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OSPREY:
A mmWave Approach to Tire Wear Sensing

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Tire wear is a leading cause of accidents. Tire wear is measured either manually, or by embedding sensors in tires, or using off-tire sensors. Manual sensing is extremely tedious. Sensors embedded in tire treads are challenging to design and expensive to embed. Off-tire sensors like laser range finders are prone to debris that may settle in grooves. To overcome these shortcomings, we propose a mmWave radar based tire wear sensor, which is easy to install, and continuously provides accurate and robust tire wear measurements even in the presence of debris.

Today, with the increasing amount of people commuting from one place to another and with the advent of autonomous driving, safety and performance of automobiles are extremely important. Automobiles are being loaded with sensors so that they are aware of themselves and their surroundings. As a step towards this, our interest is in ensuring that the automobile is aware of its tires. Sensing tires is important because they are the only parts that actually touch the terrain. Any terrain impact can be sensed by measuring and monitoring the health of the tire. While tire pressure monitoring systems (TPMS) have become pervasive today, they are only concerned with monitoring issues related to tire pressure, such as underinflation, overinflation and blowouts. Several other terrain impacts like tire tread degradation, accumulation of harmful foreign objects in the grooves (e.g., nails, large stones), and deformation due to load and terrain, which are crucial for ensuring safety [1] and achieving performance efficiency, [2] often go unnoticed. Our focus in this work is in measuring and monitoring tire wear.

Tire tread degradation makes the vehicle lose traction with the terrain. In the event of loss in braking efficiency or unanticipated weather conditions like rain and snow, this might cause a driver to lose control of the vehicle completely. There exist laws [3] to ensure safety by making it illegal for drivers to use bald, worn-out tires. Accurate sensors monitoring tire wear and enforcing such laws automatically, create a much safer environment. While tires wear down slowly, for trucks which travel hundreds of kilometers each day, effects of tire wear are more prominent. An accurate tire wear

Photo, istockphoto.com

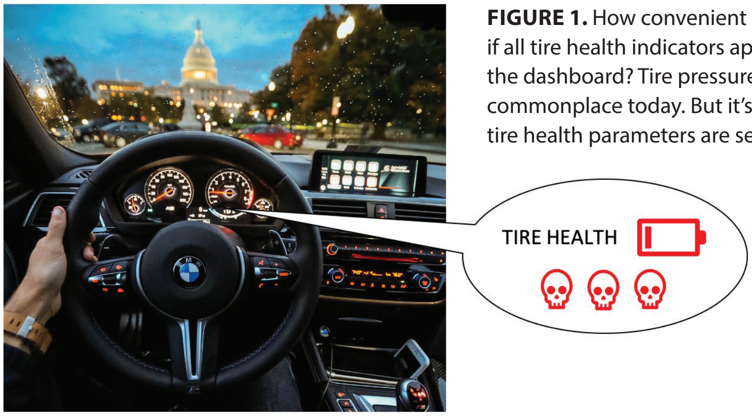
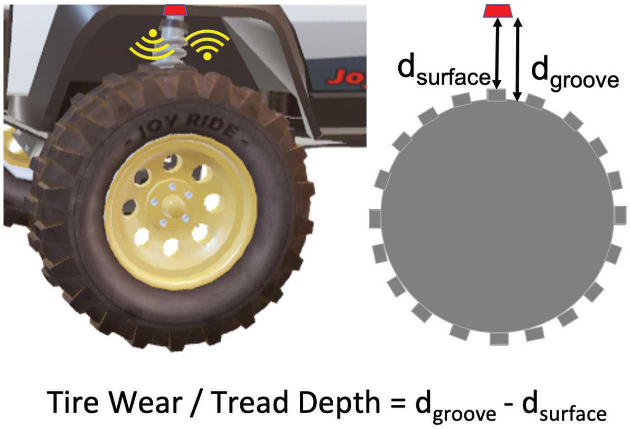


FIGURE 1. How convenient would it be if all tire health indicators appeared on the dashboard? Tire pressure sensors are commonplace today. But it's crucial that other tire health parameters are sensed as well.

FIGURE 2. Osprey mounts automotive mmWave radar in the tire well, observes reflections from the tire surface and estimates tread depth.



sensor would help tracking fine grained changes in tire wear, thereby helping run truck fleet operations, such as planning tire maintenance and replacing/retreading tires in a more efficient manner. It also opens up opportunities like creating an economically viable leasing model for trucks. With benefits ranging from passenger cars to trucks, we believe that it is imperative to measure and monitor tire wear continuously in all automobiles, just as we monitor tire pressure with TPMS today.

The commonly used approach to measure tire wear is by visual inspection or by sticking a ruler in the groove and reading the depth, which is fairly inconvenient to perform frequently and periodically. From the perspective of safety, we would ideally want tire wear measurements to be recorded regularly. Past sensor solutions, [4] which design electronic tire wear sensors to be embedded in treads are challenging to design given the extreme temperatures, pressures and dynamics of tires and they are expensive to embed, as existing assembly lines would need modifications. For this reason, many of the state-of-the-art systems measure tire wear indirectly using TPMS readings and models of tire dynamics [5]. While TPMS is an easy to mount sensor on the inner lining of tires, indirect measurements from it are prone to large errors. Moreover, off-tire solutions, such as laser rangefinders or laser scanners, which can generate high resolution images of tires provide useful information only when tires are clean. They easily experience errors due to accumulation of debris in grooves. A practical tire wear sensor would be one that is easy to install, provides accurate and continuous measurements in a convenient way and is resilient to the accumulation of debris.

In our quest to design such a sensor, we realize that the tire wears down at very fine scales. Hence, we think of off-tire solutions (easy to install), which are as accurate as lasers but are resilient to debris. Radio signals are known to penetrate debris. In order to image/range like a laser using radio signals, we need signals with huge bandwidth, narrow beamwidth or hardware with precise time resolution. As one goes to higher frequencies in the electromagnetic spectrum, wide bandwidths are allocated for communications and sensing. Compared to the popularly known lower frequency radio technologies like Wi-Fi and RFID, millimeter wave (30 - 300 GHz) bands provide the widest of bandwidths and narrower beamwidths – ideal for accurate imaging/ranging. Incidentally, mmWave radars, which generate signals with huge bandwidths, are commonplace in the automotive industry as collision detection radars and cruise control systems. Moreover, unlike their ultrasonic ranging counterparts, mmWave radars benefit from the ability to transmit more frequently, which is critical for dealing with high speed tire dynamics.

Our solution, a joint collaboration with Bridgestone, *Osprey*, is a sensor system design built on top of commercial automotive mmWave radars. We install the radar in the well of the tire (see Figure 2), process the radar's signals, and extract precise locations of the surface and groove of the tire. Tire tread wear is then estimated as the difference between the surface and groove locations. Exploiting mmWave signals and the already pervasive mmWave radars, our solution provides easy to install, accurate and robust tread depth estimation. The following are two main challenges in making our system practical.

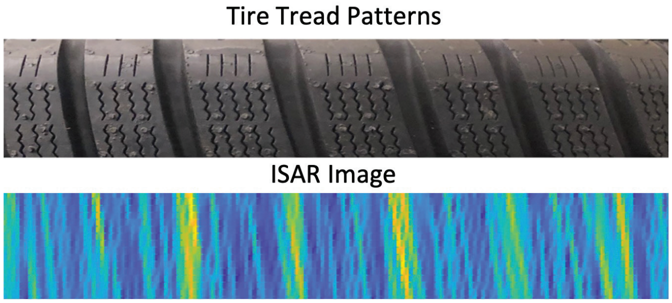


FIGURE 3. An ISAR image reveals the characteristic tread pattern found on tire surfaces.

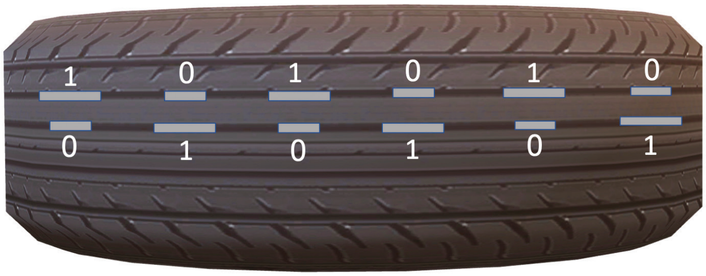


FIGURE 4. Osprey combats debris by laying aluminum strips in the groove, which emulate a spatial code. Different grooves have different coded bit patterns encoded using pulse width modulation.

Insufficient resolution: Tire tread depths vary all the way from 20 mm for brand new trucks to 2 mm for completely worn out tires at the legal limit. State-of-the-art automotive mmWave radars, with 4 GHz of bandwidth, provide a range resolution of 3.75 cm and beamwidth of about 15 degrees. The spatial separation between surface and grooves are much smaller compared to the resolving capability of the best automotive radar. This would mean that straightforward processing of radar signals results in reflections from the surface and groove would be indistinguishable, leading to erroneous tread depth measurements.

Debris resilience: In the presence of debris accumulated in the groove, while radar signals penetrate the debris and reflect off of the groove, because the locations of the debris and groove are spatially close, the radar fails to distinguish between reflections from debris and groove. This results in corrupt estimates of the groove's depth.

In the following section, we describe our system and how we tackle these challenges.

SYSTEM DESIGN

At a high level, our system gathers multiple radar signals as the tire rotates, and processes all of them to yield a super high resolution image of the tire surface, from which we filter out the effects of debris, and then obtain the locations of the tread and the groove.

TIRE SURFACE IMAGING

Traditionally, obtaining high-resolution radar images requires scanning a target with a large array of antennas that span a wide length or "aperture." While we can't afford to mount a gigantic radar in the tire well/move the radar, we exploit the fact that the tire, our target, rotates naturally. Our approach is based on the concept of Inverse *Synthetic Aperture Imaging* (ISAR), traditionally used in aircraft radar imaging. This technique combines recordings of the signal that the radar captures as the tire moves to emulate a large aperture and obtains a fine-grained image of the tire surface. Our complete algorithm models the effects of vehicular dynamics, such as speed, suspension, automobile body vibrations, and wheel misalignment, all of which are detailed in [6].

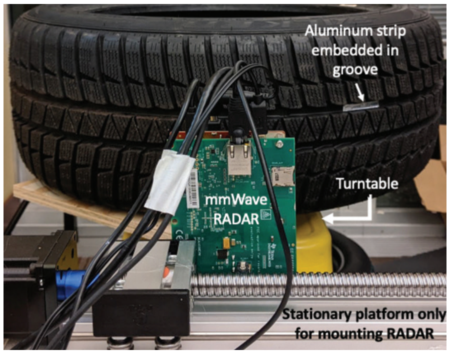


FIGURE 5. Osprey was evaluated on a rotation rig. The tire is seen mounted on a turntable at a distance similar to that of a tire well.

DEBRIS RESILIENT GROOVE RANGING

To avoid confusion between the groove and the debris reflections, Osprey places metallic strips in tire grooves in specific coded patterns (see Figure 4). The objective of this is to enhance the reflectivity of grooves over and above the debris grooves. This way, detecting patterns at a location tells us that the grooves are at that location. Aluminum strips are cheap, laying them in grooves require no modification to manufacturing processes as they are laid on the surface, and are twice as reflective as other materials [6]. To maximize reflectivity of the coded patterns, we encode both 1 and 0 with metallic structures. Since many tires have circumferential grooves, the structures are pulse width modulated and the code is laid along the circumference like a 1D barcode. Specifically, we use Optical Orthogonal Codes [7]. We choose our codes to be robust to bit flips from heavy debris accumulated at one specific region in the groove, improving debris resilience overall. Once the tread and groove are identified in the ISAR image, one can read off and subtract their respective distances from the center of the tire to obtain tread depth.

FOREIGN OBJECT DETECTION AND LOCALIZATION

In addition to tread depth sensing, our algorithm's principles, which lead to creation of ISAR image, also help in detecting harmful foreign objects and localizing them. Early detection can help avoid fatal tire problems. Foreign objects include stones, nails/sharp metallic objects, ice, sawdust, etc.

Intuitively, foreign objects can be detected when their presence affects the coded-metallic structures causing bit flips or their presence creates an unexpected bright patch on the magnitude of the ISAR image. Once detected, their position on the tire is obtained by reading off the pixel coordinates of the image. We further train classifiers to distinguish if an ISAR image contains a harmful object (nails/metallic objects) or non-harmful (stones, ice, sawdust) and alert the user accordingly.

FIGURE 6. Osprey was evaluated in the wild on a passenger car. Osprey's hardware is shown to be mounted on a 2019 Honda Odyssey.

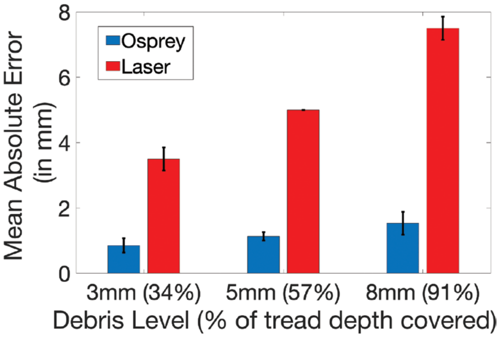


FIGURE 7. Osprey is robust to accumulation of debris in grooves.

SYSTEM EVALUATION

We implement Osprey on the 77-81 GHz automotive radar - TIAWR1642BOOST. We interface the radar with DCA1000EVM, an FPGA board which streams raw I/Q samples to the computer running the algorithm.

We build a tire rotation rig (see Figure 5), similar to a rig used to test tire performance, using stepper motors that allow reliable speeds up to 5.45 kmph of the tire. We also evaluate our system on a 2019 Honda Odyssey (see Figure 6) and test for different vehicle dynamics. We test our system on tires with diverse tread patterns: Falken Eurowinter HS449 and Bridgestone Blizzak LM001. While we present exhaustive evaluation of our system for different speeds of rotation, debris types, intensities of vehicular vibrations, terrain types and for foreign object localization and classification [6], here, we only describe one crucial result regarding accuracy in the presence of debris.

In a tire with off-the-shelf tread depth of 8.75 mm, the groove is filled with sawdust with different trials covering the metallic code structures partially or completely, and different levels of debris from 34% to 91%. The ground truth tread depth is obtained using a digital Vernier caliper. The performance of the system is compared against the output of a Bosch GLM40 laser range finder. We show (see Figure 7) that while the laser's error increases proportional to increasing debris level, Osprey's output remains robust with a maximum absolute error of 1.53 mm, which occurs when the groove is almost completely covered in debris. This shows Osprey's resilience to the accumulation of debris.

CONCLUSION

We introduced the sensor system design for an easy to install, accurate and robust tire wear monitoring. This sensor paves the way for a future with safer driving and running tire operations more efficiently. Some of the limitations of our design include the use of debris-resilient metallic structures in grooves. While they are easy to embed in grooves and do not touch the terrain, it is possible that they peel off or affect the flow of water in grooves. We identify the possibility of reusing steel belts already present in tires to serve as resilient markers. We also envision scenarios in which radio reflective paint is coated in grooves to provide debris-resilience. Beyond tire wear sensing, the principles behind our sensor design are extensible for monitoring the wear and tear of other abrasive surfaces, such as paint on aircraft or anti-fouling systems in ships. ■

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