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Accelerating the Validation of Motion Control for a 4WD4WS Ground Vehicle Using a Hierarchical Controller Hardware-in-the-loop System*

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***Abstract*— Due to the actuator redundancy and complexity of the unmanned ground vehicle actuated by four-wheel drive and four-wheel steering powertrains (4WD4WS UGV), it is a significant challenge to conduct fast verification of the complex control system. This work presents a dedicated hierarchical controller hardware-in-the-loop system to accelerate the verification of the motion control system for a 4WD4WS UGV. The hierarchical controller, that is implemented in a combined onboard-computer and embedded micro-controller, adopts a three-layered architecture. The upper layer uses a model predictive control algorithm (MPC) to calculate the desired heading angle and vehicle speed. The middle layer converts the control effect into the desired speeds and steering angles of four wheels. The bottom layer controls the drive motor and steering motor to track the desired speed and steering angle of each wheel. The proposed HC-HIL system establishes a multibody dynamics model of the 4WD4WS UGV with high fidelity, and accelerates the validation process of the motion control performance, via which the complex control strategy can run in the actual control hardwares and be verified in a virtual model with high fidelity. The HC-HIL system provides a fast and low cost method for initial testing prior to the real implementation, thereby reducing the potential failures in future real testing.**

***Index Terms*— Unmanned ground vehicle, 4WD4WS, Hardware-in-the-loop, Hierarchical control, Motion control.**

I. INTRODUCTION

The automated guided vehicle (AGV) has become prominent in the warehousing logistics and production lines [1]. With the rapid development of modern industry, the conventional AGV will progress towards intelligence and flexibility [2] [3]. The four-wheel-drive four-wheel-steering unmanned ground vehicle (4WD4WS UGV) is potentially an ideal mobility platform of future flexible manufacturing system (FMS), thanks to its flexible mobility in narrow space. However, due to the actuator redundancy and dynamics complexity, how to develop effective motion control system iteratively with fast validation becomes a critical challenge.

It is often desired to verify the control system in the laboratory prior to the real field test [4], so as to evaluate the real-time performance and find potential faults at early stage. A validation method closely matching the real field test is of great significance. The hardware-in-the-loop (HIL) system uses the real-time processor to control the simulation model for early validation [5], which can simulate the running states of the controlled object, thereby accelerating the development process, reducing the test cost, and improving the software quality of control system. The HIL system has been broadly used in the development of various control systems. A high fidelity model of vehicle and brake system is built using Matlab-Adams co-simulation to test an advanced brake system in [6]. Ref. [7] presents a HIL system in the development of electric variable transmission. Ref. [8] presents a HIL simulation study of an adaptive trajectory following strategy, which uses a knowledge-based adaptive mechanism to guide an armoured vehicle along a desired path. A visual serving control of a fixed wing UAV is verified via a HIL system in [9]. Although the HIL method has been used in diverse applications, to our knowledge, there's not a HIL platform dedicated for the hierarchical control system validation for the 4WD4WS UGV.

This paper presents a novel hierarchical controller hardware-in-the-loop system (HC-HIL), to accelerate the validation process of the motion control performance for a 4WD4WS UGV prototype in face of redundant actuators, complex dynamics, multi control units and a CAN control network. To cope with the complex dynamics induced by multi-actuator powertrains, a multibody dynamics model instead of the mathematical model in conventional HIL system is built to generate a high fidelity control plant. A hierarchical control system involving an on-board computer and an embedded micro control unit in a CAN network is established as the control hardware. Via the novel HC-HIL system, the motion control system can be verified at

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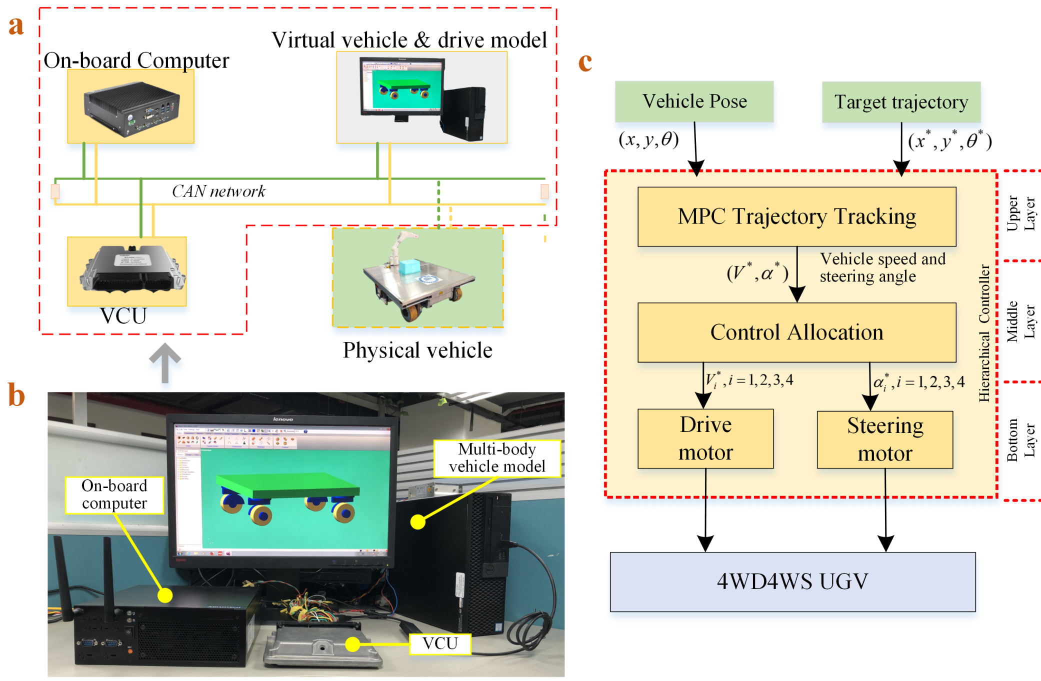

Fig. 1. The HC-HIL validation system.

an early stage, and many faults may be found prior to the real field test, thus shortening the development process, reducing the development cost and ensuring the safety of subsequent experiments. The main contribution of this work is to establish a novel multi-layer controller hardware-in-the-loop scheme that is suitable for fast and high fidelity verification for complex 4WD4WS UGVs.

The structure of the paper is as follows. Section II presents the overall system of the proposed HC-HIL involving the hierarchical controller and the virtual vehicle model. Section III details the 4WD4WS UGV model and the motion control architecture. Section IV introduces the upper layer controller of the HC-HIL system. Section V shows the HC-HIL test results followed by the conclusion in section VI.

II. System Overview of the HC-HIL

The hierarchical controller hardware-in-the-loop system (HC-HIL) for the 4WD4WS UGV is composed of four parts: an on-board computer, an embedded vehicle control unit (VCU), an desk computer, and the CAN control network. The on-board computer and the VCU are the actual control hardwares of the vehicle. The desk computer runs the virtual 4WD4WS UGV model, which is connected to the actual control hardwares via the CAN network interface. All the data of control command and states signals are transmitted and received via the CAN network. The system scheme is shown in Fig. 1.

A. The Hierarchical Control System

The hierarchical motion control system consists of three layers. The upper layer uses a MPC-based trajectory tracking control algorithm to generate the generalized control, i.e., the desired speed and steering angle of the vehicle. The upper layer runs in the on-board computer due to the computational complexity. The middle layer converts the generalized control commandt into the desired steering angles and wheel speeds of all wheels. And the bottom layer regulates the drive motors and steering motors to track the desired speeds and steering angles, respectively. The middle and bottom layers run in the embedded VCU to ensure the real-time performance. The motor torque commands generated by the bottom layer are sent to the virtual models of the mutli motors and the vehicle via the CAN network. The states signals are sent back to the control hardwares via the CAN network.

B. The 4WD4WS Multibody Dynamics Vehicle Model

An accurate virtual vehicle model with high fidelity is essential to ensure the reliability and coincidence of vehicle motion simulation. The mechanical 4WD4WS vehicle model, involving four wheels, steering gears, the chassis, etc., are created as 3D entities in Solidworks software. A ground in the 3D software is created to adjust the vehicle model in proper position. The established models of vehicle parts built in Solidworks software are saved as a file in a *x_t* format.

The models of parts are then assembled into a vehicle model in a multi-body dynamics software (i.e., Adams), in which the bearing chassis material is steel, the vehicle frame is cast iron, and the tire is rubber. The following procedures function to establish the vehicle model: 1) setting the direction of the gravity in the vertically downward direction of the vehicle; 2) integrating the ground module from Solidwarks with the ground in Adams to set the friction between the wheels and the ground; and 3) setting the vehicle

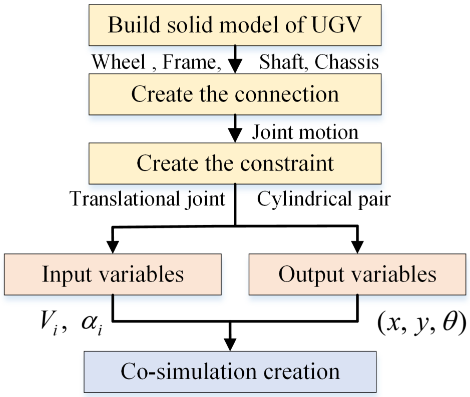

Fig. 2. The flow chart of the co-simulation setup.

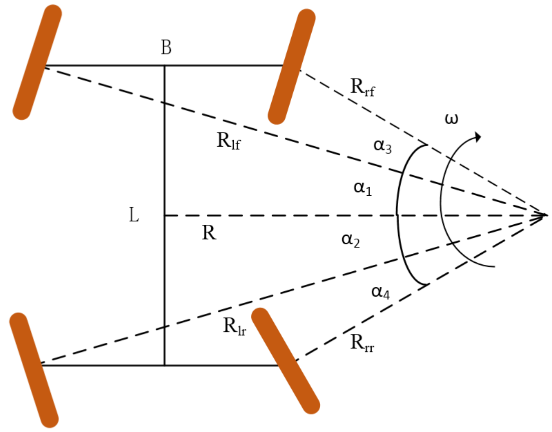

Fig. 3. The four-wheel steering principle of 4WD4WS UGV.

frame to rigidly connect to the chassis and wheel assembly. The cylindrical pairs are added between the parts that rotate relative to each other. And finally the revolute pairs are added between the wheel and the axle.

C. Co-simulation Setup

With the virtual multi-body dynamics vehicle model and the hardware control units, we use the following three steps to set up the co-simulation.

Firstly, the four-wheel independently drive and steering motion functions are added. The four-wheel speed variables of the vehicle, i.e., V_1, V_2, V_3, V_4, and the four-wheel steering angle variables, i.e., $\beta_1, \beta_2, \beta_3, \beta_4$, are created. In the motion function, a frame-based marker and a ground-based marker are added to the center of the frame, and the vehicle pose variables x, y, θ are set. The direction of the variable is set to the right hand system of the vehicle coordinate system, where x represents the distance between the reference marker and the ground marker along the longitudinal direction of the vehicle, y represents the distance between the reference marker and the ground marker along the lateral direction, and θ indicates the heading angle of the vehicle.

Secondly, in the control module, the input signals involves the speeds of four wheels, i.e., V_1, V_2, V_3, V_4, and the steering angles of four wheels, i.e., $\beta_1, \beta_2, \beta_3, \beta_4$. The output signals contain the longitudinal distance x, the lateral distance y, and the heading angle of the vehicle body θ. The target software is MATLAB, which generates the $*.m$ files. Then, we can use the command $Adams - sys$ in MATLAB to generate the Simulink model of the 4WD4WS UGV.

Finally, a new Simulink model is built, in which the Adams_sub module is included. The communication period is set to 100 milliseconds. The co-simulation flow chart is shown in Fig. 2.

III. The Lower-Layer Control System

A. The Steering Principle of 4WD4WS UGV

The 4WD4WS UGV conforms to the Ackerman steering principle when cornering at low speeds, which ensures that the four wheels are purely rolling on the road surface. Since the 4WD4WS UGV makes a circular motion along the steering instant O during cornering, the angular velocity of each point on the vehicle are the same. The linear velocity of each point on the vehicle is equal to the angular velocity *omega* multiplied by the distance, which is far from the steering center to the steering center. The four-wheel drive omnidirectional 4WD4WS UGV is shown in Fig. 3. Hence, we have

$$V = \omega R, \tag{1}$$

$$V_i = \omega_i R_i, i = 1, 2, 3, 4, \tag{2}$$

where V is the vehicle speed, V_i is linear speed of the i_{th} wheel.

According to the geometric relationship, the relationship between the four steering angles and the heading angle of the 4WD4WS UGV is obtained as

$$\beta_1 = arctan(\frac{L}{2}/(R - \frac{B}{2})), \tag{3}$$

$$\beta_2 = arctan(\frac{L}{2}/(R + \frac{B}{2})), \tag{4}$$

$$\beta_3 = arctan(\frac{L}{2}/(R - \frac{B}{2})), \tag{5}$$

$$\beta_4 = arctan(\frac{L}{2}/(R + \frac{B}{2})), \tag{6}$$

where, β_i is the steering angle of the i_{th} wheel, R is the turning radius of the whole vehicle, L is the wheelbase, and B is the vehicle track.

The heading angle φ of the vehicle is

$$\varphi = arctan(\frac{L}{2}/R). \tag{7}$$

In the hierarchical control system, the input signals are the vehicle states, i.e., the pose (x, y, θ), and the output signals are the steering angles and the speeds of four wheels, which are sent to the virtual vehicle model via the CAN bus and the data interface in Simulink.

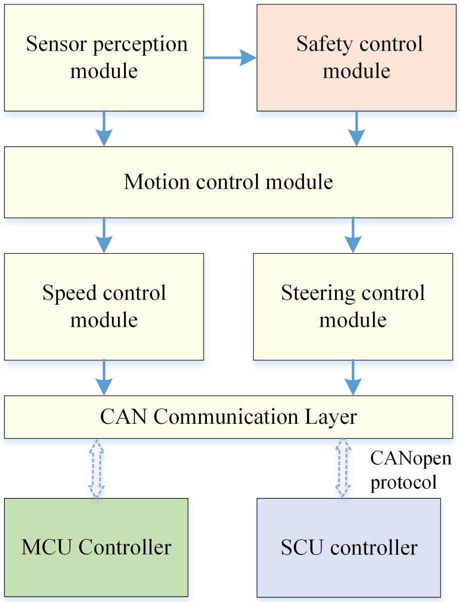

Fig. 4. Function modules of the vehicle control unit (VCU).

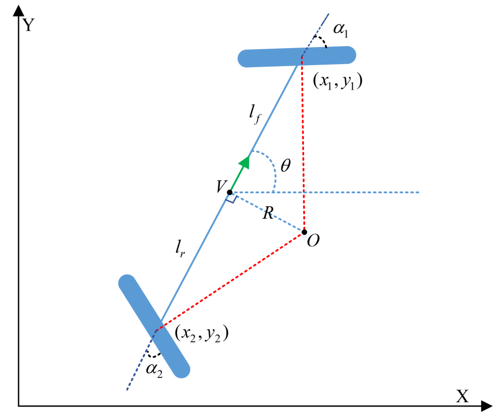

Fig. 5. The kinematic modeling of 4WD4WS UGV.

B. The Embedded Lower Layer VCU

The lower layer of the hierarchical control system uses an embedded vehicle control unit (VCU). The VCU generates the commands, i.e. the steering angles of four wheels and the drive torque commands of four in-wheel motors. The steering angles of four wheels are calculated according to the Ackerman steering principle. All the commands are sent to the drive and steering motor controllers.

The overall function blocks of the VCU is shown in Fig. 4. The sensor perception module detects the electrical signals and faults, and updates the state variables, such as the speeds and steering angles of four wheels. The safety control module prevents the program from entering an infinite loop through the built-in watchdog. Meanwhile, it will trigger the emergency braking when the vehicle runs into obstacles during the experiment. The motion control module converts the generalized control commands, i.e., the target vehicle speed and heading angle, into the target speeds and steering angles of four wheels. The speed control module generates the target torque of the in-wheel motor to achieve the target speed of each wheel. The steering control module generates the target angle of the steering motor of each wheel. In the actual test, it is found that fast steering response will lead to motion oscillation during trajectory tracking. Hence, we use a gradient control strategy to reduce motion oscillation. The CAN bus communication layer receives commands from the higher layer computer, and the state signals from the motor controllers and the battery management system. It sends the commands to four in-wheel motor drive controllers and four steering controllers as well. The *CANopen* communication protocol is adopted in the communication.

IV. The Higher-Layer Control System

A. The Kinematic Model of Trajectory Tracking

The higher layer control system mainly runs the model predictive control algorithm (MPC), which is used for trajectory tracking. In the HC-HIL system, the higher layer control system requires strong computing ability, to calculate the control variables using complex algorithms in real time, e.g., the MPC algorithm.

The model predictive control algorithm consists of three parts: predictive model, rolling optimization and feedback correction. Since the 4WD4WS UGV is a symmetrical structure, the rotational angles of the front and rear wheels are equal in absolute value and opposite in direction. The turning process of the 4WD4WS UGV is simplified to a bicycle model, which contains opposite front and rear wheel angles, as shown in the Fig. 5.

In the global coordinate system $X-O-Y$, the center coordinates of the front axis and rear axis of the vehicle can be described as (x_1, y_1) and (x_2, y_2), respectively. And (x, y) is the coordinate of the centroid of the vehicle. The wheelbase length of the front half of the vehicle is l_f. The wheelbase length of the rear half is l_r. The total wheelbase length of the vehicle is $l = l_f + l_r$. The turning radius of the vehicle is R. Due to the limitation of the operating environment, the speed of the 4WD4WS UGV is small. The vehicle is a rigid body structure. Therefore, it is assumed here that the vehicle body has no lateral deviation and the movement of the 4WD4WS UGV.

The horizontal component of the velocity at the center of mass is,

$$\dot{x} = v cos\varphi. \tag{8}$$

The vertical component of the velocity at the center of mass is,

$$\dot{y} = v sin\varphi. \tag{9}$$

Through the geometric relationship we can get,

$$\frac{sin\alpha_1}{l_f} = \frac{cos\alpha_1}{R}, \tag{10}$$

$$l = l_f + l_r, \tag{11}$$

$$\frac{sin\alpha_2}{l_r} = \frac{cos\alpha_2}{R}. \tag{12}$$

The final kinematics equation for the 4WD4WS UGV is as

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} \cos\varphi \\ \sin\varphi \\ \frac{2tan\alpha_1}{l} \end{bmatrix}. \tag{13}$$

The input variables of the model prediction controller are v and α_1. The output variables are x, y, φ, which are measured by the on-board SLAM module. At the time $t = k$, the kinematic equation can be written in (14).

$$\vec{x_k} = f(x_k, u_k), \tag{14}$$

According to the taylor formula, the higher order infinitesimal terms are ignored. Hence, the state equation is

$$\widetilde{x}_{k+1} = \begin{bmatrix} x - x_k \\ y - y_k \\ \varphi - \varphi_k \end{bmatrix}, \tag{15}$$

$$A_k = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ -vcos\varphi \cdot T & vcos\varphi \cdot T & 1 \end{bmatrix}, \tag{16}$$

where T is the sampling time. As the vehicle runs at low speed, the controller's sampling time T is set to $0.1s$. The prediction step number N_p is set to 10, and the control step number N_c is set to 2. The cost function is in (17). The constraints are in (18).

$$\begin{aligned} cost = \sum_{i=1}^{10} (x_i - x_{ref})^2 + (y_i - y_{ref})^2 \\ + (\varphi_i - \varphi_{ref})^2 + (\alpha_i - \alpha_{ref})^2 \end{aligned} \tag{17}$$

$$s.t. \begin{cases} -5 < x_i < 5 \\ -5 < y_i < 5 \\ -2\pi < \varphi < 2\pi \\ 0 < v_i < 3 \\ -0.436 < \alpha_i < 0.436 \end{cases}. \tag{18}$$

According to the state equation, the states of the 4WD4WS UGV in the next 10 steps can be obtained. Through the constraint conditions and the cost function, a series of sequences of control commands are obtained by using the optimization method, which will finally make the cost function the minimum. The MPC algorithm running in the industrial computer generates control commands. The lower-layer VCU receives the command, which then generates the target torques and steering angles of four wheels. Both the higher-layer and the lower layer controllers in a hierarchical structure function collaboratively to control the motion of the 4WD4WS vehicle.

V. RESULTS

A. HC-HIL Validation

We use the proposed HC-HIL system to perform the controller hardware-in-the-loop trajectory tracking verification. The target trajectory is a sinusoidal curve. As a case study, we use the model predictive control (MPC) method as the trajectory tracking algorithm in the upper layer. The result is shown in Fig. 6. The result shows that the actual trajectory tracks the target sinusoidal curve with high accuracy. And the MPC algorithm performs well in real time in the higher-layer physical controller. The proposed HC-HIL system is feasible for fast verification of complex control algorithms in real hareware controllers.

As an alternate of various motion modes of the 4WD4WS UGV, we verified the minimum turning radius of the vehicle in four-wheel steering motion mode which is constrained to certain steering limit, as shown in Fig. 7 and Fig. 8. The result shows that the minimum turning radius is 1.6m in continuous motion mode.

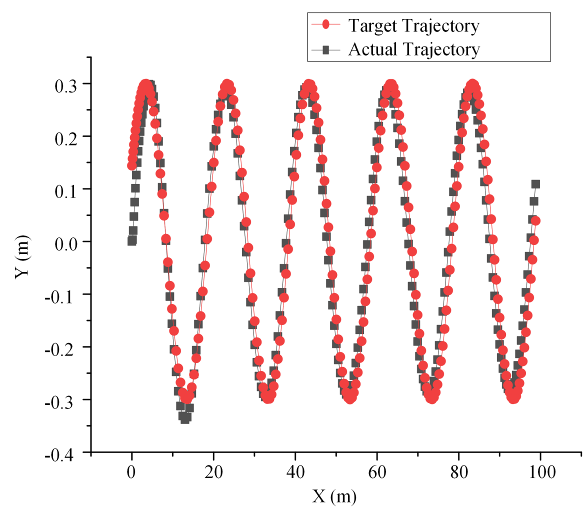

Fig. 6. Tracking a sinusoidal trajectory.

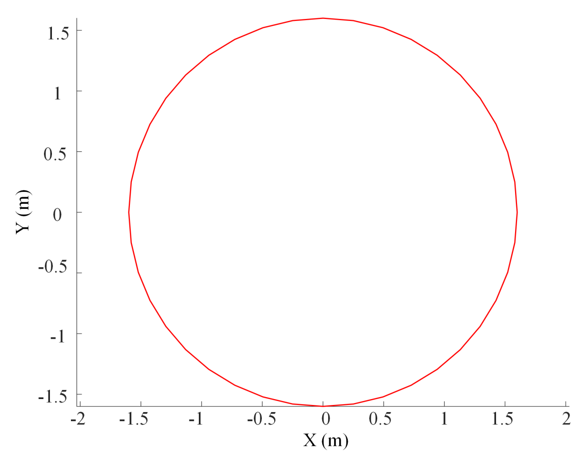

Fig. 7. The minimum turning radius curve .

Fig. 8. The experimental test for minimum steering circle tracking.

B. Experimental Validation

Benefitted from the fast validation using the proposed HC-HIL system, various motion experiments have been conducted for the omnidirectional 4WD4WS UGV prototype, as shown in Fig. 9. The 4WD4WS vehicle platform consists of four in-wheel drive motors, four steering motors, a battery pack, and other accessories. A trajectory that is combined with straight and semi-circular segments is used as the reference in a test ground. The small turning radius of the vehicle ensures the flexible mobility in narrow spaces. The experimental results show that the trajectory tracking algorithm that was verified in the HC-HIL system, achieves good trajectory tracking performance in real test as shown in Fig. 9 and Fig. 10.

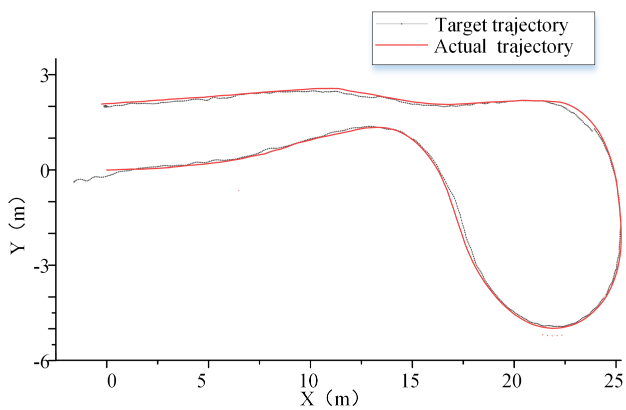

Fig. 9. The actual trajectory tracking.

Fig. 10. The experimental test for trajectory tracking.

VI. Conclusion

This research proposes a hierarchical controller hardware-in-the-loop (HC-HIL) system for the 4WD4WS UGV to verify the complex multi-layer controllers prior to the real field test, which can shorten the development process and enhance the safety of the subsequent real test. A model predictive controller for trajectory tracking of the 4WD4WSUGV is proposed in the upper layer controller, and is further validated using the proposed HC-HIL system for fast verification as a case study. After the validation in the proposed HC-HIL, the hierarchical controller combining an on-board computer and an embedded micro control unit can be implemented in the real vehicle seamlessly without any modification. The HC-HIL provides an effective tool to evaluate various motion control strategies with high fidelity. Experimental result shows the controller regulates the vehicle along a specified trajectory with high accuracy. In future study, more complex and extreme conditions, such as low adhesion road and severe signal noise, will be involved in the HC-HIL system.

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