Experimental Validation of Capacitive Touch Sliders: Recommendations for Human Machine Interface Design

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***Abstract*—Human machine interface (HMI) devices commonly use capacitive touch sliders for user interaction, where accurate and stable position detection is critical. These systems are susceptible to position jitter, defined as variation in the reported touch location under nominally constant input conditions. While prior work addresses sensor design and noise mitigation, there is limited emphasis on experimentally repeatable methods for evaluating slider performance under controlled conditions. This study presents a repeatable experimental framework for characterizing capacitive touch slider response and supporting the evaluation of position jitter. A custom mechanical test rig was developed to control probe alignment, motion consistency, and board positioning, reducing operator-induced variability. Sensor data, including instantaneous delta values and centroid positions, were collected using a UART-to-USB interface and analyzed across repeated probe sweeps. Results demonstrate consistent delta–centroid response patterns across trials, indicating that the experimental setup enables reliable and repeatable measurement of sensor behavior. Variations observed in centroid response across repeated sweeps highlight the presence of position variability and establish a foundation for future centroid-based jitter quantification. The methodology provides a practical approach for controlled evaluation of capacitive slider systems and supports further development of standardized jitter characterization techniques.**

Keywords—Capacitive Touch Sensing, Position Jitter, Measurement System Evaluation, Human Machine Interface

I. INTRODUCTION

Capacitive touch sliders are widely integrated into appliance control systems, where accurate and stable position detection is critical for both system performance and user experience. A slider consists of multiple touch sensor electrodes, each measured as an individual channel. Changes in capacitance due to touch are converted into delta values, which are combined to estimate the position of contact along the slider through interpolation [1], [4]. However, capacitive sliders are highly susceptible to position jitter, defined as small variations in the reported touch position even when the input remains constant [2]. Jitter is influenced by electrical noise, parasitic capacitance, environmental conditions (e.g., temperature and humidity), and inconsistencies in touch actuation such as probe alignment and contact variability [1], [5]. This project was conducted in collaboration with a home appliance manufacturer developing capacitive touch-based HMIs. A sample HMI board with multiple sliders was provided, and testing focused on developing a repeatable method for evaluating slider performance. Despite existing literature providing guidance on capacitive sensor design and noise mitigation, there is limited emphasis on practical experimental methods for evaluating slider position stability under controlled and repeatable conditions. In particular, isolating true sensor behavior from variation introduced by probe alignment, motion consistency, and test setup remains a challenge. This work addresses that gap by developing a controlled experimental framework that combines a mechanical test rig with software-based data acquisition to evaluate repeatability and centroid response across repeated probe sweeps.

Within this study, position jitter is defined as the variation in the software-reported centroid position for repeated measurements taken under nominally identical physical input conditions. The primary objective of this work is to develop a repeatable experimental framework that enables controlled measurement of capacitive slider response while minimizing operator-induced variability. Rather than directly quantifying jitter through a single metric, this study focuses on establishing a reliable testing methodology and analyzing the consistency of delta and centroid responses across repeated probe sweeps. This approach provides a structured foundation for subsequent centroid-based jitter quantification and validation.

II. EXPERIMENTAL METHODS: TEST RING

A custom mechanical test rig (shown in figure 1) was developed to reduce operator-induced variation during capacitive slider testing and to provide controlled, repeatable probe motion relative to the HMI board. The rig consisted of two main elements: a translation mechanism used to move the board in the horizontal plane and a probe support used to maintain consistent probe positioning during contact. An XY drill-press vise was used as the translation stage so that the board could be repositioned smoothly in the test plane without direct handling of the board surface. For motion in the x-direction, the manual drive was coupled to a drill to produce continuous, uniform translation, allowing the probe to traverse the slider more smoothly and repeatedly than hand-guided motion.

To support the HMI board, a custom 3D-printed fixture was designed and fabricated. The fixture used a three-point support layout with adjustable screw legs, allowing the board to be secured and leveled before testing. This three-point design provided stable support while also making fine leveling straightforward, since each support height could be adjusted independently. A bubble level was used during setup to verify that the board surface was level prior to data collection. Once leveled, the fixture held the board in a fixed position while the probe and drill driven translation mechanism maintained consistent alignment relative to the slider surface. Together, these components created a repeatable test setup that minimized handling effects, improved positional consistency, and supported controlled experimental evaluation of slider jitter.First, confirm that you have the correct template for your paper size. This template has been tailored for output on the US-letter paper size. If you are using A4-sized paper, please close this file and download the file "MSW_A4_format".

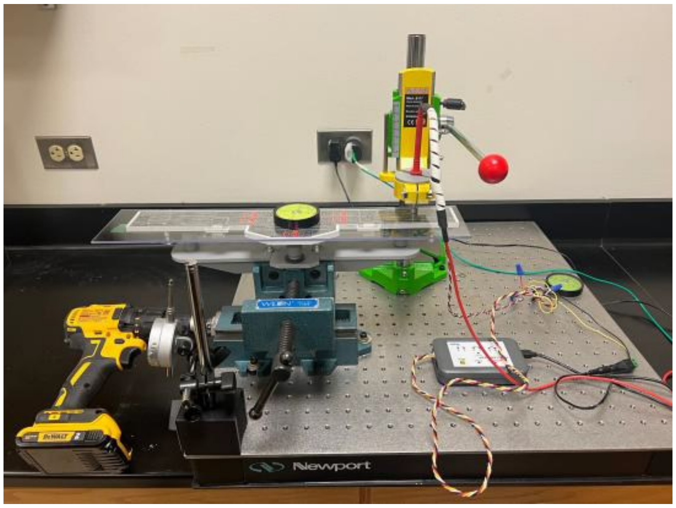

Fig. 1. Testing Rig for the A24 HMI

III. MEASUREMENT SYSTEM EVALUATION METHODS

A. Measurement System Evaluation

To ensure that the variation observed in the capacitive touch slider measurements was not primarily due to the measurement setup, a Measurement System Evaluation (MSE) was conducted. Because jitter analysis is sensitive to probe placement, motion consistency, and signal acquisition, the measurement procedure was documented and repeated under controlled conditions prior to final data analysis.

The aforementioned test rig was used to maintain consistent probe alignment and board positioning during testing. The probe was translated along the full active length of the capacitive slider labeled C in Figure 3, allowing the sensing region to be traversed in a controlled manner while reducing operator-induced variability.

Sensor data were recorded through a UART-to-USB translator interface using the designated custom software. During each trial, the system recorded instantaneous delta values and the corresponding centroid position calculated by the slider algorithm. The delta value represents the difference between the raw sensor signal and the reference baseline, providing a measure of the change in capacitance caused by probe interaction with the slider surface. Across the recorded datasets, delta values ranged from approximately 1 to 233 counts, reflecting the sensor response as the probe moved across the slider.

Each sweep across the slider was repeated five times under the same experimental setup without modifying the mechanical configuration. From the datasets collected during these full-slider sweeps, the delta responses corresponding to Key 7 within Slider C were extracted for further analysis. The resulting delta and centroid values were then plotted versus time for each trial to enable comparison of the sensor response across repeated measurements and to support the subsequent jitter analysis.

B. Results of Measurement System Evaluation

The datasets collected during the measurement system evaluation provide an overview of the behavior of the recorded delta and centroid signals under the experimental setup described previously. Observing the overall distribution of these measurements helps characterize how the sensor responses are distributed across the collected data. Understanding this distribution provides context for interpreting the slider response during probe movement and for examining variations observed in the recorded signals.

These observations are consistent with prior studies emphasizing the importance of controlled input conditions to reduce noise and measurement uncertainty in capacitive sensing systems [3], [6], as well as the expected baseline stability in such systems [1].

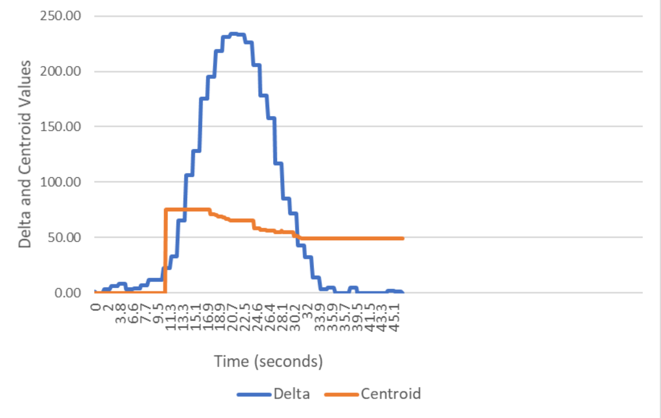

Fig. 2. Time-Series Response of Delta and Centroid Values During Slider Interaction

Figure 2 shows the time-series response of instantaneous delta values during Trial 1 for Key 7, along with the corresponding centroid positions reported by the slider algorithm. The timestamp labels have been reformatted to improve readability of the time axis.

At the start of the sweep, both signals remain near baseline. As the probe enters the sensing region, the centroid increases to approximately 70-75, while the delta rises sharply to a peak near 220-235 counts, indicating the strongest response. As the probe moves past the key center, the delta decreases toward baseline, and the centroid returns toward lower values, stabilizing as the probe exits the active region.

This response highlights how centroid position evolves with probe movement, while delta reflects the interaction strength, providing a basis for evaluating repeatability and position variation across trials.

IV. Experimental Methods: Software-Based Analysis of a Single Capacitive HMI

To support controlled testing of the capacitive slider system, proprietary software tools were used to monitor and record sensor response from the HMI board. The HMI board was connected to a computer through a UART-to-USB translator interface, enabling communication between the capacitive sensing hardware and the designated custom software environment. This interface allowed the research team to observe sensor behavior in real time while the probe interacted with the slider during testing. The overall hardware and communication setup used for data acquisition is illustrated in Figure 3.

For this study, the sensor signals associated with the capacitive slider were monitored to evaluate the response of the system as the probe moved across the sensing region. Within the software environment, several signal parameters were available for observation, including reference values, maximum delta, instantaneous delta, and centroid position. The delta value represents the difference between the raw sensor count and the reference baseline, providing a measure of the change in capacitance caused by probe interaction with the slider surface [6]. The centroid value corresponds to the position calculated by the slider algorithm based on the distribution of signals across the slider electrodes.

Instantaneous delta values were selected as the primary measurement parameter because they reflect real-time changes in capacitance relative to the baseline signal. In contrast, maximum delta values may retain previously recorded peak values unless the system state is reset, which may not accurately represent the current touch condition. Using instantaneous delta values therefore allowed the sensor response to be observed as the probe moved along the slider.

During testing, the software interface displayed the live sensor outputs while the probe was translated across the slider using the mechanical test rig. The resulting delta and centroid values were recorded as the probe moved along the slider surface and were exported from the software environment for further processing and analysis. Data processing, statistical analysis, and visualization were performed using Python [8]

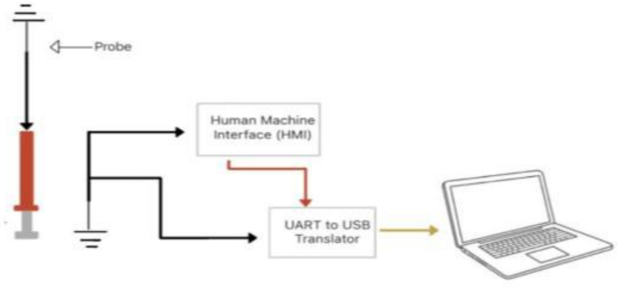

Fig. 3. HMI Wiring Schematic Diagram showing the probe, HMI board, UART-to-USB interface, and computer used for recording delta and centroid signals.

V. Results and Discussion

A. Research Objective and Validation Approach

Within the scope of this research, the objective was to develop a repeatable experimental procedure for evaluating the performance of a capacitive touch slider, with particular focus on quantifying position jitter under controlled test conditions. The study aimed to establish a practical validation method capable of characterizing how consistently the slider algorithm reports position when a controlled input is applied.

A single slider on the HMI board, identified as Slider C, was selected as the evaluation target and tested with the overlay attached to represent the intended operational configuration. By translating a probe along the slider in controlled sweeps and collecting multiple datasets, the reported centroid positions could be compared across repeated measurements. Variations in the centroid output observed across repeated sweeps of the probe along the slider were used as an indicator of position jitter. Through this approach, the experimental procedure provides a structured framework for observing the stability of the slider response and evaluating how reliably the algorithm reports position under consistent input conditions. Figures 3 and 4 were created by the authors to illustrate the experimental setup and slider configuration used during testing [7].

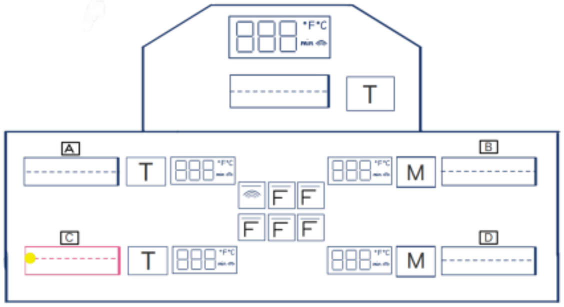

Fig. 4. A24 capacitive slider layout used for testing. Four sliders (A-D) are present on the HMI, with Slider C highlighted as the test region. The probe (shown in yellow and approximately to scale, 10 mm diameter) is initially positioned at (0,0) on Slider C and translated along the slider length to collect centroid and Delta measurements under controlled conditions.

B. *Delta Capacitance Analysis*

Instantaneous delta values were analyzed to evaluate the capacitive response of the slider during probe interaction. In capacitive sensing systems, the delta value represents the difference between the raw sensor signal and the reference (baseline) value, providing a direct measure of the capacitance change caused by a touch event. Because delta values update continuously during operation, they provide a more representative measure of real-time sensor response than maximum delta values, which store only the peak value reached during a measurement period.

Measurements were collected using the designated custom software while the probe was positioned at several locations along the slider. When the probe contacted the slider surface, the instantaneous delta values increased significantly for the electrode nearest to the contact location, while neighboring electrodes exhibited smaller responses. For example, measurements showed delta values exceeding approximately 200 counts for channels closest to the probe position, while adjacent channels exhibited lower responses due to capacitive coupling between electrodes. This response pattern is consistent with the expected behavior of capacitive slider sensors, where the electrode nearest the touch location experiences the largest capacitance change.

When the probe was removed from the slider surface, the instantaneous delta values returned to values close to zero, indicating that the sensor returned to its baseline state. This clear separation between touch and no-touch conditions confirms that the sensing system can reliably distinguish between active contact and background noise levels. These observations demonstrate that the measurement setup successfully captures localized capacitive changes along the slider and provides a reliable basis for analyzing centroid behavior and position jitter.

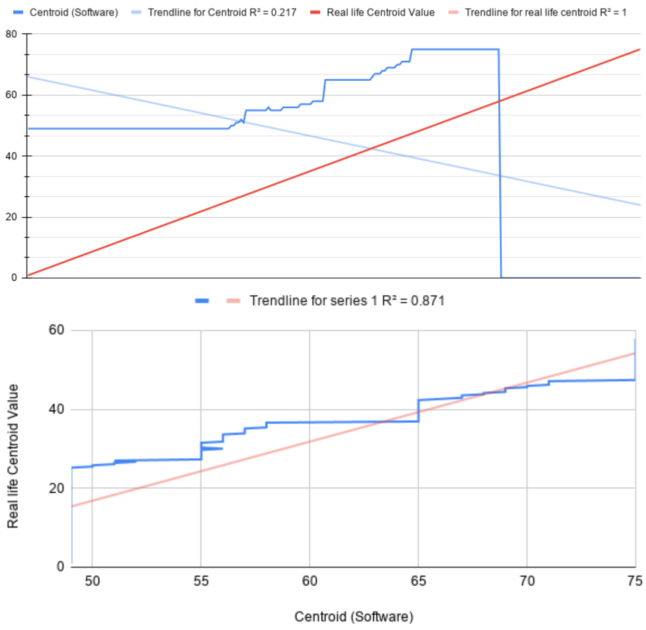

Fig. 5. Comparison of Software-Reported Centroid and Real Probe Position for Key 7, Showing Deviation from Ideal Linear Response

Figure 5 presents the relationship between the software-reported centroid values and the corresponding real probe positions for Key 7 to evaluate positional accuracy and its contribution to jitter. The top plot compares the centroid output with the expected linear probe motion, showing a weak correlation ($R^2 \approx 0.217$), which indicates that the centroid does not vary consistently with probe movement over time. The bottom plot directly maps real probe position against the software-reported centroid values, where a stronger correlation is observed ($R^2 \approx 0.871$), but with noticeable deviations from the ideal linear response. In an ideal system, this relationship would follow a one-to-one linear trend, and any deviation from this line represents position jitter. These variations in the reported centroid for a given physical position reflect inconsistency in the sensor output and therefore contribute directly to position jitter. By quantifying the spread and deviation from the ideal trend, this analysis provides a basis for evaluating both accuracy and repeatability of the slider. This approach aligns with the overall objective of the study, where jitter is characterized not by the raw delta values alone, but by the variability and inconsistency in the reported position relative to the actual probe location.

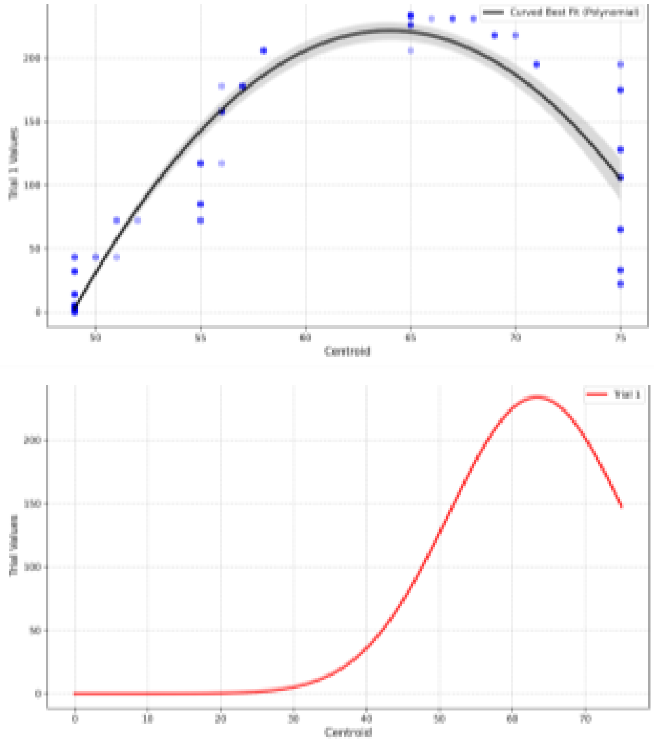

Fig. 6. Representative Delta and Centroid Response During Probe Sweep Across Keys 7

Figure 6 shows the response of Key 7 during a single probe sweep using processed representations derived from the raw measurement data. The top plot presents delta values plotted against the corresponding centroid values with a curved best-fit line, showing the response increasing from near baseline to a peak of approximately 220–230 counts at centroid values around 60–65, followed by a decrease as the probe moves past the sensing region. The bottom plot represents the same data as a smooth bell-shaped curve, highlighting the peak and the spread of the response. Transforming the raw time-based data into a delta–centroid relationship allows the sensor behavior to be evaluated independently of probe motion, while the spread of the curve provides a measure of variability used to assess repeatability and position jitter across trials. The plot shown in Figure 5 and 6 were generated using Python to visualize the relationship between delta and centroid values across repeated probe sweeps [9].

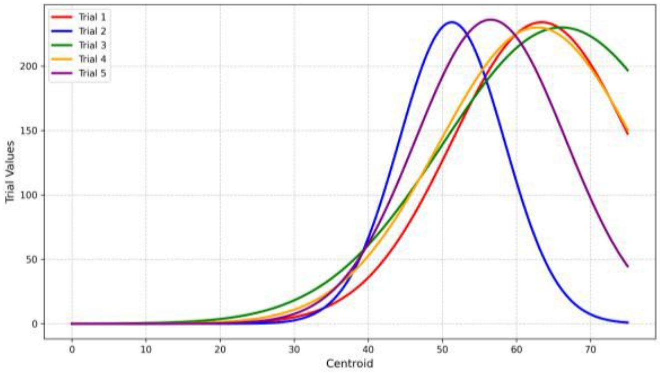

Fig. 7. Bell Curve Distribution Models of Trial Performance (Key 7)

Figure 7 compares the delta-versus-centroid response curves obtained from five repeated probe sweeps across Key 7 under the same experimental conditions. Across all trials, the response follows a consistent overall pattern in which delta increases as the probe approaches the sensing region, reaches a maximum within the active region of the slider, and then decreases as the probe moves away, indicating that the test setup produces a repeatable response profile. At the same time, small shifts in peak location and differences in curve width are observed between trials, reflecting variation in the reported centroid response across repeated sweeps. Plotting all five trials together allows the centroid behavior to be directly compared under identical conditions, where these small shifts in peak centroid position represent variation in the reported touch location. This variation forms the basis for evaluating slider position jitter, as it captures the inconsistency in reported position for repeated probe motion, and provides a clear visual representation of how the HMI slider response varies across repeated measurements, supporting the jitter analysis performed in this study.

TABLE I. SUMMARY STATISTICS OF DELTA RESPONSES ACROSS REPEATED TRIALS, INCLUDING MEASURES OF CENTRAL TENDENCY AND VARIABILITY USED TO EVALUATE MEASUREMENT CONSISTENCY AND JITTER

Metric	**Count**	**Mean**	**Std. Dev.**	**Min**	**Q1 (25%)**	**Med. (50%)**	**Q2 (75%)**	**Max**	**Variance**	**Skewness**
Trial 1	248	68.76	84.86	0	3	14	128	234	7201	0.902
Trial 2	248	71.95	81.21	0	6	34	126	234	6595	0.88
Trial 3	248	56.17	79.86	0	0	8	92	230	6377	1.169
Trial 4	248	67.05	82.09	0	0	17	123	230	6739	0.886
Trial 5	248	74.69	83.67	0	5.75	27	141	236	7001	0.753
Centroid	248	44.98	26.26	0	49	49	65	75	689	-0.855

While fluctuations in delta values can influence centroid calculation, the statistics presented here should be interpreted as supporting indicators of measurement consistency rather than direct measures of jitter. A complete characterization of position jitter requires centroid-based metrics that quantify variation in reported position under controlled input conditions.

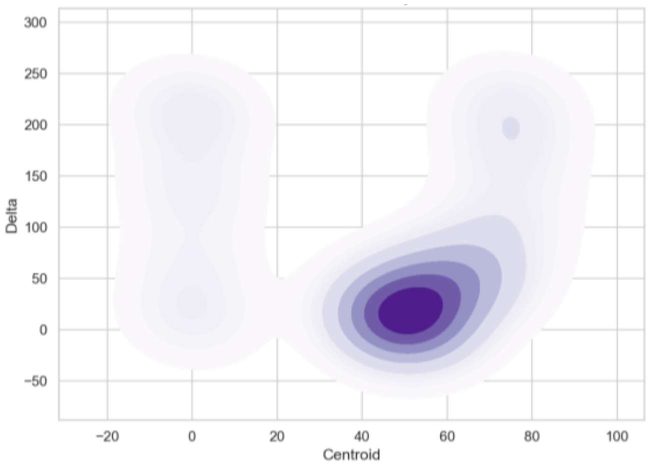

Fig. 8. X-Y Bell Curve Density Plot of Centroid vs. Delta Values (The topographical density map illustrates the distribution of collected data points. Darker regions indicate higher data concentration, highlighting areas of consistent sensor response.)

Figure 8 presents a density plot of centroid versus instantaneous delta values from the collected measurements. Color intensity indicates the concentration of recorded data points, with darker regions representing combinations of centroid and delta values that occurred more frequently across the repeated sweeps. The observed clustering indicates that similar response patterns were recorded consistently under the controlled test conditions. The broader spread of points surrounding the main cluster reflects the transition of the probe into and out of the active sensing region, while the less dense high-delta region corresponds to the shorter portion of each sweep during which the probe passed directly over the area of strongest response. Viewed together, these distributions provide a compact visual summary of repeatability and signal behavior across the measurement set.

VI. CONCLUSION

This study developed a repeatable experimental procedure for evaluating the response of a capacitive touch slider under controlled conditions. A custom mechanical test rig, combined with software-based data acquisition, enabled repeated probe sweeps to be performed with improved positional consistency and reduced operator-induced variation. The resulting measurements showed repeatable delta-centroid response patterns across trials, supporting the use of the setup for controlled slider characterization. While the present analysis primarily demonstrates repeatability and signal stability, it also establishes a foundation for more direct quantification of centroid-based position jitter in future work. Overall, the methodology provides a practical framework for experimental validation of capacitive slider behavior in appliance HMI applications.

VII. FUTURE WORK

Future work should focus on improving both measurement resolution and direct quantification of centroid-based position jitter. One limitation of the current study is that probe motion was mechanically assisted but not fully automated, which may still allow small variations in speed and path between trials.

Implementing a motorized translation system would provide more uniform motion, improve spatial sampling density, and further reduce operator-induced variability. In addition, future analysis should include direct centroid-based metrics, such as variation in reported position at matched locations or shifts in peak centroid response across repeated sweeps. These additions would strengthen the ability of the method not only to observe repeatable slider behavior but also to quantify position jitter more rigorously.

ACKNOWLEDGMENT

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