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# CYBER-PHYSICAL MODELING OF THE LEADING AND LED ELECTRIC CAR'S JOINT MOVEMENT

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With the help of cyber-physical modeling, the main features of the movement of the master-slave communication of self-driving electric vehicles are determined. Leading electric car leader made in the form of a light tricycle. A driven electric car realized on a heavy caterpillar platform. There is no mechanical connection between the master and the driven electric car. Both electric cars have a microcontroller that controls the speed of rotation of the wheels. It uses the driving control principle similar to driving a tractor. The main information is the value of the master and slave electric vehicle speeds, which measures every 0.1 s. Both microcontrollers equip with a Bluetooth module. The most crucial part of implementing the cyber-physical model of the leader-driven electric car is the need to introduce a human-driver team into the model. It proposes to give the driver the ability to remotely control the movement of the leader-driver of the car via Bluetooth radio on a smartphone. The connection between the leader and led of electric vehicles in the joint's movements and the human control team is based on the Mesh Network (Flood) principle.

*Ключові слова:* cyber-physical system, control, master-driven electric cars, self-driving electric cars, safe distance between vehicles.

**Introduction.**

When modeling the movement of motor transport, the required safe distance considers the distance front, side, and rear according to different movement directions. In-vehicle tracking modeling, each vehicle is independent, but it also affects the other. Concerning the leader, each car is a follower, while it is the leader of the car behind him. There is an equilibrium distance, which is of necessary safe distance between vehicles. It is enough to consider the pair movement - the leader and the driven to identify the peculiarities of the car's movement in the flow. A required safe distance for the car movement's simulation based on molecular dynamics.

It provides that the braking efficiency of vehicles is the same, and the braking distance is affected only by speed [2]. The method of preventing a rear-end collision is given [3]. The safe distance model is your base. The movement-driven car following the leading model, which includes the concept of exceeding the critical speed, is considered [4].

In this paper, using cyber-physical modeling, the features of the joint movement of the leader and the driven electric cars are considered. The man driving an electric car is a leader. A self-driving electric car is a led. The mechanical coupling between the electric vehicles is absent. The necessary information to control the safe movement of the self-driving led the electric vehicle to transmit from the leading electric vehicle via the Bluetooth radio channel. The driven electric car state is transmitting to the leading electric car state on the same radio channel feedback and at the same time. It is determined based on the parameters of electric vehicles in space (road), travel time, and relative speed of vehicles.

**Theoretical fundamentals of movement of electric vehicles pair - leading and drove.**

The model of the safe distance between vehicles on a single-lane road in conditions where vehicles continue to move at a constant speed can be described as follows: during longitudinal driving, the safe distance is a critical maneuver for the driven electric vehicle. It depends on the vehicle's speed and the distance between them because the master vehicle can stop suddenly, and the master has a speed limit.

Both vehicles are moving at a certain speed range or limited speeds, and the sudden braking of the leader's vehicle is due to the driver's reaction. The self-driving electric car brakes using automatic emergency braking (AEG). The driving and driven vehicles have the same braking process. Taking into account the model of safe distance based on the movement course and braking process the safe distance is presented by the formula

$$D_f = (D_{bH} + D_m) - (D_{bA}), \tag{1}$$

where: $D_f$ is the safe distance between the leader and the driven electric cars, $D_{bH}$ and $D_{bA}$ - braking distance of the driven and leading vehicles, respectively, $D_m$ – critical distance (at real conditions is within 2-5 m).

The driven electric car is located at the required distance behind the leader and moves at the same speed as the leader. As for the leader's speed, the minimum safe space that the leader expects and adheres to is called the back distance. When the driven electric vehicle detects a change in the state of movement of the leader, there is a necessary minimum safe distance to which it responds by braking. But he will not lag long due to the process efficiency. And will not be too close given the next procedure safety.

The vehicle operation results show that the reaction time and the braking coordination time $t_r$ are from 0.8 to 1.0 s, and the deceleration time $t_i$ is in the range from 0.1 to 0.2 s. You can get the braking distance *X*, which is determined by (2)

$$X = v_0\left(t_r + \frac{t_i}{2}\right) + \frac{v_0^2}{2a_m}, \tag{2}$$

where $v_0$ is the initial speed, $a_m$ is the maximum deceleration.

Let $v_L$ and $v_F$ be the initial speeds of the master and the slave electric vehicle, respectively, $a_{Lm}$ and $a_{Fm}$ are, respectively, the maximum decelerations, and the relative speed $v_d = v_F - v_L$

The following situations are possible here.

If $v_F = v_L$ and the driven electric vehicle moves with steady motion or uniform acceleration, it can easily continue to follow in a safe state. It will move at its initial speed for a while to avoid colliding with the leader as long as the leader maintains a steady motion. The driven electric car always tries to reach the speed close to the leader to increase the travel efficiency.

If $v_F > v_L$ and the distance between adjacent vehicles exceed the required safe distance, then two vehicles can maintain a safe condition for a certain time, but until the space between adjacent vehicles exceeds the critical distance by about twice. Then the master electric vehicle performs a uniform deceleration. The driven electric vehicle's required safe distance should be analyzed for changes in vehicle speed before and after the leader maneuver.

Provided $v_F > v_L$ that the speed of the driven electric car is higher than the speed of the leader, the slave car can collide with the leader without timely deceleration. This process will continue until the distance between adjacent vehicles reaches a critical space $D_m$, which in real conditions is within 2-5 m depending on the leader speed and the weight of the loaded driven electric vehicle.

The required safe distance $X_R$ between the leader and the driven electric vehicle can be obtained as follows (3):

$$X_R = v_F(t_i + t_r) - \frac{2v_F v_d + v_L^2}{2a_{Lm}} + \frac{v_F^2}{2a_{Lm}} - \frac{v_L t_i}{2} + d \,, \tag{3}$$

where $d$ - the minimum clearance between adjacent vehicles after stopping, ranging from 2 to 5 meters.

**Implementation of movement control system of electric vehicles in pair-leading and drove.**

Following the principles of construction of cyber-physical systems [5, 6] the model of the control system of movement of the leading and driven electric cars is realized. The electric car leader is made in the form of a light three-wheeled chassis weighing 0.5 kg with dimensions of 17*25*6 cm. The driven electric car is implemented on a heavy tracked platform weighing 2.2 kg with dimensions of 21*36*8 cm. Each electric car has a microcontroller that controls the speed of rotation of the wheels. The driving control principle is similar to driving a tractor used here. The electric vehicle speeds $v_L$ and $v_F$ measures every 0.1 s.

The microcontrollers equipped the Bluetooth modules. Fig.1 illustrates the model of the control system of movement of the leading and driven electric cars. Antenna 1 of the microcontroller of the driven vehicle is a printed receiving antenna of the wave channel type. The antenna 2 of the microcontroller of the leading vehicle is the wave channel type printed transmitting antenna. The antenna 3 of the microcontroller of the leading vehicle is the wave channel type printed receiving antenna.

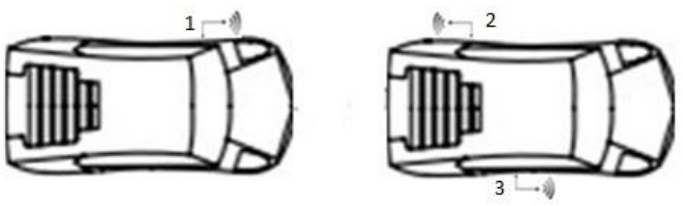


Fig.1. Model of the control system of movement of the leading and driven electric cars.

The microcontroller of the slave vehicle with printed receiving antenna 1 type wave channel receives a new speed setting (Motor Service) from the microcontroller of the leading vehicle with printed transmitting antenna 2 type wave channel.

The most difficult part of implementing a cyber-physical model of a leader-driven electric vehicle is the need to introduce human teams into the model. It is proposing to give the driver the ability to remotely control the movement of the leader-driver of the car via Bluetooth radio channel on a smartphone. The microcontroller of the leading vehicle with a printed receiving antenna 3 type wave channel receives a new speed setting (Motor Service) from the smartphone of a human driver.

In the joint movement of the driving and drover electric vehicles, the connection between them and the human control team is based on the principle of Mesh Network (Flood).

Mesh Network is a communication topology where all devices can connect to all other devices on the network. This network model does not use a specific central node. For Bluetooth, the Mesh Network is becoming an important feature that will allow devices to be integrated into the IoT and effectively increase the range and convenience of Bluetooth connectivity.

Because there are no Bluetooth SIG specifications for the Mesh Network yet, there are different ways to implement Bluetooth Mesh. Each method has its pros and cons and is better suited to one program than another.

This project implements a Mesh Network with a Flooding mechanism via Bluetooth. Flooding means, that there is no routing when transferring data from one node to another, and each node can receive the transmitted data. Bluetooth connections mean that nodes connect via Bluetooth before data can be transmitted. Thus, there is no limit to the amount of payload that can be transferred between nodes.

The project supports the central and peripheral profile roles. The default state is the peripheral profile where the nodes are advertising. Ad data contains its data counter, which has a value from 0 to 100. When each time new speed parameters are transmitted to the node, then this counter value increases and is later announced. This project uses a connection method where a Bluetooth connection is established between two nodes before data transfer. When the data is received by a node, then the node switches the profile role to connect to other nodes and transmit the same data. Mesh Network allows you to transmit certain signals to each node in this network.

Implemented cyber-physical model consists of master and slave electric vehicles. The leading electric car leader is made in the form of a light tricycle weighing 0.5 kg with dimensions of 17*25*6 cm. The driven electric car is realized on a heavy caterpillar platform weighing 2.2 kg with overall dimensions of 21*36*8 cm. The driven electric car is controlled by Bluetooth device signals from the leading electric car. The leading electric vehicle is controlled by signals from the human driver. New speed settings (Motor Service) are sent by a central Bluetooth device, such as the CySmart PC Tool or similar, for example, by a smartphone. The implemented cyber-physical model of the joint movement of the master and the driven electric car showed satisfactory results when driving in a straight line in one lane with remote control of a human driver at a distance of up to 62 m.

**Conclusion**

Cyber-physical systems' internal heterogeneity, parallelism, and time sensitivity pose many problems. Implemented cyber-physical model of joint movement of leading and led electric cars showed satisfactory results.

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## КІБЕР-ФІЗИЧНЕ МОДЕЛЮВАННЯ СПІЛЬНОГО РУХУ ВЕДУЧОГО І ВЕДЕНОГО ЕЛЕКТРОМОБІЛІВ

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Відповідно до принципів побудови кібер-фізичних систем реалізована модель системи управління рухом ведучого і веденого електромобілів. Ведучий електромобіль-лідер виконаний у вигляді легкого триколісного шасі масою 0.5 кг з габаритними розмірами 17x25x6 см. Ведений електромобіль реалізований на важкій гусеничній платформі масою 2.2 кг з габаритними розмірами 21x36x8 см. Механічний зв’язок між ведучим і веденим електромобілями відсутній. Акумуляторні батареї забезпечують електричне живлення кожного з електромобілів. На кожному електромобілі встановлений мікроконтролер, який керує швидкістю обертання коліс. Тут використовується принцип керування рухом подібним до керування трактором. Головною інформацією є значення швидкостей руху ведучого і веденого електромобілів, які вимірюються кожні 0,1 с. Обидва мікроконтролери обладнані модулем Bluetooth. Найважливішою частиною реалізації кібер - фізичної моделі спарки лідер-ведений електромобілі є необхідність ввести в модель команди людини-водія.

Пропонується надати людині-водію можливість дистанційного управління рухом лідера-ведучого автомобіля по радіоканалу Bluetooth на смартфоні. При спільному русі ведучого і веденого електромобілів зв'язок між ними, а також команди управління людиною базується на принципі Mesh Network (Flood). Mesh Network дозволяє передавати кожному вузлу в цій мережі певні сигнали. Нові параметри швидкості (MotorService) надсилаються центральним пристроєм Bluetooth, таким як CySmart PC Tool або подібним після підключення до будь-якого вузла. У цьому проекті використовується метод підключення, де Bluetooth з'єднання встановлюється між двома вузлами перед передачею даних. Опісля того, як дані були отримані вузлом, вузол перемикає роль профілю для підключення до інших вузлів і передачі тих самих даних. Реалізована кібер-фізична модель спільного руху ведучого і веденого електромобілів показала задовільні результати під час руху в одній смузі по прямій при дистанційному управлінні людиною-водієм на віддалі до 62 м.

*Ключові слова:* кібер-фізична система, контроль, електромобілі з керуванням людиною, електромобілі з автономним керуванням, безпечна відстань між транспортними засобами.

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