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Implementation of Automated Vehicle Electrical and Electronic System based-on Cyber-physical System

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〈Abstract〉

As the automated vehicle system evolves, electronic devices and control software installed in vehicles are increasing. Therefore, automated vehicle electrical and electronic system (E/E system) design for ensure system integration, software modularization, system reusability, and scalability at the design stage of the automated vehicle is actively studied. This paper introduces a design methodology for automated vehicle E/E systems that employs by using cyber-physical systems (CPS). An automated forklift system was designed to examine the effectiveness of the proposed methodology. This paper showed that the proposed CPS design methodology enables an effective development of automated E/E control systems. Compare to existing design methodologies, it provides higher reusability of individual modules and an easier way to integrate control system elements such as controllers, sensors, and actuators.

Keywords : Automated vehicle, Cyber-physical systems, Electrical and electronic System, System design methodology

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1. Introduce

Future generations of intelligent cars equipped with automated systems have an increased number of electrical and electronic (E/E) devices, such as various kinds of controllers, sensors, and actuators [1]. Also, more than one hundred million lines of code are included in an automated vehicle system. As next-generation vehicles increasingly rely on a variety of E/E devices and embedded software, there are more design variables to consider. Major automotive companies and research organizations have been studying effective ways to design E/E systems for next-generation vehicles. In particular, a significant amount of research has been devoted to studying E/E systems for automated vehicles. Main research topics here are system integration, software modularization, and system reusability and scalability. Reinhardt et al. proposed a scalable E/E architecture for automotive systems by means of AUTOSAR technology and virtualization [2]. Axelsson studied cost estimation involving the architectural complexity of electronic control systems [3].

This paper introduces a design methodology for automated vehicle E/E systems that employs the mechanisms of cyber-physical systems (CPS) [4]. While traditional design methods create electronic control systems connected via wired and wireless networks, the introduced CPS design methodology builds a complex embedded system characterized by large numbers of tightly integrated cyber elements (e.g., control software and mathematical models) and physical elements (e.g., ECUs and actuators) in a network.

This paper consists of five sections including the introduction. Section 2 describes the concept of CPS based on networked control system and embedded systems for automated vehicle E/E systems. Section 3 and Section 4 state the experiments performed to evaluate the effectiveness of the proposed design methodology. An automated forklift is used as a test vehicle in the experiments. Finally, conclusions and future works are given in Section 5.

2. Cyber-Physical System Concept based on Networked Control System

A CPS [4] is composed of physical components, cyber components, and cyber-physical interfaces. Physical components are physical devices (or their states) that constitute a physical system in the real world, such as plants, system parameters, and physical links. Cyber-physical interfaces indicate devices that are linked to, and influence, cyber and physical components, such as sensors and actuators. Cyber components include all virtual devices that are neither physical elements nor cyber-physical interfaces, such as computational nodes, network links and routers, node

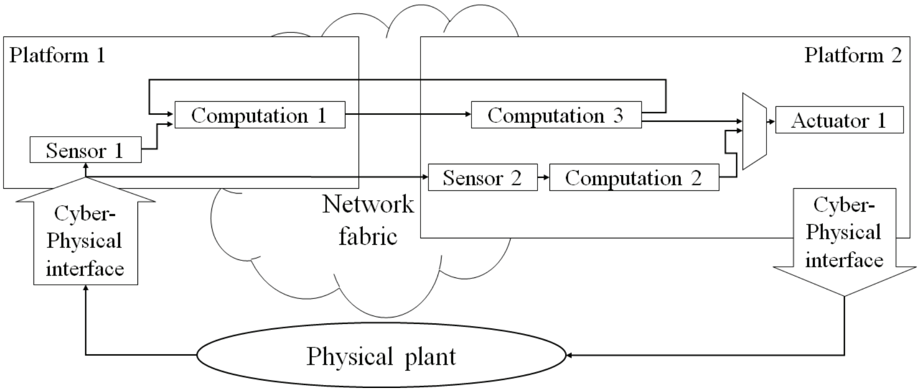


Fig. 1 The structure of a cyber-physical system based on networked control systems for automated vehicle E/E systems.

platforms and applications, modes, tasks, mode change logics, sensor and actuator ports, and input and output message ports.

Figure 1 shows the architecture of a CPS. An area in the CPS that is neither computerized nor digitally networked is called the physical plant. Machine parts, processes, and workers are included in this section. The CPS has more than one computational platforms, each of which consists of sensors, actuators, and computing devices. The CPS also has a network that connects multiple computational platforms. The computational platforms and network form the cyber elements of the CPS. Precisely, there are two networked computing platforms in Figure 1. The actions of the actuator influence the physical plant, which, in turn, influences the data collected by the sensors. In the figure, Platform 2 controls the physical plant using Actuator 1 and monitors the states of the physical plant using Sensor 2. Computation 2 computes the control rules and determines the control commands for Actuator 1 based on the data passed from Sensor 2. Platform 1 monitors the states of the physical plant using Sensor 1 and sends messages to Platform 2 over the network. Computation 3 computes additional control rules with the outputs of the preceding computational unit, Computation 2. The physical and cyber elements of the CPS make use of input and output information shared via the network in order to satisfy the requirements involving the entire system as well as the requirements of individual modules. The CPS can add various forms of virtual controllers, sensor, and actuators without affecting the existing physical system, which facilitates increasing system performance.

Although a lot of research efforts have been made to develop CPS-based design methods for E/E systems, standard models and methods suitable for large scale heterogeneous systems are not available yet [5]. Existing CPS design models are restricted

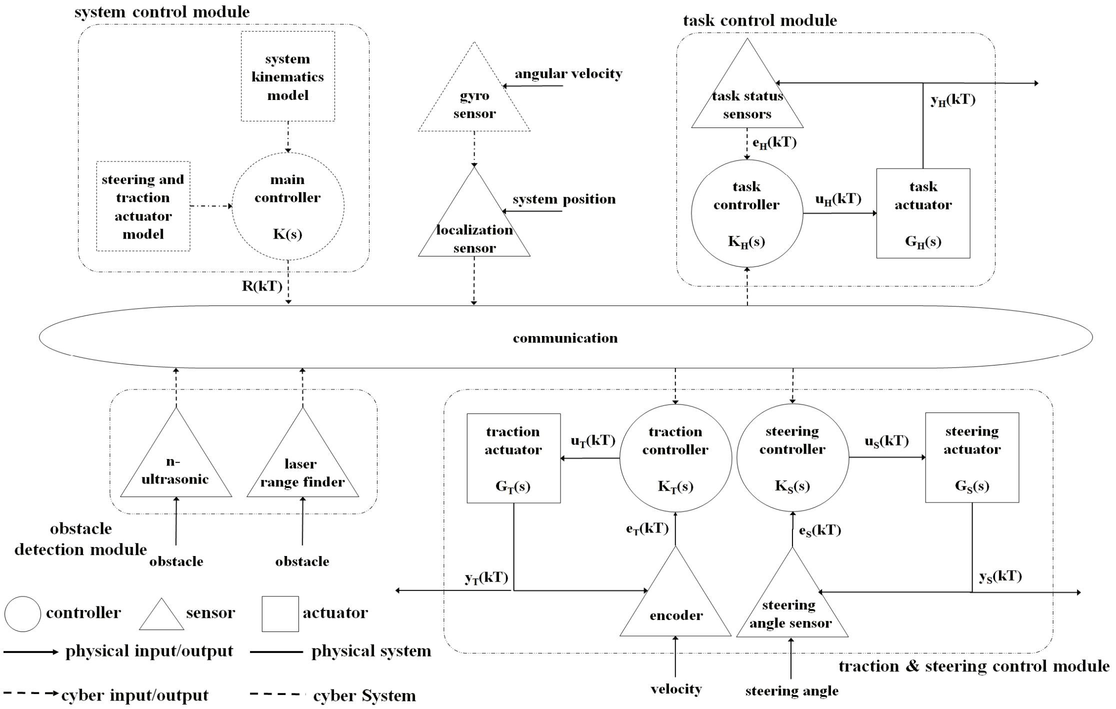


Fig. 2 Design architecture of an automated forklift system, an example of automated vehicle E/E systems consisting of sensors, actuators, and controllers.

to certain application domains, development environments, or theoretical settings. They are typically tailored to specific applications, and fail to fully cover diverse requirements and limitations in CPS. Thus, more research is required to develop universally applicable CPS models [6]. Unlike traditional embedded systems, CPS place greater emphasis on cyber elements. CPS also emphasize a holistic coordination of cyber and physical systems, so the design of such systems requires understanding the joint dynamics of computers, software, networks, and physical processes. In CPS, the interaction and interdependency between cyber and physical elements that are necessary to achieve the system-wide goals should be clearly defined beforehand, so the analysis, design, and verification of CPS are more difficult than those of previous embedded systems [7]. This stresses that CPS constitutes a new engineering discipline that demands its own models and methods.

3. System Design of Automated Vehicle E/E Systems for Forklift

Figure 2 presents the design architecture of an automated forklift system, an example of automated vehicle E/E systems consisting of sensors, actuators, and controllers. The functionality of the automated forklift was analyzed and divided into three modules: system control, obstacle detection, traction and steering control. In addition to the identified three modules, a special-purpose module called task control is included, thus producing a design with four function modules. A separate module for the position recognition function was not created because this function is relatively less important in this system. Note that the position recognition function is optional in automated vehicles while it is necessary for indoor autonomous robots. The designed modules incorporate software-based cyber elements and hardware-based physical elements, as can be seen in Figure 2. For example, the system actuator and kinematics models in the system control module are cyber elements. On the other hand, hardware-based controllers in the system are classified as a physical element.

The system control module is composed of the kinematics model, actuator model, and main controller. The main controller is a main cyber controller that controls the forklift based on the information about obstacles, tracking paths, and positions. The system kinematics and actuator models are cyber actuators, both of which aim at improving system performance. When a designer wants to replace the system actuator or he/she wants kinematic changes of the forklift, the kinematics and actuator models that are cyber elements are replaced or modified. The traction and steering control module is a sub-controller in a control hierarchy, and it is controlled by the main controller. This module is composed of physical actuators, sensors, and controllers. The task control module uses a physical sensor and actuator to perform the tasks. The task controller is made as a cyber controller so that it can be easily replaced or modified to fit different task contexts. The obstacle detection module includes physical sensors-an ultrasonic sensor and a laser sensor-commonly used in automated vehicle systems. For position recognition, a physical sensor for localization and a software-based gyroscope sensor for angular velocity measurements are added.

This system design for the automated forklift was created using the proposed CPS design methodology. First, the technical requirements of the automated forklift were analyzed for modularization, and then each of the required ECUs was designed by engineers in their respective fields. After that, a network that shares data between ECUs was designed. Finally, an integrated architecture for sharing information between ECUs was designed [8]. The next section describes the implementation of this design and the performance evaluation results of the implemented forklift system.

4. Implementation of Automated Forklift with E/E Systems

This section presents the results of the experiments performed using the implemented automated forklift system. A standing motor-operated forklift model, was used to build a test vehicle for this study, as shown in Figure 3. This 1.0-ton class electric forklift [9] has 4.2 kW AC traveling motor, 8.3 kW hydraulic motor, and 0.15 kW steering motor. Four wheels, two front wheels at both sides, a rear right castor wheel, and a rear left traveling and steering wheel (main wheel), are mounted to the underbody of the forklift.

Experiment was performed to evaluate the flexibility of design provided in the proposed design methodology. In this experiment, the existing traveling control algorithm of the main controller was replaced with a new engineer's fuzzy control algorithm and rules shown in Table 1, while maintaining all the other system configurations intact. Only the network input and output information was given to the new designer, without extra information about the automated forklift system design.

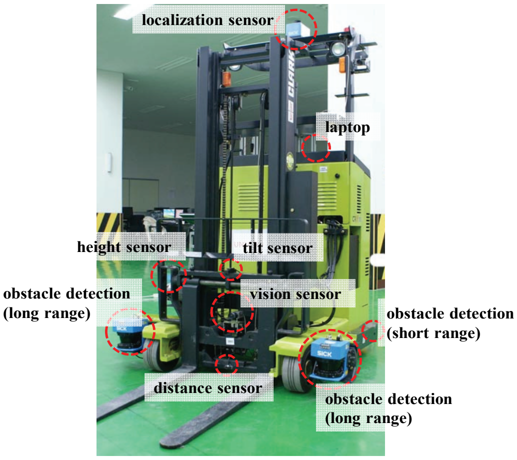
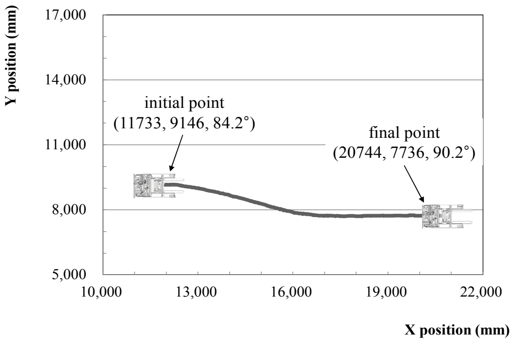


Fig. 3 Experimental model of automated forklift with localization sensor and obstacle detection sensor.

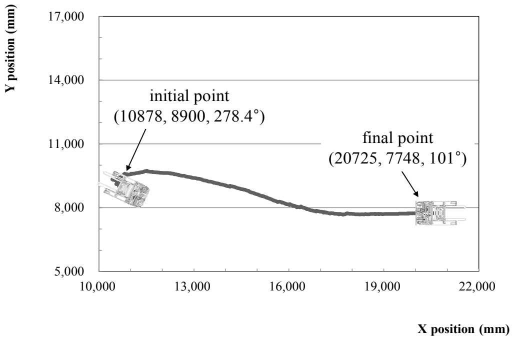
The membership function of a symmetric triangular fuzzy number is used to obtain the traveling velocity and steering angle of the automated forklift. The triangular fuzzy number is symmetric with regard to angle and distance errors between the current position and the destination. The fuzzy linguistic variables are set based on past experiences in designing fault tolerance systems. The fuzzy linguistic variables regarding the distance and angle errors are negative big (NB), negative middle (NM), negative small (NS), zero (Z0), positive small (PS), positive middle (PM), and positive big (PB). Similarly, the fuzzy linguistic variables regarding the traveling velocity and steering

Table 1. Fuzzy Rules for Fuzzy Controller of Automated Forklift

e_d \ e_θ	NB	NM	NS	Z0	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	Z0
NM	PB	PB	PM	PM	PM	Z0	NS
NS	PB	PM	PS	PS	Z0	NM	NM
Z0	PB	PM	PS	Z0	NS	NM	NB
PS	PM	PM	Z0	NS	NS	NM	NB
PM	PS	Z0	NM	NM	NM	NB	NB
PB	Z0	NS	NM	NB	NB	NB	NB



(a) forward direction driving



(b) reverse direction driving

Fig. 4 Experimental results of path tracking using fuzzy controller for automated forklift.

angle are NB, NM, NS, Z0, PS, PM, and PB. The traveling velocity is in the range [0km/h, 2.4km/h], and the steering angle is in the range [-40° , +40°].

Figure 4 presents the results of the experiments in which the automated forklift travels between two points. In Figure 4(a), the forklift is initially facing towards the destination point. The traveling direction is nearly parallel to the x-axis. The employed fuzzy control algorithm continuously corrects angle and distance errors while traveling to the destination. This experiment with a traveling distance of 9 m was repeated five times. The average time taken to travel to the destination is 12.3 sec with a standard deviation of 0.95 sec. The average traveling velocity is 0.804 m/s, and the average traveling error is 46.1 mm. In Figure 4(b), the forklift is initially facing opposite to the direction of destination. This experiment with a traveling distance of 9.9 m was repeated five times. The average time to travel to the destination is 16.2 sec with a standard deviation of 1.16. The average traveling velocity is 0.556 m/s, and the average traveling error is 56.8 mm.

5. Summary and conclusion

This paper showed that the proposed CPS design methodology enables an effective development of automotive E/E control systems. Compared to existing design methodologies, it provides higher reusability of individual modules and an easier way to integrate control system elements such as controllers, sensors, and actuators. However, some research areas like theoretical foundations and interpretations of CPS that can assure design feasibility have not been sufficiently studied yet. This is why the proposed design methodology rely on experimental performance evaluations rather than theoretical interpretations, in verifying its feasibility. In the future, a theoretical analysis of the proposed design methodology and the optimization of ECU function distributions will be studied.

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