Social Challenge: Advanced Sensing Technologies for the Infrastructure

Developing an Intelligent Tire Concept

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One of the capabilities that can potentially advance the use of Intelligent Transportation Systems in the Complex Networks and Complex Systems area of Critical National Needs is the Intelligent Tire Concept. Although there have been progress made in the area of intelligent transportation over the past decade and the subject has been researched by various organizations in the US and abroad, one of the key enabling technologies, namely intelligent tire, has not received as much attention. Without the capacity to be able to estimate, at low cost, tire load, slip angle, friction, and forces, the implementation of the technologies that will emerge as a result of the intelligent transportation research will be too costly to implement. This is only possible through developing an intelligent tire concept with sensors embedded in the tire that will provide the needed information to the chassis control systems onboard vehicles of different size and to provide load data for the trucks as they move along the road through their GPS system without the need to stop at the weigh stations across US therefore eliminating the need for these stations. This technology will have a profound effect on transportation safety as well as infrastructure.

A vehicle's interaction with the road surface initiates at the contact patch of the tires. This small patch dictates the resulting motion of the vehicle and is a major governing factor of the vehicle's stability and control, especially under severe maneuvers. This relationship makes it desirable to know the coefficient of friction between the tire and road surface. For most drivers this is not something that they know about as long as the vehicle progresses in the path intended by the driver. However, when the vehicle does not respond to drivers commands as expected, the safety on the driver and passengers of the unstable vehicle as well as other vehicles in its path are jeopardized. This brings up the social challenge that requires helping and protecting those people using the transportation system that are placed in harm's way by others. This work proposes a method to estimate the coefficient of friction, vehicle speed, tire pressure, and tire load through direct measurement of the tire as it interacts with the road surface. In this respect, the coefficient of friction, vehicle speed, and tire load will all be used in the advanced chassis control systems that are being developed under the Intelligent Transportation Initiative. This will enhance the performance of such systems to a great extend [11]. The load can also be used to estimate vehicle weight and report that via GPS to a central location. In case of an overloaded passenger vehicle or a minivan, truck, or van, the driver can be alerted that the tire load capacity has reached its limit and action should be taken. In case of a commercial vehicle, the weight estimated on each wheel will be averaged to produce an estimate of the vehicle weight which can be broadcasted to a central location hence providing valuable information to the State and eliminating the need for weigh stations.

Background

Since its mass production a few decades ago, tires have always been passive elements which play a crucial role in vehicle safety and stability. Although the science of tire compounding, design, and manufacturing has grown tremendously, its inclusion as part of the vehicle chassis control system has lagged all the other subsystems. In order to be able to provide the much needed tire road contact characteristics to the chassis control designer, it is required that the tire becomes part of the intelligent system that provides the information to the controller. One approach in accomplishing such a complex task is to combine modeling, instrumentation, testing, signal processing, and algorithm development. This research aims at developing such technology.

In the field of intelligent tire systems, Tire Pressure Monitoring Systems (TPMS) have been the first products introduced in the market. The first patent for the system appeared in 1985 [12]. Since then, several systems were introduced in the market [13-14]. This development was mainly driven by vehicle manufacturers. The basic functionality of a TPMS is to monitor tire inflation pressure and temperature. The range of available solutions and products comprises various indirect and direct systems as well as simple or sophisticated means for the relevant driver information. The direct TPMS are using RF technology for transmitting sensor data to the vehicle and they are powered by batteries. Most direct TPMS are installed at the rim or attached to the valve.

Although TPMS systems provide a new level of safety, they lack essential information regarding the state of the tire road contact characteristics. Continental Tire, the German tire manufacturer, introduced the side wall torsion sensor (SWT) in 1999 [15]. The SWT sensor allows measurement of the tire sidewall deformation and estimation of forces acting at the tire-road contact. As a result of this more precise information about the driving states of the tires can contribute to further optimization of the electronic vehicle stability control systems.

Another innovative application in the field of intelligent tire technology is the sensor system developed by the researchers in Darmstadt University of Technology, Germany. In this invention a magnet is placed inside the tire tread block and the movements of this magnet are monitored by a Hall-sensor [16].

The Apollo Program [17-18] started in 2002 in Finland and concluded in 2005 that the tire intelligence is necessity for vehicle active safety systems of the future. They developed a self energized light-based sensor. Their results showed that the possibility exists to predict tire characteristics based on sensors embedded in the tire.

However, the technologies described above are not equipped to sense and transmit high speed dynamic variables used for real-time active safety control systems. In order to accomplish such a task, a more complex data processing and intelligent algorithms are required.

In [19], the authors present a distributed architecture for a data acquisition system that is based on a number of complex intelligent sensors inside the tire that form a wireless sensor network with coordination nodes placed on the body of the car. Although this complex system is not practical for implementation, it provides a good framework for understanding the complexities involved in developing such practical technology.

In addition to direct sensor data manipulation and algorithm development to characterize tire road contact, many procedures have been developed which make use of the existing control and sensory architecture that is used by various chassis control systems such as anti-lock braking system and electronic stability system [20-27]. Although these methods present a relatively accurate solution, they rely heavily on tire and vehicle kinematic formulation and break down in case of abrupt changes in the measured quantities.

Road-traffic injuries still represent the leading cause of injury-related deaths with an estimated 1.2 million deaths worldwide each year [28]. In order to help the situation, the original equipment manufacturers and suppliers have implemented active safety systems. These systems use information about the external environment of a vehicle to change its behavior in pre-crash time period or during the crash event, with the ultimate goal of avoiding a crash altogether. Early work on active safety systems were primarily focused on improving the longitudinal motion dynamics, particularly on more effective antilock braking systems and traction-control (TC) systems. TC systems prevent the wheel from slipping while improving vehicle stability and control by maximizing the tractive and lateral forces between the vehicle’s tire and the road. This was followed by more powerful vehicle-stability control (VSC) systems, e.g., electronic stability program, VSC, and dynamic stability control. These systems use both brakes and engine torque to stabilize the vehicle in extreme handling situations by controlling the yaw motion. The active safety control systems described are based upon the estimation of vehicle dynamics variables such as forces, load transfer, actual tire–road friction (kinetic friction) μ_k, and maximum tire–road friction available (potential friction) μ_p, which is probably the most important parameter for the improvement of vehicle dynamic control systems [29]. The more accurate and “real time” the parameter estimation is, the better the overall performance of the control system. Currently, most of these variables are indirectly estimated using onboard sensors. With a more accurate estimation, we could even identify road-surface condition in real time. By detecting the change in the slope of the friction versus slip curve, regions of slippery surface can be identified [29], [30].

The solution that is sought for in this research combines many facets of science and engineering and builds on some of the existing technologies and develops an intelligent tire concept through use of sensors, Neural Networks, Fuzzy Systems, and Kalman Filters. In particular, this solution will have a dramatic effect on automobiles, particularly when considering safety.

Challenges

Although the research outlined in this white paper will require that sensors be implemented in the tire, after the initial research where we plan on attaching the sensors to the inner liner of the tire using various techniques that has already been developed, the real challenge in implementing such technology in production tires can be categorized as follows. 1) the most challenging task which requires collaboration with a tire company is placing the sensors in the "green" tire to be cured at high temperatures. This requires a sensor design that can withstand extreme temperatures and can operate when cured into the tire. 2) the sensors must be small enough (micro) not to cause any uniformity problems as the tire rotates at high speeds. Non-uniformity in a tire is the number one cause of discomfort for the driver and passengers and must be avoided at all costs. 3) the system power usage requirements must be understood and researched prior to finalizing a sensor design. The system must use an energy harvester which in addition to providing power to the batteries, it will house the sensor.

References

1. Taheri, S., "Intelligent Tire Phase I Report", Goodyear Tire and Rubber Company, December 2009.
2. Taheri, S., "Intelligent Tire Phase 2A Report", Goodyear Tire and Rubber Company, May 2010.
3. Taheri, S., "Intelligent Tire Phase 2B Report", Goodyear Tire and Rubber Company, August 2010.
4. Hopkins, B., Fox, D., Caffee, J., Sides, B., Burke, W., Craft, M.J., and Taheri, S., "Construction and Operational Verification of a Medium Duty Truck Tire Force and Moment Testing Trailer Suitable for On or Off Road Use," Tire Society Meeting, Akron, OH, 2009.
5. Tamaddoni, S. H., Taheri, S., and, Ahmadian, M., "Dynamic Game Theory Application in Vehicle Driver-In-The-Loop Direct Yaw Control" Journal of Vehicle System Dynamics, 2009, (accepted).
6. Ding, N., and Taheri, S., "An Adaptive Integrated Algorithm for Active Front Steering and Direct Yaw Moment Control Based on Direct Lyapunov Method," *Int. J. of Vehicle System Dynamics*, 2009, (accepted).
7. Taheri, S., "A Simple ABS Control Algorithm," *ASME J. of Dynamic Systems, Measurement, and Control*, 2008, (accepted).
8. Hopkins, B. and Taheri, S., "Rollover Mitigation Control Algorithm Development for Military Trucks," *Int. J. of Vehicle Design*, 2010, (accepted).
9. Singh, K. and Taheri, S., "Energy Harvesting System for Next Generation Intelligent Tires with a Real Time Adaptive Control System for Optimized Power Output," Tire Society Journal, 2010 (accepted).
10. Ding, N., and Taheri, S., "A Modified Dugoff Tire Model for Combined-slip Forces," Tire Society Journal, 2009, (accepted).
11. O. Mokhiamar and M. Abe, "Simultaneous Optimal Distribution of Lateral and Longitudinal Tire Forces for Model Following Control," *ASME Transactions on Journal of Dynamic Systems, Measurement, and Control,* vol. 126, pp. 753-763, 2004.
12. *ASME Transactions on Journal of Dynamic Systems, Measurement, and Control*, vol. 126, pp. 753-763, 2004..
13. US-Patent 4,510,484 by Daniel S. Snyder, Apr. 9, 1985.
14. http://www.smartire.com
15. http://www.tiresmonitor.com.tw
16. Jim Gill, "Continental Teves and Team of Developers Working Hard to Ready 'Intelligent Tire' for Mass Production," *PRNewswire*, Aug. 24, 1999, http://www.prnewswire.com.

17. Breuer, B.; Bachmann, V.; Fach, M.: Future Car-Tires as Provider of Information for Vehicle Systems to Enhance Primary Safety. SAE Special Publication 1375, Society of American Engineers, Warrendale, USA, 1998.
18. Apollo Final Report “Intelligent Tyre for Accident-free Traffic”, The Apollo Consortium, IST-2001-34372, 2005.
19. Schrüllkamp, T., Goetz, H., and Husemann, T., “Development of an intelligent tire –experiences from the APOLLO project”, Intelligent Tire Technology Conference, Munich, Germany, 2005.
20. Sinem Coleri Ergen, Alberto Sangiovanni-Vincentelli, Xuening Sun, Riccardo Tebano, Sayf Alalusi, Giorgio Audisio, and Marco Sabatini, “The Tire as an Intelligent Sensor”, IEEE TRANSACTIONS ON COMPUTER-AIDED DESIGN OF INTEGRATED CIRCUITS AND SYSTEMS, VOL. 28, NO. 7, JULY 2009.
21. Rajamani, R.; Piyabongkarn, D.; Lew, J.Y.; Grogg, J.A*., “Algorithms for real-time estimation of individual wheel tire-road friction coefficients”,* American Control Conference, 14-16 June 2006.
22. RAY L. R, “Nonlinear tire force estimation and road friction identification: Simulation and experiments”, Automatica, vol. 33, n°10, pp. 1819-1833, 1997.
23. J. Matuško, I. Petrović, and N. Perić, “Neural network based tire/road friction force estimation”, Engineering Applications of Artificial Intelligence, Volume 21 , Issue 3 Pages 442-456, April 2008.
24. Canudas de Wit, C., Horowitz, R., “Observers for tire/road contact friction using only wheel angular velocity information”, 38th IEEE Conference on Decision and Control, Phoenix, USA.
25. Canudas de Wit, C., Tsiotras, P., “Dynamic tire friction models for vehicle traction”, 38th IEEE Conference on Decision and Control, Phoenix, USA.
26. Canudas de Wit, “A new model for control of systems with friction”, IEEE Transactions on Automatic Control. v40 i3. 419-425.
27. Chen and Chen, “Approximation capability to functions of several variables, nonlinear functionals, and operators by radial basis function neural networks”, IEEE Transactions on Neural Networks. v6 i4. 904-910.
28. Chen et al, “Approximation capability in c(r) n by multilayer feedforward networks and related problems” IEEE Transactions on Neural Networks. v6. 25-30.
29. World Health Organization, World Report on Road Traffic Injury Prevention, 2004.
30. S. Muller, M. Uchanski, and K. Hedrick, “Estimation of the maximum tire–road friction coefficient,” *Trans. ASME, J. Dyn. Syst. Meas. Control*, vol. 125, no. 4, pp. 607–617, Dec. 2003.