Haptic Human-Robot interfaces: Lab 4

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1 Introduction

The goal of the lab was to implement a feed forward compensation for the haptic paddle to make it feel transparent when moved. To achieve this, the dry friction of the paddle had to be measured and then a friction model was implemented to compensate for the friction. Furthermore, also for the gravity and the viscous friction acting on the paddle, a compensation torque was implemented. Once the paddle felt transparent enough, a virtual wall at the positions ± 15 degrees was implemented. This was achieved by giving the wall a certain stiffness and a damping coefficient. To optimize for the stiffest wall possible, K-B plots with different filtering frequencies were found and their Z-width was calculated.

2 Methods

2.1 Identification of the Paddle Friction

2.1.1 Identifying the static friction

Identifying the static friction involved increasing the motor torque from 0 in very small steps until we saw a small step change in the motor angular encoder. We recorded these values multiple times and for both directions of the motor torque. The values we observed are recorded in Table 1.

In addition to finding how the static friction value changes with positive and negative directions of torque, we also wished to investigate whether it varied with the paddle angular position as well. Indeed, we noticed not too much variation of the static friction value at a particular position but more variation across different paddle angles.

	0°		**+20°**		**-20°**		**Mean**	**Std Dev**
Positive motor torque	0.0014	0.0016	0.0015	0.0016	0.0020	0.0018	**0.00165**	**0.000217**
Negative motor torque	-0.0013	-0.0012	-0.0013	-0.0012	-0.0011	-0.0010	**-0.0012**	**0.000117**

Table 1: Static Friction Observations

We also noticed a significant difference between the friction for each direction of paddle motion. This difference could be due to many reasons such as manufacturing flaws of the screw surface over which the paddle cable slides or because the cable is not always in the middle of the screw which creates an additional normal force onto the screw which increases the friction at higher angles.

2.1.2 Measuring the sliding friction

Measuring the sliding friction is very complicated since it is lower than the static friction. One way to measure could be to apply a high torque which moves the paddle and then during the movement reducing the torque. Once the paddle motion stops the sliding friction is dominant and the value of the motor torque can be taken as the sliding friction.

Since this is a difficult measurement to perform, the sliding friction was considered to be equal to the dry friction.

2.1.3 Calculating the viscous friction

We calculated the motor viscous friction with the values taken from the datasheet as:

$$B_m = \frac{I_m k_t}{\omega_m} = \frac{53.8mNm \times 13.7mA}{8450rpm} = 8.33 \times 10^{-7} Nm/rad.s^{-1} \tag{1}$$

3 Results

3.1 Friction and gravity compensation:

3.1.1 Implementing the compensation

The implementation of the friction compensation takes into account two different dry friction values depending on the displacement direction as well as a linear zone in between the noise levels of the velocity. The dry friction for a positive velocity is 0.0014 and 0.0012 for a negative velocity in line with the readings for the static friction in Table 1. Instead of having a dead zone if the velocity is smaller than the absolute value of 10 deg/s, we chose to have a linear compensation between these points.

As for the gravity compensation, the torque acting on the paddle which needs to be compensated is the following:

$$\tau_G = M_d \times g \times r_g \times sin(\theta)$$

where M_d is the mass of the paddle, g the gravity constant, r_g the distance between the center of rotation and the center of mass of the paddle, and θ the current position. Since this gravitational force is in the frame of the paddle (i.e, about the paddle center of rotation), we need to divide it by the reduction ration to get the value in terms of the motor torque. This is not necessary for the damping and the static friction compensation torques because they are already in the motor frame of reference.

Together with the viscous compensation this results in the following code:

```
float32_t Compensation(float32_t position, float32_t velocity){
        float32_t MD = 0.075;
        float32_t rg = 0.01988;
        float32_t g = 9.81;
        float32_t dryfriction = 0.0014;
        float32_t viscousfriction = 8.33e-7;
        float32_t CompensationTorque = 0.0;
        int sign = 1;
        if(enable_DryFrictionCompensation){
                if(velocity < 0){
                        sign = -1;
                        dryfriction = 0.0012;
                }
                if(velocity>10 || velocity < -10){
                        CompensationTorque += sign*dryfriction;
                }
                else{
                        CompensationTorque += velocity/10*dryfriction;
                }
        }
        if(enable_ViscousFrictionCompensation)
                CompensationTorque += viscousfriction*velocity;
        if(enable_GravityCompensation)
```

```
                CompensationTorque += MD*g*rg*sin(3.14/180*position)/REDUCTION_RATIO;
        return CompensationTorque;
}
```

This compensation is called feed forward since there is no feedback loop in which the measurement of the actual force on the paddle is taken into account. In a feedback compensation one could achieve a very transparent behavior since the force can be eliminated with a controller. But for this to be possible one would need a force sensor on the paddle.

3.1.2 Observed Behaviour

The most significant compensation factor was the static friction, while the viscous friction compensation was barely noticeable.

Initially the paddle was very unstable and in order to reduce these oscillations due to the compensation, the dry friction values were manually fine tuned to get a little weaker compensation. This was necessary since if the compensation is a little too high, the system starts to be unstable. Therefore the used dry friction values are: 0.0014 at positive velocity and 0.0012 at negative velocity.

Another observation was that at the highest positive position, the paddle snapped towards the stopper. This is due to reduced friction at this position and maybe small errors in the gravity compensation.

It was also possible to feel small variations of the friction over the whole displacement which reduced the transparency of the compensation. In order to get rid of these variations, the modeling of the dry friction and sliding friction would need further investigations.

Right now everything was done on a one degree of freedom device. Doing the same analysis on a multiple DOF device can be very difficult with the same approach as for the paddle. One way would be to discretize the workspace and evaluate the friction at each position. An easier approach would be to calculate the system dynamics and then using a model to get the friction compensation.

3.2 K-B Plot

Figure 1 shows the K-B plots for different cutoff frequencies. The associated Z-Widths are:

	$f_{cutoff} = 10$	$f_{cutoff} = 50$	$f_{cutoff} = 100$
Z-Width	6.805e-4	1e-3	8.586e-4

Table 2: Z-Width of the different K-B plots

We see that for heavy filtering (cutoff frequency of 10 Hz), we can reach higher stiffness K of the wall, but lose stability quickly as we increase the damping B. This is because with heavy filtering, we have larger delays in the system response because now, fast changes in the position and velocity are filtered out and not detected quickly. This drives the system to instability. On the other hand, with weaker filtering (cutoff frequency of 100 Hz), we automatically have more noise in the velocity estimate which also reduces the Z-width. This indicates the existence of an optimal filter frequency that offers the best compromise for the trade-off between delays and noise.

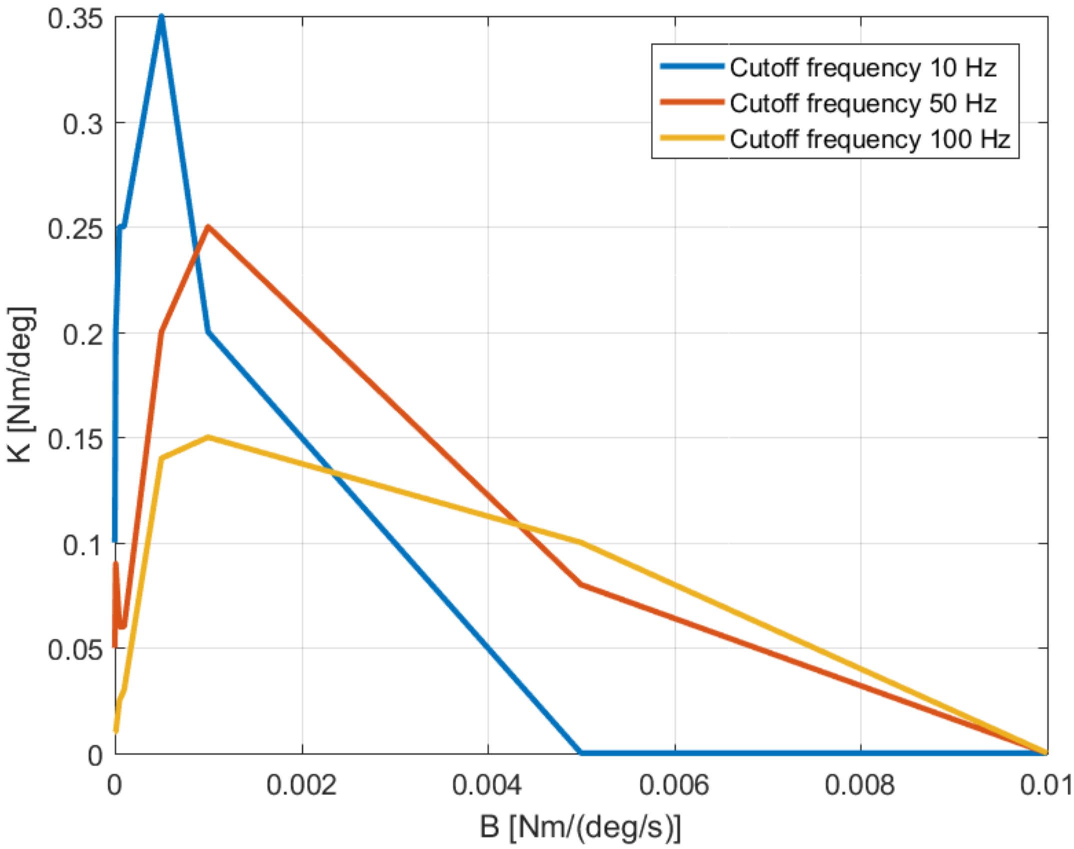

Figure 1: K-B Plot for different cutoff frequencies of the position and velocity filter

3.2.1 Effect of Compensation

When we turn off friction compensation, this adds a significant amount of physical damping to the system. This automatically increases the Z-width by allowing us to go to much higher stiffnesses without driving the system into instability.

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3.2.3 Using the Hall-effect sensor

The Hall-effect sensor is much noisier than the encoder. In this case we would need to filter the signal much more strongly. This would make the K-B plot narrower. Furthermore, while before the noise was mostly in the velocity, now we will have noise in the position signal as well. This means that instability will be reached at lower stiffness as compared to the case with the optical encoder, making the K-B plot shorter in addition to making it narrower.

3.2.4 Improving the Z-width

By increasing the physical damping, the stability of the system can be increased and thus the Z-width will also increase. Another possibility would be to fine tune the filter frequency to get a good trade-off between the stiffness and damping coefficient. This means that for a low frequency we can have high K values but small B values and vice versa for a high frequency, so a solution in between would be needed.

4 Conclusion

This lab session made it clear that a good friction model is crucial to achieve transparent behaviour in a haptic device. But since the exact dry and sliding friction are difficult to measure, this task can be very hard. The lab also demonstrated the intricate trade-offs that comes with filtering the position and velocity measurements in the form of the Z-width or the region of stability in a haptic device.