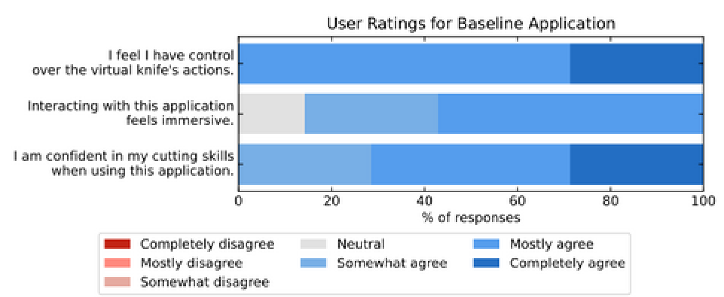


Figure 7: Ratings given to the baseline application in the user study.

4.3 Visual feedback delay

- Visual delay was noticeable at the minimum tested delay of 25ms.
- At 75ms task starts getting more difficult and application turns more unusable.
- At 200ms the task is significantly harder, while system is still somewhat usable.

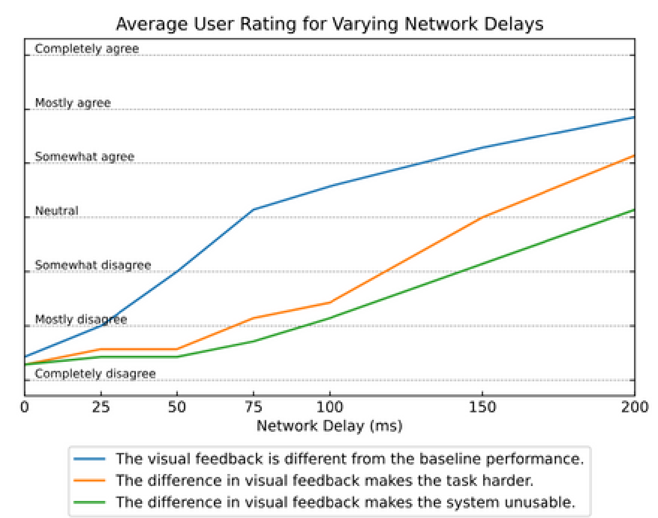


Figure 8: Ratings given to the different network delays in the user study.

5. Conclusions

Finding a model capable of creating convincing cutting interactions was successfully achieved by implementing a simple physics based model, based on the model proposed by Atkins [1].

The implementation was evaluated in a user study, where users were able to experiment with the system in a simulation environment while using a haptic controller. The users reported that the system was immersive, and that they had great control and confidence over their actions while cutting objects during the experiment.

The user study also explored the impact of visual feedback delay on the experience. It was found that up to a 75 ms delay was acceptable, after which the users reported progressively worse experiences with the system.

6. Limitations

- Small sample size for user study, who were familiar with the system and controllers ahead of time.
- Imperfect knife modelling, ignoring mass and length.

7. Future work

- Connect and test in full teleoperation system.
- Implement better knife modelling, with weight and limited length.
- Bigger user study.

References

[1] Anthony G Atkins. *The science and engineering of cutting : the mechanics and processes of separating and puncturing biomaterials, metals and non-metals*. Butterworth-Heinemann: Amsterdam, 2009.