A Cost-Effective Testbed for Measuring the Performance of Reference Switches*

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***Abstract*— Reference switches are widely used in automation and robotics for positioning tasks. However, typically data sheets do not provide specifications regarding their repeatability performance. This work presents a cost-effective testbed to measure the repeatability of different switch types. It uses a high-resolution linear scale and an ATmega microcontroller to detect small deviations in switch trigger points. The firmware is optimized for low latency and openly available. Finally, the proposed testbed is used to assess the performance of different reference switch types.**

***Index Terms*— Repeatability, Reference Switches, Automation**

I. INTRODUCTION

In robotics and automation, accurate positioning is required to ensure results being consistent and of high-quality. This is typically achieved using integrated measurement systems. Measurement systems based on incremental encoders are widely used due to their cost-effectiveness, however they require switches for homing the system to a known reference position. While accurate detection of the reference position is critical for overall repeatability, data sheets for switches typically do not specify their repeatability performance. This work therefore proposes a testbed for evaluating the repeatability of various reference switches experimentally, addressing two research questions: How can a cost-effective testbed be designed to evaluate the repeatability performance of reference switches? How repeatable is the performance of commonly used reference switches? While this topic certainly is studied for commercial applications, to the authors' knowledge, no publication on this topic exists so far.

The further content is structured as follows: Section II introduces the terms accuracy and repeatability, along with different types of reference switches. Section III then describes the testbed design, covering the mechanical and electrical setup as well as the firmware implementation. Next, Section IV presents selected results. Finally, Section V summarizes the work and outlines future tasks.

II. BACKGROUND

Accuracy describes how closely a target position can be reached. Any deviation from the target position can be considered an accuracy error [1].

Repeatability refers to how closely the same position can be reached again under identical conditions [1]. A high repeatability is possible even with low accuracy, as long as consistently the same accuracy error occurs.

Different types of reference switches are used in automation and robotics. They can be categorized as mechanical or electrical, and as contact or contactless. The most common types are capacitive, inductive, photoelectric, and mechanical switches.

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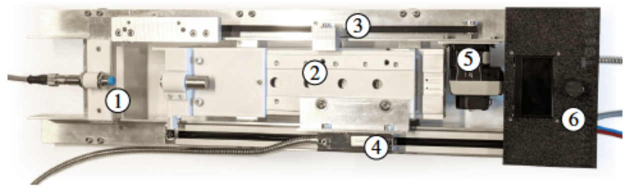

Fig. 1. Top view of the assembled testbed, with ① indicating the reference switch under test, ② the linear slide, ③ the belt drive, ④ the linear scale, ⑤ the stepper motor, and ⑥ the user interface, consisting of a display and input encoder knob.

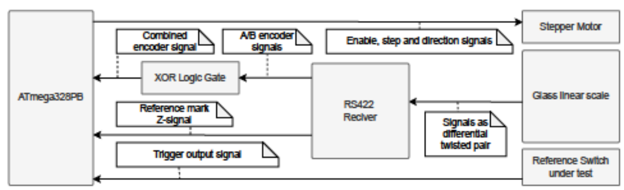

Fig. 2. The electrical communication diagram of the proposed testbed.

III. EXPERIMENT SETUP

The hardware is selected with cost-effectiveness in mind. Fig. 1 shows the assembled testbed. A pneumatic slide (SMC EMXS20-125) is used as a linear axis, with its cross-roller bearings providing low friction and adjustable mechanical play. Its pneumatic cylinders are decoupled from the motion axis and instead actuated by a NEMA17-sized MDrive stepper motor via an MXL belt. The slide's mass helps dampen stepper motor pulses, while the movement is measured using an incremental Aikron MDI series linear scale (1 µm resolution with quadrature encoding). The system is controlled by an ATmega328PB evaluation board. To allow for different sensors with varying physical dimensions and mounting options, the sensor is attached to the testbed via a swappable adapter plate. The total hardware cost is approximately 400 €, with the linear scale being the most expensive component at around 200 €.

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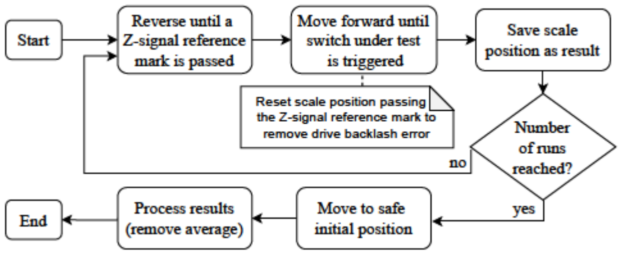

Fig. 3. The experiment flow implemented in the firmware.

A. Electrical Setup

Fig. 2 gives an overview of the testbed's electrical communication setup. The central control unit is an ATmega328PB microcontroller and all signals, inputs or outputs, are processed or generated by it. The output signals for the stepper motor and input signal of the reference switch are directly interfaced to the microcontroller. The scale provides three separate signals – A, B, and Z – as differential RS-422 signals to increase noise immunity. A separate RS-422 receiver is used to read the differential signals. The Z-signal is the reference signal of the scale and occurs every 50 mm. The A/B signals indicate the incremental position change of the scale. They are 90° phase-shifted relative to each other, and allow to determine the direction of movement. In this setup, the A/B signals are combined using an XOR logic gate to increase the effective resolution by counting every edge on both signals.

B. Firmware Implementation

Fig. 3 shows the implementation for a test cycle in the firmware[1]. First the slide is reversed until a reference mark (Z-signal) on the linear scale is passed. Next the slide is moved forward until the reference switch under test is triggered and the position of the linear scale is saved. The linear scale position is tracked using XOR-ed A/B signals as a clock source for two 16-bit hardware timers. As the ATmega328PB supports only one clock edge per timer, two timers are used to count on both edges. An overflow counter is added for both timers to track distances beyond the 16-Bit counting range. The resulting distance is calculated by combining both timer values and the overflow counter.

The Z-signal is handled as an external interrupt, resetting both timer values and the overflow counter on each reference mark. This way, after reversing until the reference mark and moving towards the switch again, a second reset occurs, removing the need to account for mechanical belt drive backlash. To ensure that the testbed firmware has a minimal reaction time, the main loop only needs to check the switch output signal while taking a measurement. The resulting measurement values with 1 µm resolution can be retrieved using the UART interface of the microcontroller.

[1]The source code is openly available under: `https://github.com/sas-o/2025-arw-refswitch-tester`

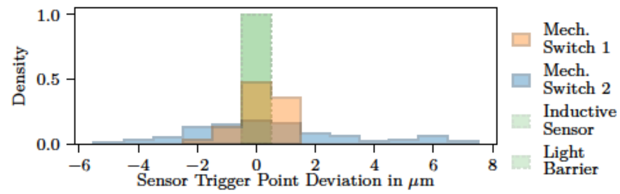

Fig. 4. Histogram of sensor trigger points deviation across $n = 200$ runs.

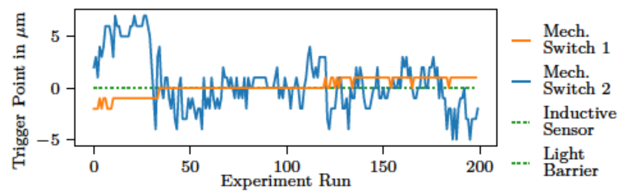

Fig. 5. Deviation of the sensor trigger points per experiment run.

IV. Results

The results for different types of end switches are briefly presented in Fig. 4 and Fig. 5. For each sensor, the experiment was repeated $n = 200$ times. Based on the tested sensors and results, both the selected optical light barrier and the inductive sensor perform better than the provided measurement accuracy of 1 µm. Therefore, we conclude that their repeatability is smaller than 1 µm, exceeding the testbed's measurement resolution. At the same time, it also demonstrates the repeatability provided by the testbed itself. For mechanical switches, a larger deviation is expected, as they require physical contact. Two different models were tested, with model 1 clearly outperforming model 2. In Fig. 5, the deviation of the sensor trigger point is shown per run. No linear error is visible, which could have indicated an issue with the testbed itself.

V. Conclusion

In robotics and automation, switches are widely used for reference positioning. However, most data sheets for switches do not specify a repeatability performance for such a task. This work presents a cost-effective testbed for measuring the repeatability of different types of reference switches. Measurement results with a repeatability of 1 µm are achievable. Next, the testbed will be used to evaluate a broader range of reference switches under varying conditions, such as different movement speeds and trigger directions. Further improvements to the testbed could include replacing the stepper motor with a hollow cup DC motor to reduce induced vibrations, installing limit switches for improved safety, and adding temperature and humidity logging to monitor the test environment.

References

[1] K. C. P.S. Shiakolas and T. Yih, "On the accuracy, repeatability, and degree of influence of kinematics parameters for industrial robots," *International Journal of Modelling and Simulation*, vol. 22, no. 4, 2002. [Online]. Available: https://doi.org/10.1080/02286203.2002.11442246