Bridging the gap between design requirements and application performance: using human observers?

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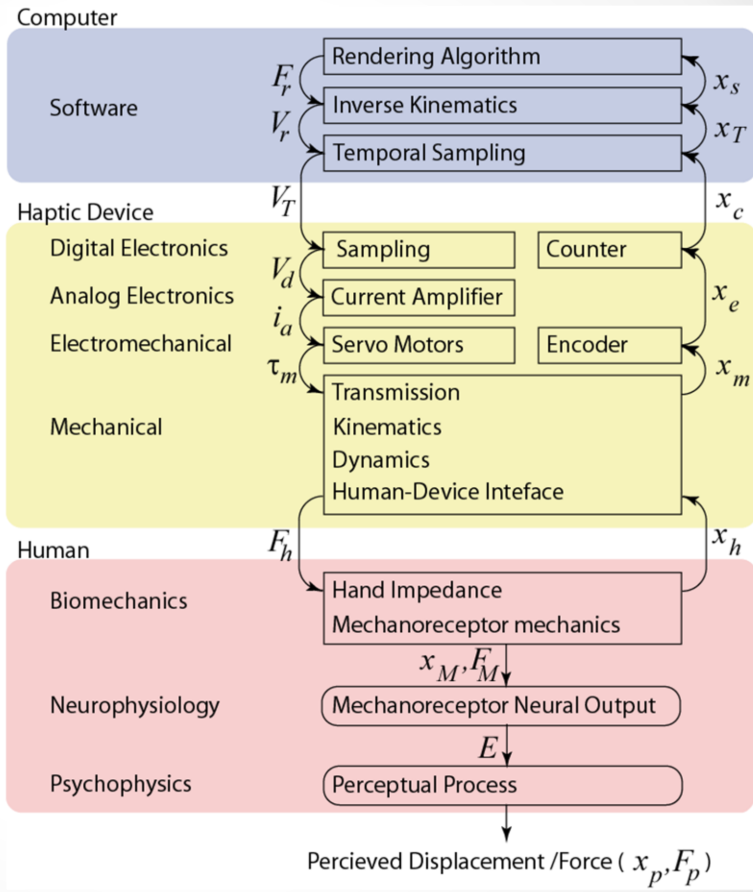
Haptic Hardware: a signal modifier

Haptic hardware can be considered as a signal modifier:

- It takes reference signals from the computer and converts the signal into a force applied to the human user
- It takes the position of the human-device interface and converts it into a signal read by the computer



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In order to effectively evaluate the performance of haptic hardware, it is important to understand how haptic hardware generates haptic signals.

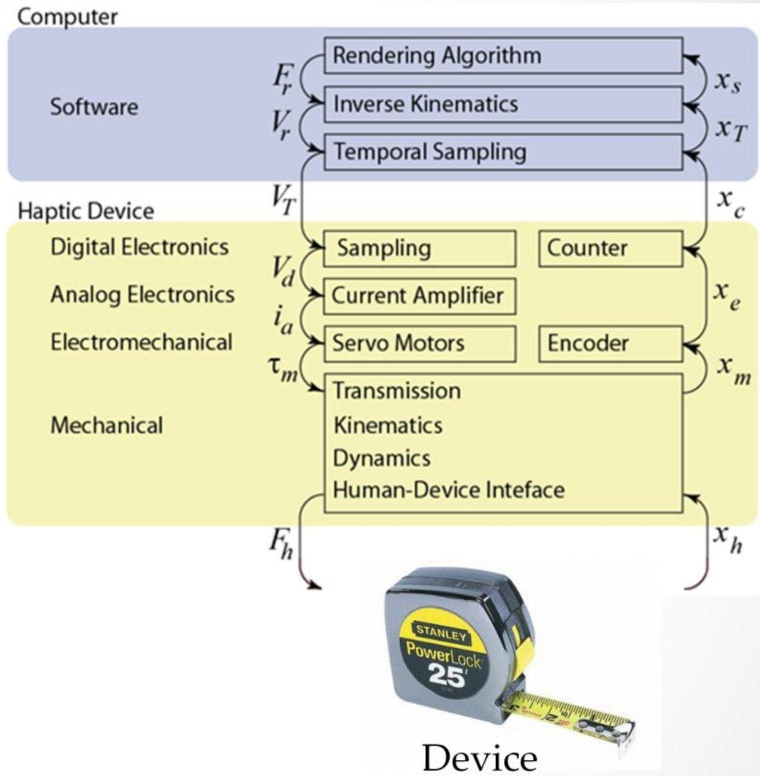
There are three components to haptic interactions – the computer and its algorithms, the haptic hardware, and the human. The haptic signals originate in the software of the rendering algorithm. They then…

One might expect that the evaluation of haptic hardware would entail measuring one or more of these haptic signals.

Device Centered Evaluation

One common approach to evaluating haptic hardware is to replace the human with sensors (i.e. force transducers and accelerometer)

In general, Device Centered evaluations do not facilitate assertions of hardware sufficiency for particular applications



Device Centered

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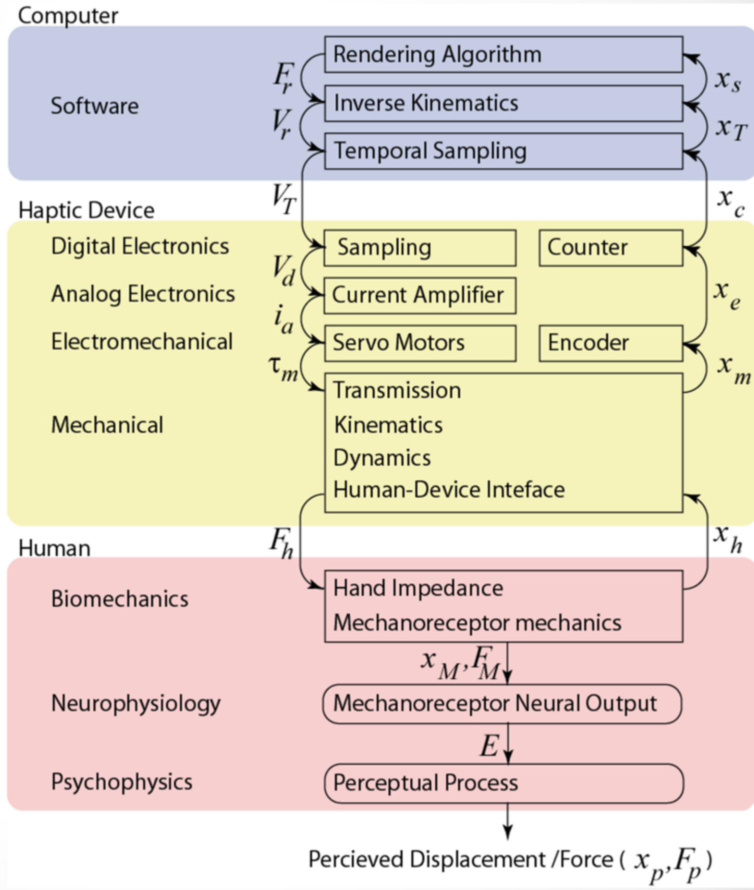
Many of the evaluation techniques described in the literature replace the human with an array of measurement sensors such as force transducers and accelerometers. They will also measure intermediate haptic signals and characterize the effects of hardware elements on the signals. I call this type of evaluation device-centered. Many of the evaluations in the academic literature are device-centered.

Because device-centered evaluations remove the human from the evaluation, they do not consider the finite ability of humans to perceive haptic signals. As a result, device-entered evaluations do not reveal the adequacy of a particular haptic hardware product.

Application Centered Evaluation

Another common approach to evaluating haptic hardware is to measure a human user's performance with the haptic hardware

In general, Application Centered evaluations facilitate assertions of hardware sufficiency for particular applications, but provide little insight to hardware designers



The rest of evaluation techniques in the literature leave the human in place for the evaluation. They evaluate the performance of the human in a particular application with the haptic hardware, rather than evaluating the haptic hardware alone. I call this type of evaluation application-centered.

These evaluations are the most relevant to selecting a particular haptic device for a particular application, but they do little to drive hardware designs as investigators rarely correlate their results with hardware attributes. Often times, the application used in the evaluation is not well suited for drawing such correlations.

Human observers as the measurement instrument

We have explored the effects of haptic hardware on application centered evaluation – providing results that inform both the designer and the user about hardware adequacy.

We do this by:

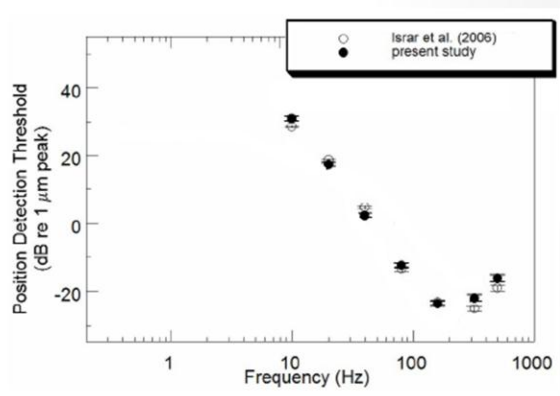
1. Comparing human performances with and without the haptic hardware
2. Identifying discrepancies in the performances
3. Drilling down to find the haptic hardware causes of these discrepancies
4. Suggesting specific hardware design guidelines which ensure the adequacy of the haptic hardware for a particular application

Case Study: Application: Texture Rendering

Vibration Perception (Detection) Experiment

- Forces can be considered in a spectral sense as vibrations
- Relates directly to texture rendering, a common application for haptic devices
- Human Capability is known
- Amenable to root cause analysis

A, Israr et al., 2007.



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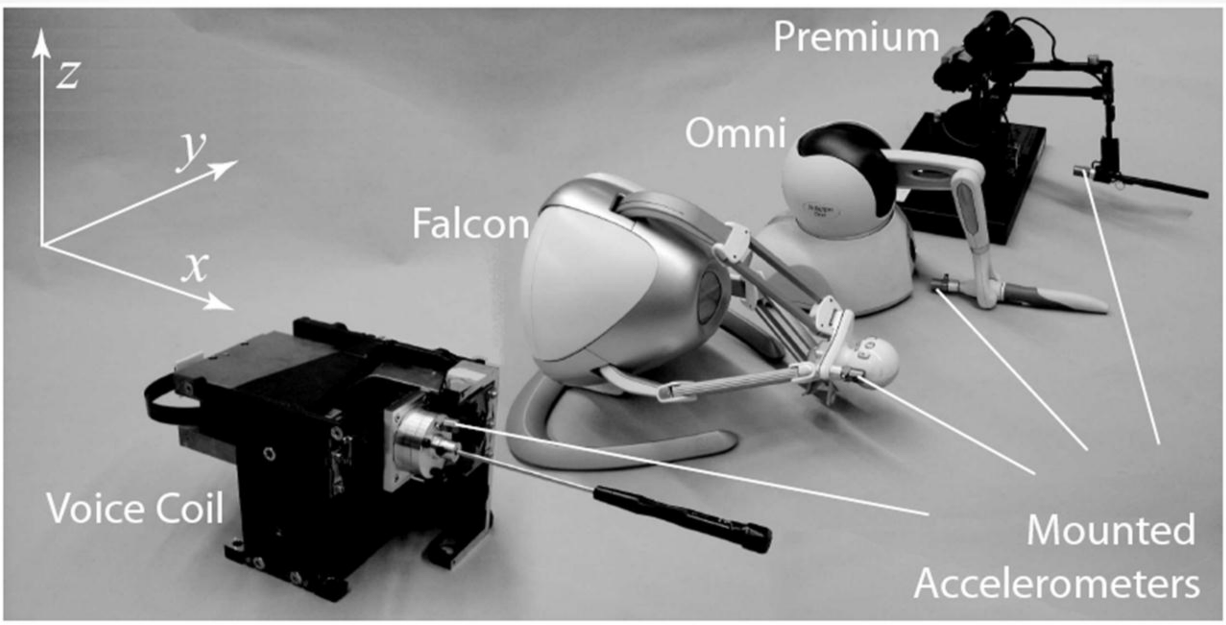
The haptic analog to the CSF is a vibration perception experiment. This is reasonable as a haptic evaluation because the haptic devices we work with are designed to render forces and vibration is a spectral form of force. Furthermore, texture rendering is realized through vibrations. Lastly, human vibration perception capability is well characterized (see figure). Vibration detection was selected as the most likely to reveal hardware limitations. Additionally, it is straightforward to relate performance on this experiment to specific hardware attributes.

Case Study: Application: Texture Rendering

5 participants (1 female)
Age: mean: 26 year old, range: 23-31
All right handed



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Now we will describe our implimentation of this evaluation technique using 5. In this experiment, we used 4 haptic devices, 3 of which were commercial devices. They were selected with the intent to span the cost spectrum. As such, the Falcon is a $200 device, the Omni a $2k device, and the Premium a $20k device. The assumption was that a more expensive device would produce detection thresholds most consistent with published data.

The fourth device was a high-fidelity voice coil linear actuator and was selected as the “gold standard.”

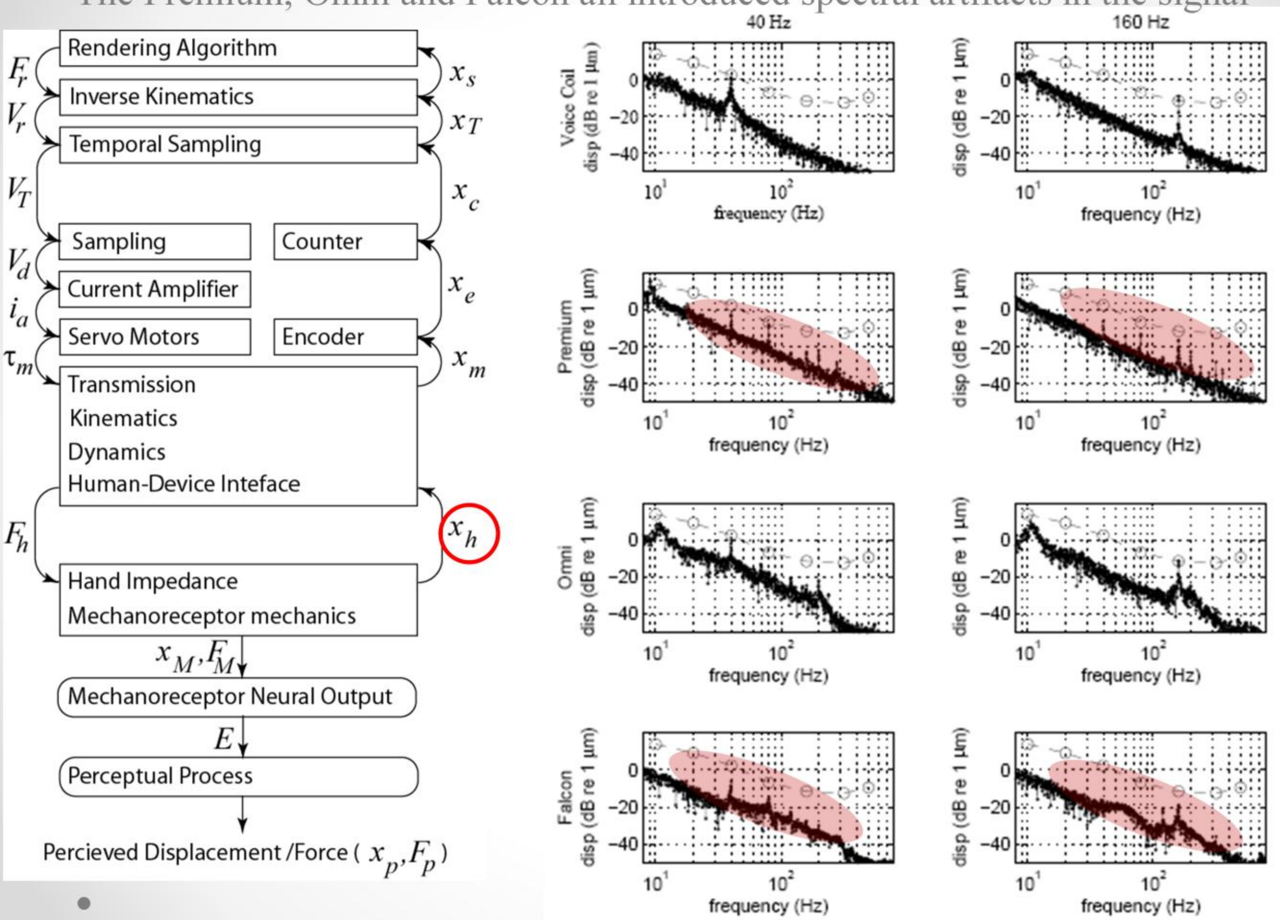
Case Study: Application: Texture Rendering

The voice coil was able to facilitate detection thresholds that were consistent with published detection thresholds for humans

None of the commercial devices facilitated detection thresholds that were consistent with published detection thresholds

Case Study: Application: Texture Rendering

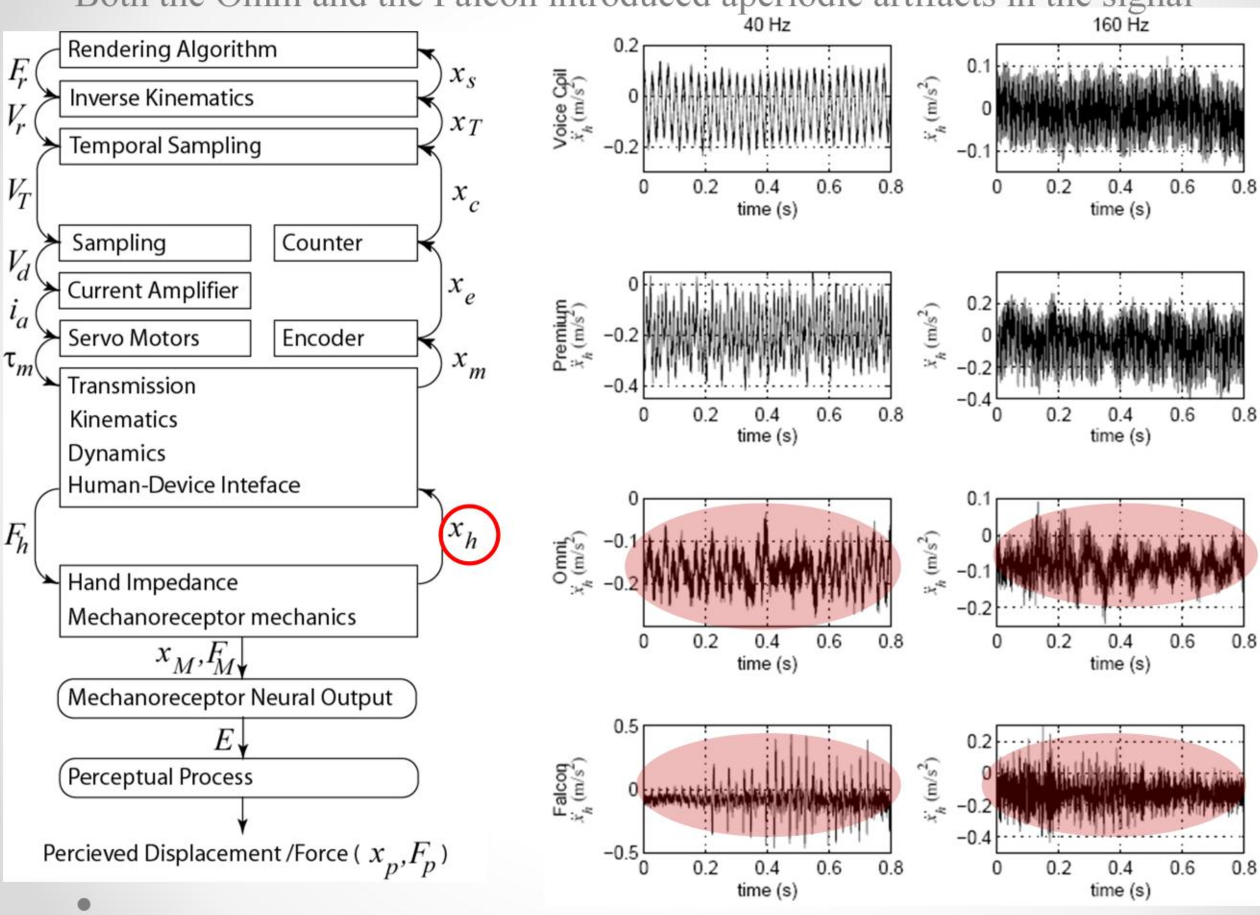
The Premium, Omni and Falcon all introduced spectral artifacts in the signal



We then look at accelerometer data on the human-device interface for detrimental effects
In particular, we looks at the spectral content of the accelerometer data
We notice that the only perceptible frequencies on the voice coil are the commanded frequencies and the detection levels are consistent with the published data (dashed line)
At 40 Hz, the only perceptible signal is the 80 Hz signal, a detrimental effect
At 160 Hz, no signal is at the perceptible level found in the literature
With the Falcon, no signals are at the perceptible level found in the literature

Case Study: Application: Texture Rendering

Both the Omni and the Falcon introduced aperiodic artifacts in the signal



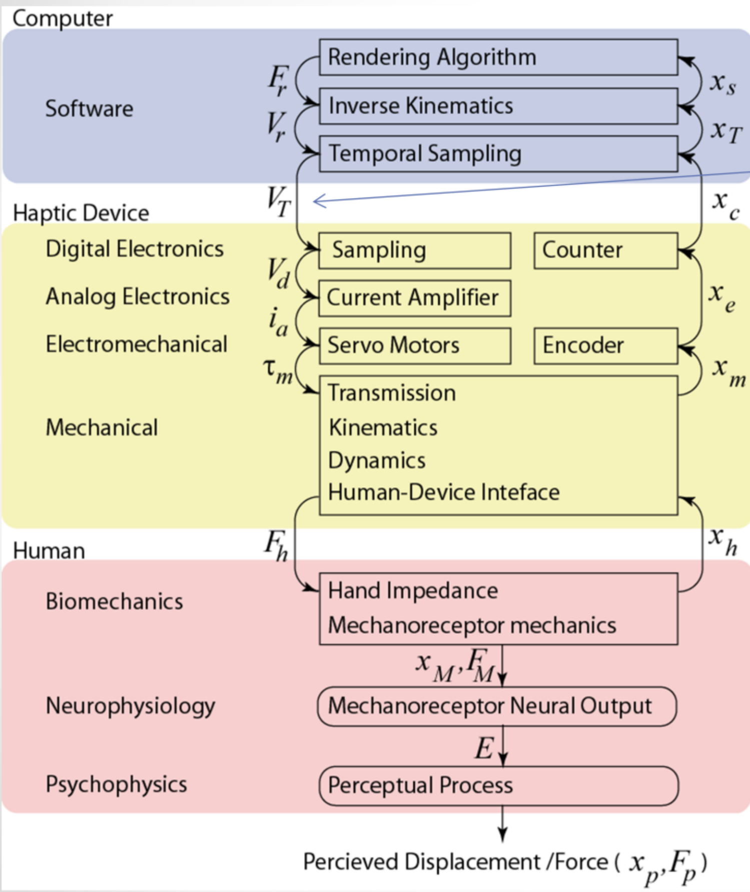
Lastly, we looked at the temporal data of the accelerometer to investigate the periodicity of the vibration signal

Both the voice coil and premium exhibit consistent periodicity

Both the Falcon and the Omni exhibit inconsistently periodic behavior, a detrimental effect

For these reasons, we conclude that none of the commercial devices were able to ….

Case Study: Application: Texture Rendering



The signal is clean here

But not here

We will measure the signals at other points along the flow path to identify the root cause of hardware deficiencies

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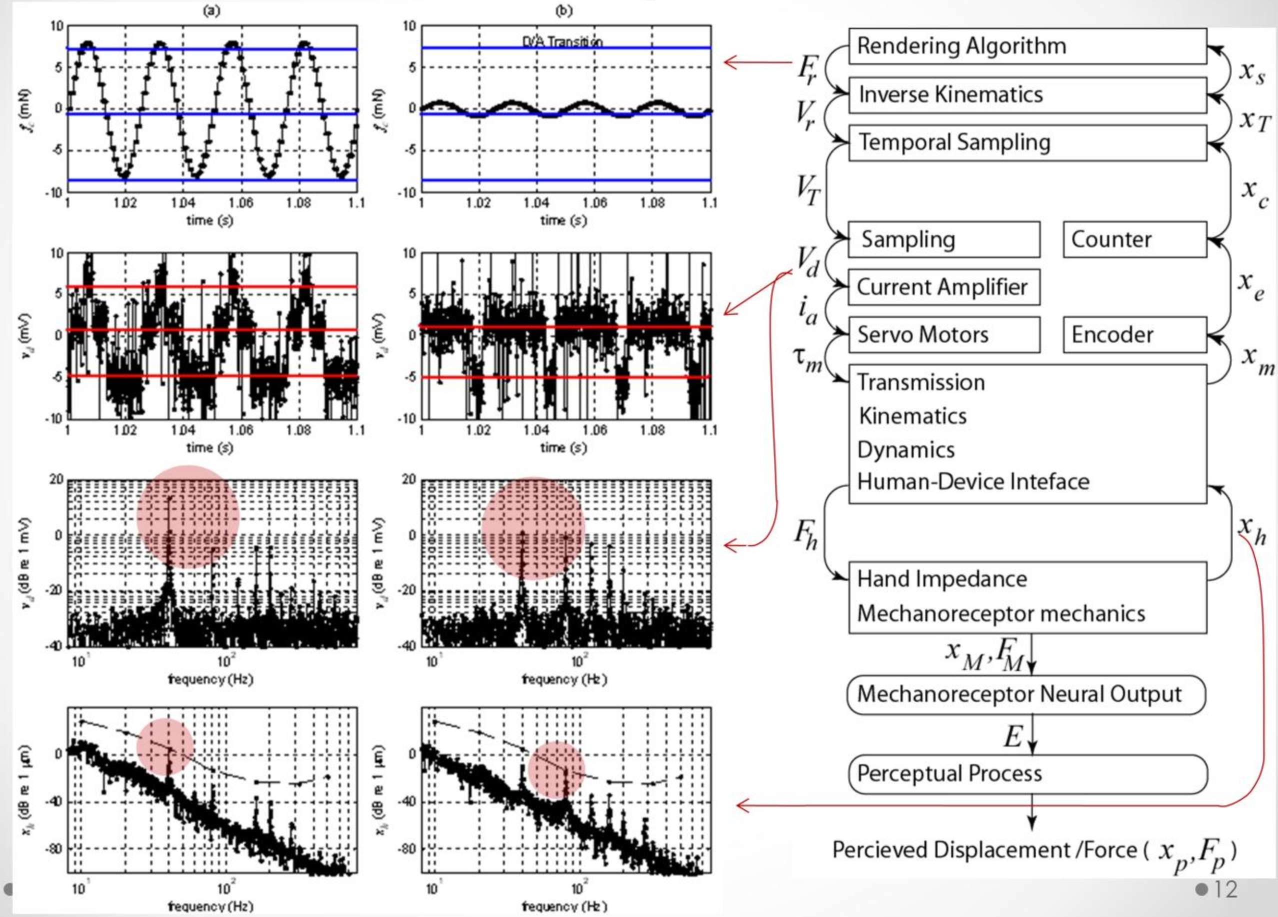
At this point, I investigated the device-centered root cause of these effects
My approach was to measure the signal at various points along the haptic signal flow path

Case Study: Application: Texture Rendering

The D/A converter was the root cause of spectral artifacts



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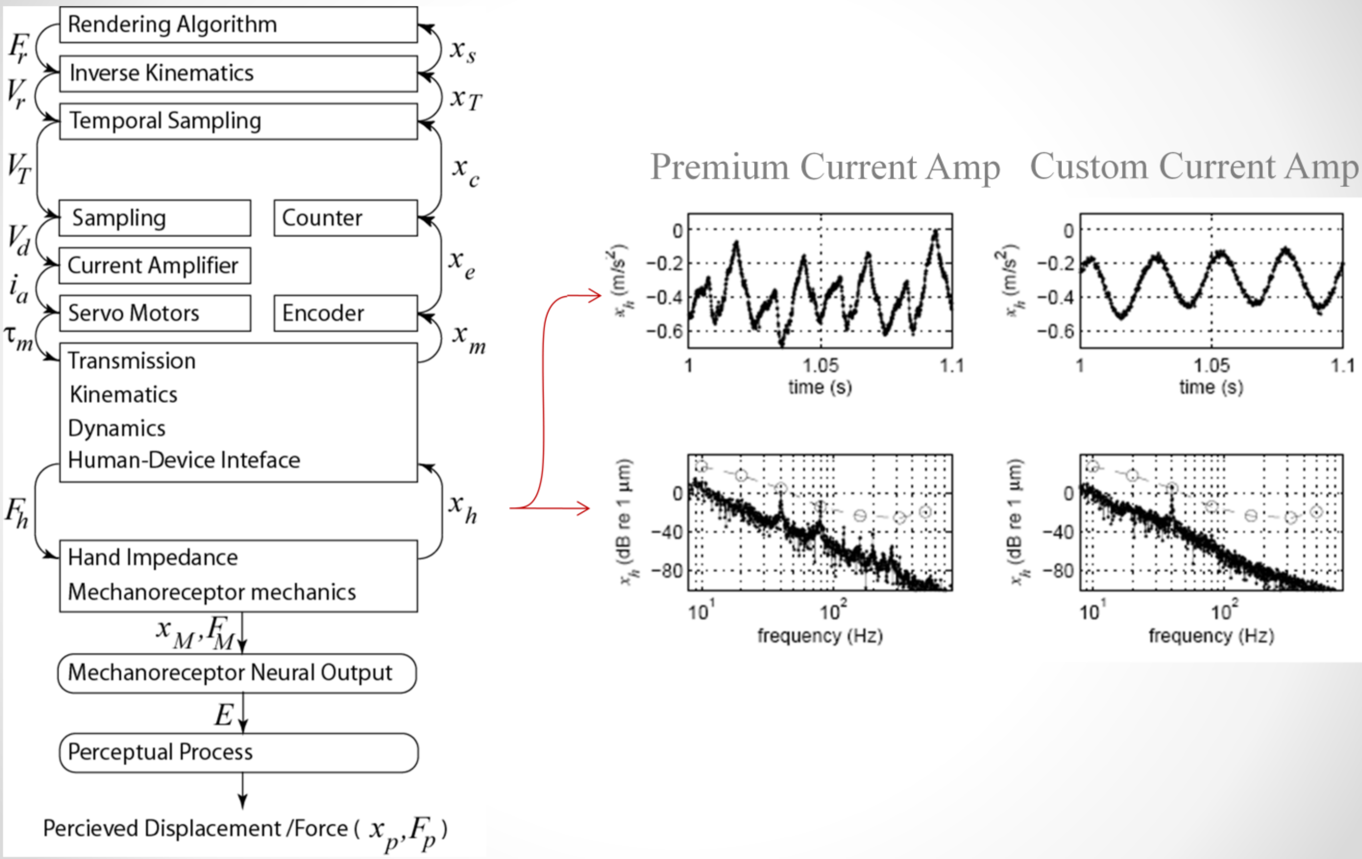
We discovered one of the causes of the detrimental effect from the Premium: the D/A resolution
Here we have signals from the two states of the bimodal distribution
We see that the larger signal crosses 2 D/A transition levels
The smaller signal crosses 1 level, just barely, but it registers a full transition level of the D/A
Consequently, even though the original signal is small, the D/A maintains a larger amplitude signal
Lastly, since the crossed transition and the centerpoint of the signal are offset, the resultant D/A signal has a duty cycle lower than 50%
The effects are seen in the spectrum of the D/A signal and at the accelerometer
We would expect these effects to go away given sufficient D/A resolution

Case Study: Application: Texture Rendering

The Premium's current amplifier introduced aperiodic artifacts in the signal



We discovered another of the causes of the detrimental effect of the Premium: current amplifier distortion

Here a high-res signal is passed to the current amplifier and the accelerometer was measured

the signal distortion is clear

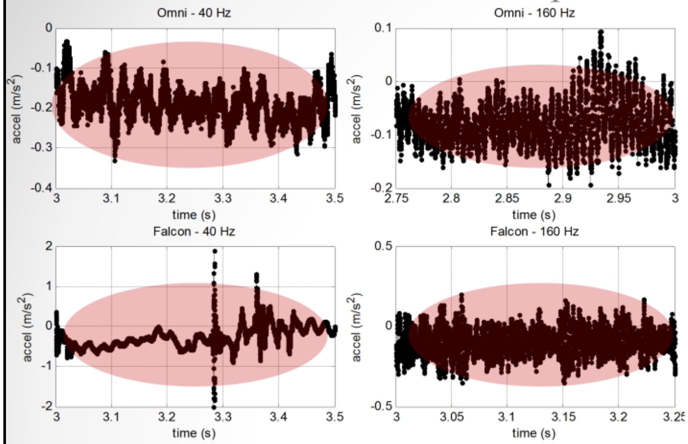
To verify that the cause this effect is the amplifier, we then sent a high-resolution signal directly to the servo-motors and the accelerometer was measured

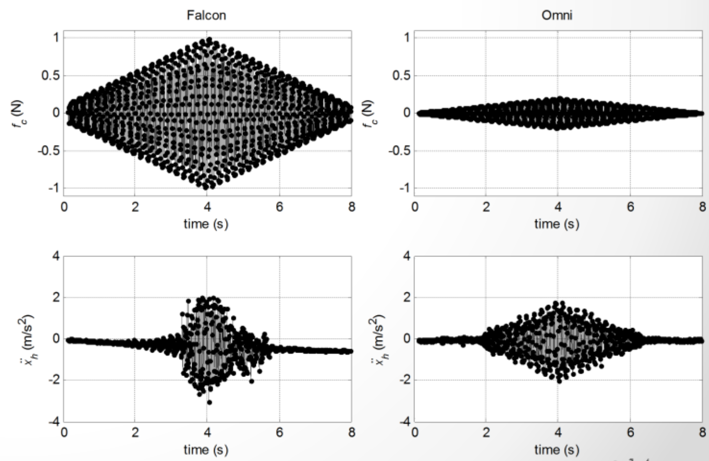
More specifically, these amplifier effects come from the drift, hysteresis, and delay in the directional switch

We would expect these effects to go away if a locked anit-phase PWM scheme were used

Case Study: Application: Texture Rendering

Stiction caused the observed aperiodicity in the Omni and Faclon





Case Study: Application: Texture Rendering

- All of the commercial devices introduced detrimental effects to vibration detection thresholds
- We were able to identify the root cause of these effects
- Haptic device non-linear attributes have the most detrimental effect on human vibration detection thresholds
- As such, we have been able to correlate device-centered measures with application-centered performance

Case Study: Application: Texture Rendering

Proposed Design Guidelines for Texture Rendering Adequacy:

1. Non-linearities can be conservatively modeled/enveloped as white noise
2. Scale device transfer function from noise source locations to stylus acceleration such that transfer function is below detection threshold
3. Scalings determine design requirements for non-linearities

Conclusion

We have shown that for one application for haptic hardware (texture rendering), we have been able to connect design level requirements with application level requirements and establish quantitative levels of sufficiency for both.

We are interested in exploring whether or not this concept can extend to other haptic applications