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Safety system delay measurement and implementation to VR- simulation

Abstract

This paper examines the distinctions between virtual and real-world environments in the assessment of machine safety applications. The high-speed camera was employed for the actual configuration for measurement of single DC motor stop time, which represents part of the real machine architecture. The delay between the activation of the safety laser scanner to the cessation of the motor was measured. Additionally, the delay from the safety laser scanner to the contactor shut down operation was measured. The result serves to establish a benchmark for comparison with a virtual model developed in Unity.

The virtual environment is constructed in such a way as to replicate the real-world system, with the objective of implementing real-world measured delay and safety performance under controlled conditions. By simulating different scenarios, researchers can assess the system's response and identify critical weaknesses without the inherent risks associated with physical machinery.

Latency is a critical factor in the context of safety. It is defined as the time interval between the triggering of a safety condition and the corresponding system action. The reduction of latency is of paramount importance for the implementation of effective safety responses. In the virtual setup, computational latency is analyzed in conjunction with real-world mechanical delays to ascertain the viability of utilizing virtual simulations for safety-critical assessments.

Moreover, the study assesses compliance with ISO 13849, a foundational safety standard that delineates the specifications for control system design. Verification of adherence to these criteria in both the virtual and physical setups serves to validate the robustness of simulations for machine safety systems. The integration of high-speed camera data improves the accuracy of the virtual model, enabling a comprehensive analysis of system behavior under dynamic conditions.

Methodology

To replicate key aspects of the actual machine architecture, a real-world experimental setup was constructed. Delay measurements were performed using a Citius Imaging C100 high-speed camera in conjunction with Citius Imaging 1.48 software, which captured images at intervals of 2.306 milliseconds. The safety laser scanner (Sick nanoScan3), configured with a 20 mm finger detection resolution, was mounted vertically on an aluminum profile bar and aligned with the camera to ensure reliable observation of the safety field activation. The camera's field of view also encompassed a small DC motor equipped with a mechanical rotation indicator and signal lights. These lights indicated the activation of the safety relay (Pilz PNOZ s4) and the switching of the contactor. For the experiment, an operator's hand was employed to trigger the safety light curtain, and the subsequent video recordings were analyzed—using the known frame rate—to calculate the delay from safety field activation to motor cessation.

After the real-world measurements, a virtual reality (VR) model of the test setup machine and its safety control system was developed in Unity. This VR model replicated the stopping architecture of the physical system, with delays for each component (safety light curtain, safety relay, contactor, and motor) parameterized based on the high-speed camera data. The Unity object code was modified to incorporate the motor's ramp-down time, and parameters encompassed an error margin ranging from 1 millisecond to 1 second. This was included in the test using a random generator to emulate the similar standard deviation effect observed in real-world tests.

Results and Discussion

The high-speed camera system was employed to conduct two distinct measurement configurations. In the first measurement, the delay from the activation of the safety scanner to the cessation of the motor was evaluated. This test was repeated ten times, yielding a mean delay of 1404.79 ms with a standard deviation of

50.12 ms.

In the second configuration, indicator lights were incorporated into the circuit following the safety relay and motor contactor. These lights visually indicated the activation of the respective components, which were captured by the high-speed camera. The results from this setup revealed a mean delay of 14.87 ms with a standard deviation of 16.08 ms for the time between the activation of the safety sensor and the triggering of the safety relay. Additionally, the mean delay from safety scanner activation to the state change of the contactor was found to be 26.20 ms, with a standard deviation of 16.63 ms. The total delay from the activation of the safety laser scanner to the cessation of the motor in this second setup was 1388.74 ms, with a standard deviation of 66.68 ms. When combining the results from all 20 trials, the total mean delay from the activation of the safety scanner to the cessation of the motor was 1396.77 ms, with an overall standard deviation of 61.10 ms.

The largest portion of the delay arises from mechanical deceleration of the motor rather than from the electronic or sensing components. The brief intervals measured between the scanner activation and the safety relay (~15 ms) or contactor off (~26 ms) are minimal in comparison. This is consistent with typical small motor inertia and the absence of an electronic brake in the test setup.

The short delays (e.g., scanner-to-relay or scanner-to-contactor) exhibit relatively higher standard deviations (on the order of 16 ms) compared to their mean values. This likely reflects the frame-based measurement resolution of the high-speed camera and potential jitter in signal switching. While the camera provides accurate timing over the full 1.40 s window, sub-30 ms intervals are proportionally more affected by each frame's ~2.36 ms increment.

Conclusions

The experimental results indicate that the high-speed camera reliably detected the laser light emitted by the safety scanner, thereby facilitating precise alignment during testing. However, further investigation is required to refine the accuracy of event timestamp extraction from the video frames, as the software-based frame measurements exhibit a non-negligible tolerance.

In developing the virtual reality (VR) model, it was essential to parameterize two key factors: the nominal delay associated with each component and the additional delay introduced by measurement

tolerance. This approach enables simulation of safety responses under various conditions, providing a robust framework for analyzing system behavior. Moreover, the VR environment allows for rapid testing and optimization of safety measures without the inherent risks and costs of physical trials.

The high-speed camera proved to be an effective tool for validating total delay times—from safety scanner activation to motor cessation—under conditions where safety tolerance is critical. Nonetheless, its precision diminishes when capturing very short time intervals, such as those between the activation of the safety scanner and subsequent events like safety relay or contactor switching. Furthermore, while manufacturers typically provide component reaction times and delay values that incorporate built-in safety factors for practical applications, additional optimization may be necessary to reflect the dynamic performance of the system more accurately under test. However, based on the test, it is more feasible to inspect the stopping time of mechanical systems rather than electrical control systems in simple automation cases.

Keywords: delay, stopping time measurement, virtual reality, safety validation, digital twin

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