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TELEOPERATED GROUND VEHICLE ROLLOVER PREVENTION VIA HAPTIC FEEDBACK OF THE ZERO-MOMENT POINT INDEX

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ABSTRACT

Many rollover prevention algorithms rely on vehicle models which are difficult to develop and require extensive knowledge of the vehicle. The Zero-Moment Point (ZMP) combines a simple vehicle model with IMU-only sensor measurements. When used in conjunction with haptic feedback, ground vehicle rollover can be prevented. This paper investigates IMU grade requirements for an accurate rollover prediction. This paper also discusses a haptic feedback design that delivers operator alerts to prevent rollover. An experiment was conducted using a Gazebo simulation to assess the capabilities of the ZMP method to predict vehicle wheel lift-off and demonstrate the potential for haptic communication of the ZMP index to prevent rollover.

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1. INTRODUCTION

A key issue across all ground vehicle disciplines, particularly UGV applications, is the prevention of vehicle rollover. A UGV's ability to maneuver offroad through rough terrain coupled with large payload capacities result in these technologies often being brought past the limits of safe operation. Rollover indices have been developed to aid in safe UGV operation by using inherent vehicle geometry in conjunction with sensor measurements to provide a depiction of a vehicle's current state. This creates a real-time predictive index of rollover likelihood [1].

In military applications, UGVs allow for soldiers to have access to a vehicle in landscapes that would not be conducive to traditional vehicle operation. These UGVs also have the ability to transport gear, reducing soldier loads and fatigue. However, teleoperation lacks natural operator feedback inherent to manned ground

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vehicles. Operators of manned vehicles rely on years of training and experience along with sensor measurements (e.g., inclinometer) to make control decisions. Teleoperation is at a disadvantage because it must be supplemented by focused visual attention. This can become very taxing, particularly over long periods of time, and can reduce an operator's ability to maintain situational awareness. As autonomy becomes more sophisticated and common, particularly in UGVs, teleoperation will be replaced by or supplemented with this technology. Therefore, having adequate rollover prevention technology in place is crucial.

Teleoperation of UGVs commonly relies on operator vision to convey information and warnings to the operator. Haptic feedback has been demonstrated to be effective in shared control of steering [2], increasing operator perception of UGV attitude [3], and obstacle avoidance of teleoperated UGVs [4]. However not all haptic warnings are situationally appropriate. Haptic feedback devices (HFDs) used in UGV operation commonly rely on vibrotactile responses and bulky hardware which can disrupt situations that require a discreet (quiet) output, or be difficult to wield in climates where thick gloves may dampen sensation. Conversely, squeeze stimuli can be produced with low noise output, while also not relying on firm skin contact to transfer the haptic cue, as needed in vibrotactile methods [5].

This paper will discuss the merits of a real-time IMU-only-based approach for rollover prediction and will demonstrate a practical application of the ZMP index in vehicle rollover prevention through operator-delivered haptic feedback. The HFD introduced in this paper instead provides a squeeze stimulus applied to the back side of the intermediate phalanges of the operator's hand.

2. METHODS

Since our interest is to determine methods that prevent ground vehicle rollover, a simple prediction algorithm was created based on vehicle geometry, and available sensor measurements. To determine the relationship between IMU grade and accurate wheel lift-off prediction, real UGV data was analyzed. To test the efficacy of this approach, a human-in-the-loop simulation experiment was conducted.

2.1 Vehicle Model-Based Estimation

There are certain vehicle parameters linked to an increased likelihood of rollover, including a high center of gravity location [6], a small trackwidth length, and large or uneven mass. The algorithm this paper uses to index rollover is the Zero-Moment Point (ZMP) index. This index combines vehicle geometry with real-time IMU data to produce a current prediction of the of wheel lift-off.

While wheel lift-off is not a guarantee that rollover will occur, it is a powerful indication that rollover is imminent. This warning can alert the operator and allow time for reaction to correct the course before rollover occurs. Shown in Fig. 1, the zero-moment point is illustrated for a ground vehicle in a safe configuration.

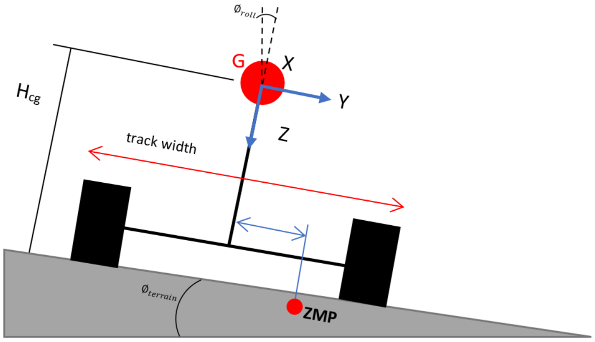

Figure 1: Visualization of the Zero-Moment Point.

The zero-moment point describes a point in space where the reaction forces on the object in contact with the ground are equal to zero [7]. In the case of a UGV, the contact object would be the wheels. When the zero-moment point moves outside of the track length's y-coordinate, (outside the object of contact's reach) a tipping moment occurs, the mass is deemed no longer stable, and the respective wheel is no longer in contact with the ground. The zero-moment point becomes an index when its inputs are taken from real-time sensor measurements. The IMU readings of roll rate and acceleration are adapted and updated at each time step to give a real-time account of the vehicle's operational status [8].

$$ZMP = \frac{50}{TW}\left(-\frac{I_{xx}\ddot{\phi}}{mg} + H_{cg}\phi - \frac{H_{cg}a_y}{g}\right) \quad (1)$$

The variables for this equation are defined in Table 1:

Table 1: ZMP Variables.

Parameter	**Definition**
TW	Track width
I_{xx}	Mass moment of inertia (x-axis)
$\ddot{\phi}$	Roll acceleration
m	Vehicle mass
g	Acceleration due to gravity
H_{cg}	Height of sprung mass from CG
ϕ	Roll angle
a_y	Lateral acceleration

The ZMP is normalized about half the vehicle's trackwidth and its absolute value is considered. The output can then be converted into a percentage of wheel lift-off. The x-axis mass moment of inertia, vehicle mass, and relative center of gravity location are the only vehicle parameters the algorithm requires. Further analysis was conducted to determine how accurate these values must be to produce an accurate ZMP output.

2.2 IMU Grade Analysis

Due to the ZMP algorithm's dependence on IMU measurements, data was collected from a UGV using two IMUs of varying grade. The high-grade IMU was a fiber optic sensor, and the low-grade IMU was of consumer grade. The goal of this data comparison was to determine if a relationship existed between IMU grade and accurate wheel lift-off prediction.

There are three terms in the ZMP index equation that are based solely on IMU measurement. Those terms are roll acceleration, lateral acceleration, and roll angle. Extracting roll acceleration and lateral acceleration from either IMU was straightforward: the roll acceleration is the integration of roll rate taken from the gyroscope's x-axis output. The lateral acceleration is the y-axis output from the accelerometer.

However, deducing the roll angle was more complex. As the IMUs did not have a magnetometer imbedded in either sensor, there was no quaternion orientation output that could be simply converted to Euler roll angle. Thus, a few methods were tried to get an accurate roll angle. The IMU-generated roll angle was compared to a 3-anntenna GPS roll angle output which was considered "truth" for this experiment. The data set that will be analyzed was collected on an off-road course, recorded at a comfortable walking pace, with the UGV operated conservatively.

2.3 Simulation Environment

To establish the efficacy of the ZMP index and demonstrate potential for implementation in semi-autonomous UGV systems, an experiment was performed. The experiment was conducted in a virtual simulation environment created in Gazebo. In this simulation, a world was built with a rough terrain containing hills and depressions. Walls were built to create a course that limited the operator to a particular segment of land surrounded by steep hills with a flat middle section (Fig. 2). The UGV in this experiment was teleoperated and equipped with a singular IMU. The goal of this experiment was to show that vehicle wheel lift could be forecasted accurately and rollover could be prevented given haptic alerts.

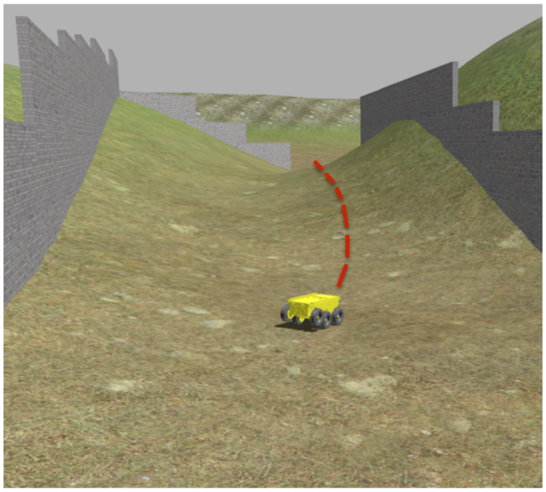

Figure 2: Gazebo simulated course used in human-participant experiment. The course contained steep hills to increase rollover likelihood, with walls to constrain the operator's path.

2.4 Simulation Experiment

The simulation experiment consisted of three tests conducted in a Gazebo simulation along with one human participant in a protocol approved by Auburn University IRB Protocol #21-262 EP 2106. The goal of this experiment was to test the efficacy of the ZMP algorithm in a real-time application and to evaluate how operator intervention can prevent rollover. The UGV was teleoperated with a controller enabled with haptic capabilities.

The experiment consisted of three tests. The first was a baseline test, where the operator was given full line of sight of the UGV while completing the course, without haptic feedback. This scenario simulated a perfectly aware operator, without any distractions. The next test removed the operator's visual feedback of the UGV. This was designed to simulate the opposite end of the spectrum: a scenario where the operator had no visual feedback. Without haptic feedback or sight, the operator would be unable to perceive that the UGV was in a compromised state. Rollover events in this case demonstrate that the simulation course has sufficient terrain to cause vehicle rollover without operator feedback. The third test provided the operator haptic feedback, but limited view of the UGV. This was to simulate a scenario in which the operator's attention is divided amongst more pressing tasks, such as those present in real world military applications. The operator can remain confident that the UGV is in a safe configuration, with confidence that the HFD will provide an alert if the vehicle shows signs of rolling. An illustration of the three tests conducted can be seen in Fig. 3.

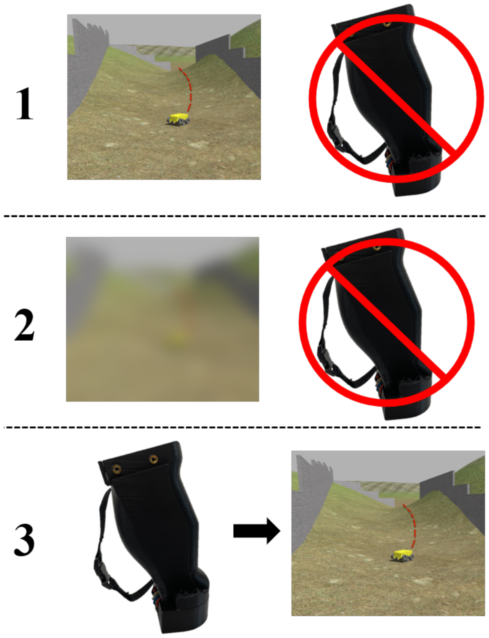

Figure 3: Row 1 represents test 1 in which the operator was given full visual contact of the UGV with no haptic feedback. Row 2 represents test 2 in which the operator had neither visual nor haptic feedback. Row 3 represents test 3 where the operator was not given visual contact of the UGV until haptic feedback was received.

The HFD used in the experiment relies on a squeeze sensation provided by a strap that surrounds the operator's fingers, actuated through a direct fabric spooling mechanism, which can be seen in Fig. 4.

Figure 4: Haptic Feedback Device provides squeeze stimuli to the intermediate phalanges of the operator's fingers to provide clear, unambiguous alerts of vehicle state.

Squeeze sensations are used in haptics to convey low-fidelity, low-bandwidth information to users. In UGV applications, a squeeze sensation would avoid the discussed pitfalls associated with vibrotactile based haptics, while still sending a clear but discreet alert to the operator. Care was taken in the development of the HFD to ensure that the squeeze sensation was recognizable and consistent with that of commonly experienced sensations such as a handshake or the sensation of grabbing one's shoulder to get their attention. A smooth pressure distribution across the operator's medial phalanges, as illustrated in Fig. 5, was obtained through the design of a curved handle.

The pressure distribution along each finger for four different strengths of the HFD can be seen. The pressure perceived during a typical handshake is denoted on the graph, as well as the force output of a comparable haptic squeeze device [5]. It can be seen that the HFD provided more than triple the pressure output of a normal handshake. While the full pressure output of the HFD may not be typically required, this additional capability may be beneficial when communicating through gloves or in distracting, high stress environments. In general, it is not expected for the short duration squeeze forces to exceed interactions commonly found in everyday activities. To ensure safe operation during development, the HFD incorporates software e-stops as well as a buckle for rapid removal.

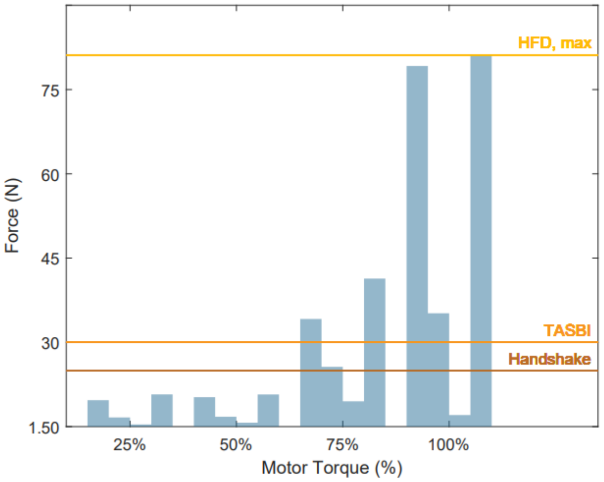

Figure 5: Pressure distribution as a function of torque output of the prototype HFD. At each ouput percentage, groups of four bars represent the four fingers, index, middle, ring, small respectively. While the experiments were conducted at 75% of the HFD's full capabilities to simulate the sensation of a firm handshake, the HFD is capable of producing far higher torques in necessary situations.

3. RESULTS

Firstly, the results of the IMU grade analysis are provided. It was found that implementing an attitude and heading reference system based on accelerometer and gyroscopic data was the most successful way to find roll angle. This allowed a quaterion orientation vector to be created based on the known sensor outputs, which was then converted to Euler angles and the x-component was used for the

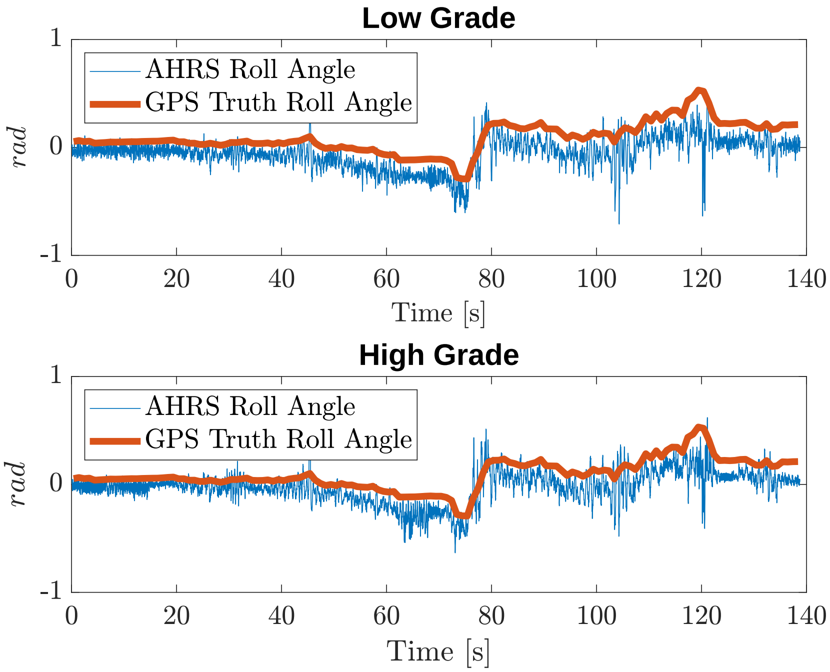

Figure 6: GPS roll angle compared to AHRS roll angle for a low and high grade IMU

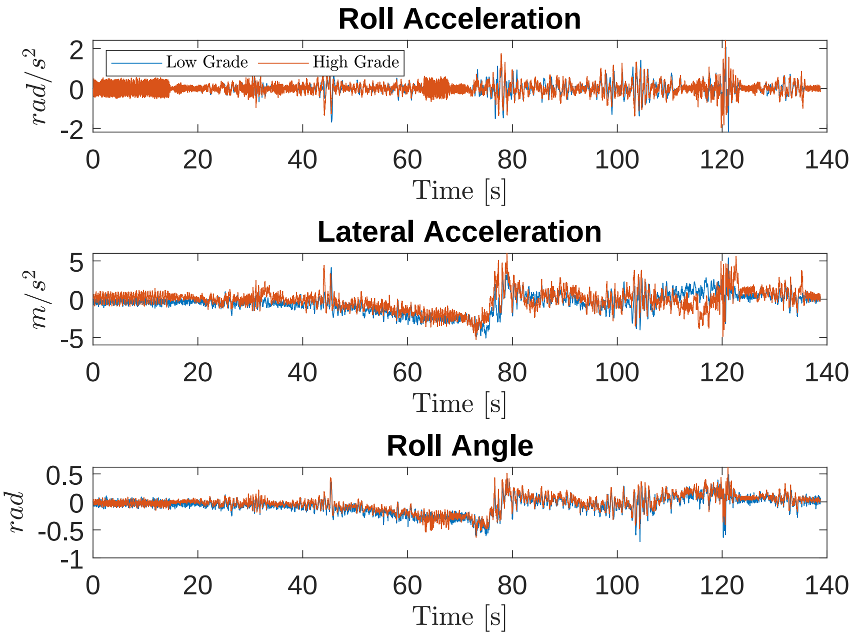

Figure 7: Low and high grade IMU sensor outputs.

roll angle. This method matched the shape and trend of the GPS "truth" roll angle and was used for both IMU analyses, as seen in Fig. 6.

These results show a very minimal difference in the gyroscopic performance of these IMUs when compared to GPS "truth". Once the roll angle was found to be a good match for the GPS truth, the roll acceleration, lateral acceleration, and roll angle outputs were plotted to compare between the high and low grade IMUs, as seen in Fig. 7. Once again, there was not too much of a difference for the outputs of the high and low grade IMUs. Both had similar noise characteristics and required similar filtering.

Next, these sensor outputs were passed through the ZMP index equation, along with the required vehicle parameters, to record the wheel lift-off likelihood throughout this data set. As this data set could be characterized as having low dynamics, it was not expected for the ZMP index to record any instance of high wheel lift-off probability, as seen in Fig. 8. The trend of similar performance continues as the trend and spikes of the respective IMU outputs match once again.

Next, the simulation experiment results will be analyzed. The three tests were analyzed in terms of the number of wheel lift-off events. The first test from the experiment allowed the operator both complete sight and haptic feedback to finish the course without achieving wheel lift-off. With full sight the operator was able to select the flattest part of the course to finish safely, as seen in Fig. 9. Noise from the IMUs can be observed, along with an outlier as minimal filtering was done to the measurements to preserve the raw data. A moving mean with a 0.02 second window was also plotted to better observe trends and to mimic what further filtering of the measurements could accomplish.

The second test from the experiment had the operator attempt to complete the course again, this time without sight or haptic feedback. This simulates a scenario where line of sight to the UGV is severely disrupted. From the results, one can see that wheel lift-off occurred multiple times and the UGV was put in a vulnerable position for about one half of the data set, as seen in Fig. 10. From this data set it is very likely that the UGV experienced rollover.

The third and final test from the experiment had the operator attempt the same course with the simulation screen hidden from sight. However, the operator was able to receive haptic feedback. Once a squeeze was provided from the HFD, the operator knew that the UGV was in a compromised position and was allowed to see the simulation screen. As soon as the operator felt confident that the UGV was once again in a safe position, the simulation view was hidden. From the results, the squeeze was triggered once, and the operator was quickly able to adjust the UGV's position and rollover was avoided, as seen in Fig. 11.

4. DISCUSSION

The results of the data analysis would suggest that IMU grade is not directly proportional to accurate wheel lift-off prediction. The limits of this finding will need to be explored with more experimental data, but preliminary results would suggest that, for this application, a high grade IMU is not required to get an accurate estimate of wheel lift-off likelihood. There are many benefits to using a low grade IMU in this application, such as lower cost and the high availiability of consumer grade IMUs. One may expect that a higher grade IMU would out-perform a cheaper sensor, but these results suggest this is not always true. However, more data is required to make a definitive conclusion.

From the simulation experiment, the trends seen in both the raw likelihood and the moving mean of each plot reveal interesting insight into operator tendencies. When paying full attention and with haptic feedback available, the operator is able effectively prevent rollover.

The second and third tests depict a scenario where the operator has lost sight of the UGV. With the HFD, the operator was able to receive a squeeze

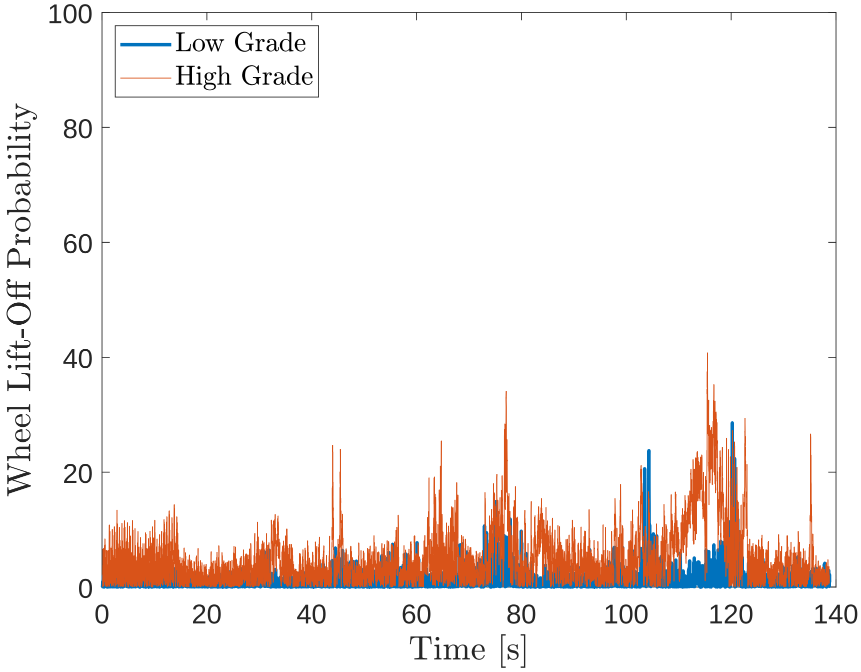

Figure 8: Wheel lift-off likelihood output based on a low and high grade IMU.

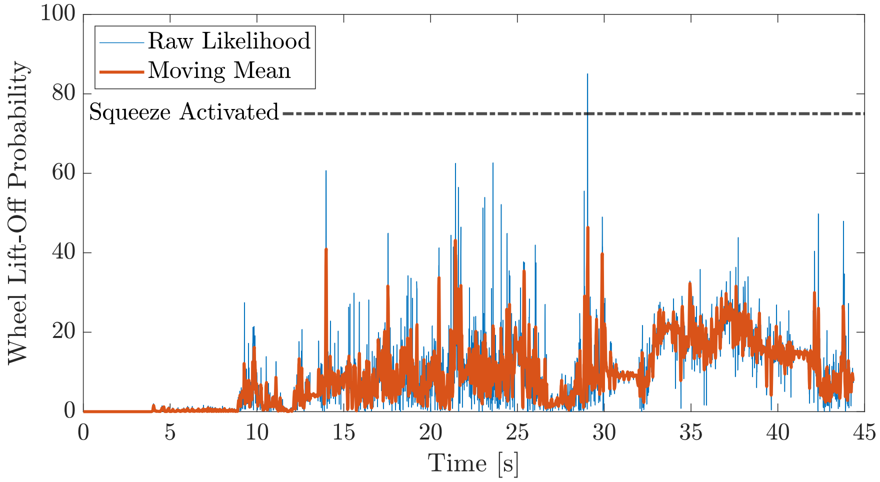

Figure 9: Test 1 Result: the operator was given full visual contact of the UGV and no haptic feedback.

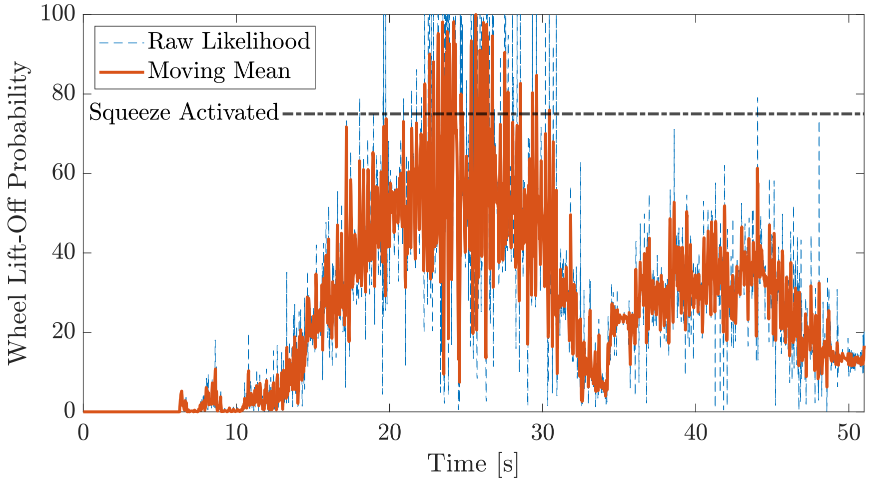

Figure 10: Test 2 Result: operator had neither visual nor haptic feedback.

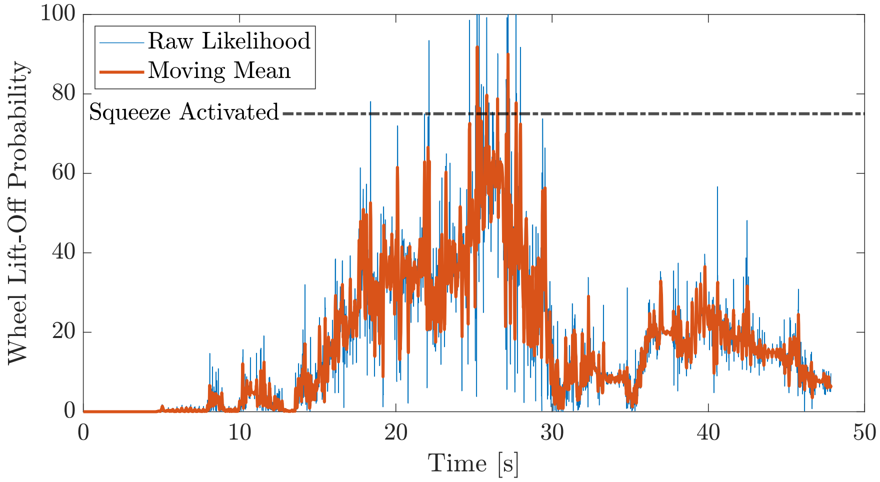

Figure 11: Test 3 Result: operator was not given visual contact of the UGV until haptic feedback was received.

warning, refocus attention to the simulation, and correct the UGV's course towards safer ground. Without the HFD, the operator remained unaware that wheel lift-off had occurred continuously for about one third of the test. Keeping the UGV in this vulnerable state without correction will cause rollover.

In all of these tests, the HFD provided only a single squeeze cue to the operator. Future work will investigate the impact of a range of stimuli, potentially scaling linearly or exponentially with ZMP indexing to help operators prevent rollovers.

5. CONCLUSION

From the results, it can be suggested that the ZMP index is capable of identifying wheel lift-off in both post-process and real-time applications. It is effective at predicting wheel lift-off when a vehicle model is unknown, basic vehicle parameters are not confidently known, and with varying grades of IMU.

It can also be suggested that when an operator has access to haptic feedback, rollover can be prevented, even with poor line of sight. The results suggest that the ZMP index and HFD are successful at preventing rollover when working in unison.

6. ACKNOWLEDGEMENT

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