CPS: Small: Collaborative Research: Fault Diagnosis and Prognosis in a Network of Embedded Systems in Automotive Vehicles (Award ID: 0931956)

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The relentless competition among automotive companies and increasing demands from customers for driver assistance functions, dynamically-controlled safety systems, driving comfort and infotainment services in vehicles are creating mounting time-to-market pressures and, consequently, shortened development times. With the increased vehicle complexity and shortened development times, guaranteeing hardware-software integrity and, hence, vehicle performance has become a salient issue. This is because poor vehicle performance increases warranty costs to automotive manufacturers and maintenance costs to customers; these, in turn, result in customer dissatisfaction and in reduced competitiveness of US automotive industry. GM has identified the development of methods to enhance the reliability of embedded systems (i.e., hardware, software and interfaces) designed and implemented by different suppliers, and vehicle diagnostics and prognostics as key research challenges. The objectives of this collaborative project between the University of Connecticut (UConn) and the GM Research and Development R&D) are two-fold: (i) Develop an integrated diagnostic and prognostic (D&P) modeling framework for designing high-integrity heterogeneous network of embedded systems so that (hardware, software and interface) faults can be detected and isolated rapidly, and (ii) Investigate on-line and off-line inference methods for diagnosing faults and for predicting the remaining useful life of (hardware) components based on the inferred failing components and the various tracked paths of degradation. The latter methods can be embedded in the vehicle or accessed over a network. To achieve the objectives, our high-level approach is to identify the potential failure modes associated with software, hardware and HW/SW interfaces, develop functional dependency models between the failure modes of a network of embedded systems and the concomitant monitoring mechanisms (called "tests"), perform testability analysis, generate model-based failure modes, effects and criticality analysis (FMECA), and validate the diagnostic and prognostic inference methods via fault injection prior to deployment in the field.

We addressed the first objective by formulating an integrated D&P process for fault diagnosis and prognosis of embedded systems that combines data-driven techniques, graph-based system-level functional dependency models and mathematical/physical models (for components with well-understood dynamics). A regenerative braking system (RBS) in hybrid electric vehicles is selected as the target system for experimentation with the proposed D&P framework. This is due to its complexity, and the need for the interaction among multiple subsystems, electronic control units (ECUs) and the controller area network (CAN) bus. We developed a Simulink®-based RBS model using the Powertrain System Analysis Toolkit (PSAT), a vehicle simulation software tool and segregated it into multiple ECUs and hardware components. The ensuing model consists of a driver model, a physical system model and six ECUs, namely battery control unit, engine ECU, motor1 control unit, motor2 control unit, mechanical brake control unit, and powertrain controller. The communication between the ECUs is carried out via signals on a simulated CAN bus using the Vector CANoe software (ECU network development, testing, and analysis tool). We have also categorized the faults in the regenerative braking system into parametric, sensor and network faults; and simulated 12 faults (8 sensor faults and 4 parametric faults). In the third year of the project, we plan to simulate network faults, design tests to detect the faults, generate dependency models between failure modes and tests, and validate our diagnostic and prognostic inference algorithms.

We addressed the second objective by designing inference algorithms suitable for coupled systems with delays. We have made four novel contributions. The first contribution addressed the problem of diagnosing coupled faults (coupled fault diagnosis) in complex cyber-physical systems, such as automotive systems where failure of one component (either hardware or software) may probabilistically trigger the malfunctioning of another component. The formulation involves a mixed memory Markov model within a factorial hidden Markov modeling formalism to represent coupled fault dependencies. The second contribution formulated and solved the dynamic set covering (DSC) problem, a series of set-covering problems that are coupled over time, using Lagrangian relaxation and a Viterbi decoder-based algorithm. The objective of the DSC problem is to infer the most probable time sequence of a parsimonious set of faults that explains the observed test outcomes over time. The novel feature of the DSC problem is that the test outcomes may be observed with time delays induced by network transmission and sensor processing delays. The third contribution is a delay dynamic coupled fault diagnosis algorithm (DDCFD) to deal with the problem of coupled fault diagnosis with fault propagation/transmission delays and observation delays with imperfect test outcomes, a realistic representation of practical networked embedded systems. We proposed two methods to solve the problem: Partialsampling method and a method based on block coordinate ascent and the Viterbi algorithm. Finally, we have formalized a unified data-driven prognostic framework that combines failure time data, static parameter data and dynamic (time-series) data. The framework employs Cox proportional hazards model and soft dynamic multiple fault diagnosis algorithm to infer the degraded state trajectories (complementary survival functions) of components and to estimate their remaining useful life. We also implemented a moving horizon estimation algorithm based on constrained nonlinear optimization techniques for real-time prediction of the component survival functions.

Journal Publications

- [1] A. Kodali, K. Pattipati, and S. Singh, "A Coupled Factorial Hidden Markov Model (CFHMM) for Diagnosing Coupled Faults", submitted to *IEEE Transactions on Systems, Man, and Cybernetics: Part A*, Jan 2011.
- [2] A. Kodali, S. Singh, and K. Pattipati, "Dynamic set-covering for real-time multiple fault diagnosis with delayed test outcomes", submitted to *IEEE Transactions on Systems, Man, and Cybernetics: Part A*, Jan 2011.
- [3] A. Kodali, S. Singh, K. Choi, and K. Pattipati, "Diagnostic ambiguity and parameter optimization in dynamic fusion of multiple classifier systems", submitted to *IEEE Transactions on Systems, Man, and Cybernetics: Part C*, 2011.
- [4] S. Zhang, K. Pattipati, Z. Hu, X. Wen, and C. Sankavaram, "Dynamic Coupled Fault Diagnosis with Propagation and Observation Delays", submitted to *IEEE Transactions on Systems, Man and Cybernetics: Part A*, 2011.
- [5] A. Kodali, Y. Zhang, C. Sankavaram, K. Pattipati, and M. Salman, "Fault Diagnosis in Cyber-physical Systems: Application to Automotive Electric Power Generation and Storage System (EPGS)", to be submitted, 2011.

Conference Publications

- [6] C. Sankavaram, A. Kodali, K. Pattipati, B. Wang, M. Azam, and S. Singh, "A Prognostic Framework for Health Management of Coupled Systems", IEEE International Conference on Prognostics and Health Management, Denver, CO, June 2011.
- [7] B. Pattipati, C. Sankavaram, K. Pattipati, Y. Zhang, M. Howell, and M. Salman, "Multiple Model Moving Horizon Estimation Approach to Prognostics in Coupled Systems", submitted to IEEE Autotestcon 2011.