Research on Autonomous Driving Safety System of Heavy-Duty Tracked Unmanned Vehicle

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Abstract: This paper summarizes and sorts out hazards in autonomous driving of heavy-duty tracked unmanned vehicles, proposes a hazard identification model, puts forward safety control strategy, builds a safety control system, and verifies stability of the safety system through simulation analysis and real vehicle tests. Through the research of this paper, safety is improved in autonomous driving of heavy-duty tracked unmanned vehicles, which provides ideas for the development of safety systems.

Keywords: Tracked unmanned vehicle; autonomous driving; safety system

1. Introduction

Military ground unmanned vehicles are more and more widely used in various military tasks. As early as 1969, the U.S. military used unmanned vehicles to transport supplies during the Vietnam War [1]. In the Syrian war, the Russian military used the 12-ton Uranus 9 unmanned combat vehicle for the first time in a combat mission. However, there were many problems in actual combat. Russian uav operators were unable to control their vehicles in 17 cases within one minute and twice within one and a half hours [2]. In the process of military special vehicles gradually moving towards full electric and unmanned, how to guarantee the safe driving of unmanned vehicles is an urgent practical problem to be solved [3].

2. Overview of the Vehicle

The autonomous driving system of the vehicle consists of 5 levels, namely the environment and state perception layer, the path planning layer, the remote control navigation layer, the driving control and execution layer, and the environment layer. The various element information of the environment layer is accessed through the sensing layer lidar, camera, etc. After processing, it is converted into state information required for the path planning layer or remote control navigation layer. The path planning layer gathers the desired speed command and desired position command based on the environment information and the vehicle state information. The remote navigation layer monitors the vehicle pose and position information, the vehicle motion state through equipment such as remote ground stations. The driving control and execution layer receives command from the path planning layer or the remote navigation layer and transforms it into module execution control command, so that the actuator controls the vehicle movement under the command of execution module. The driving control and execution layer has information interaction with the environment layer. The logic control structure is shown in Figure 1.

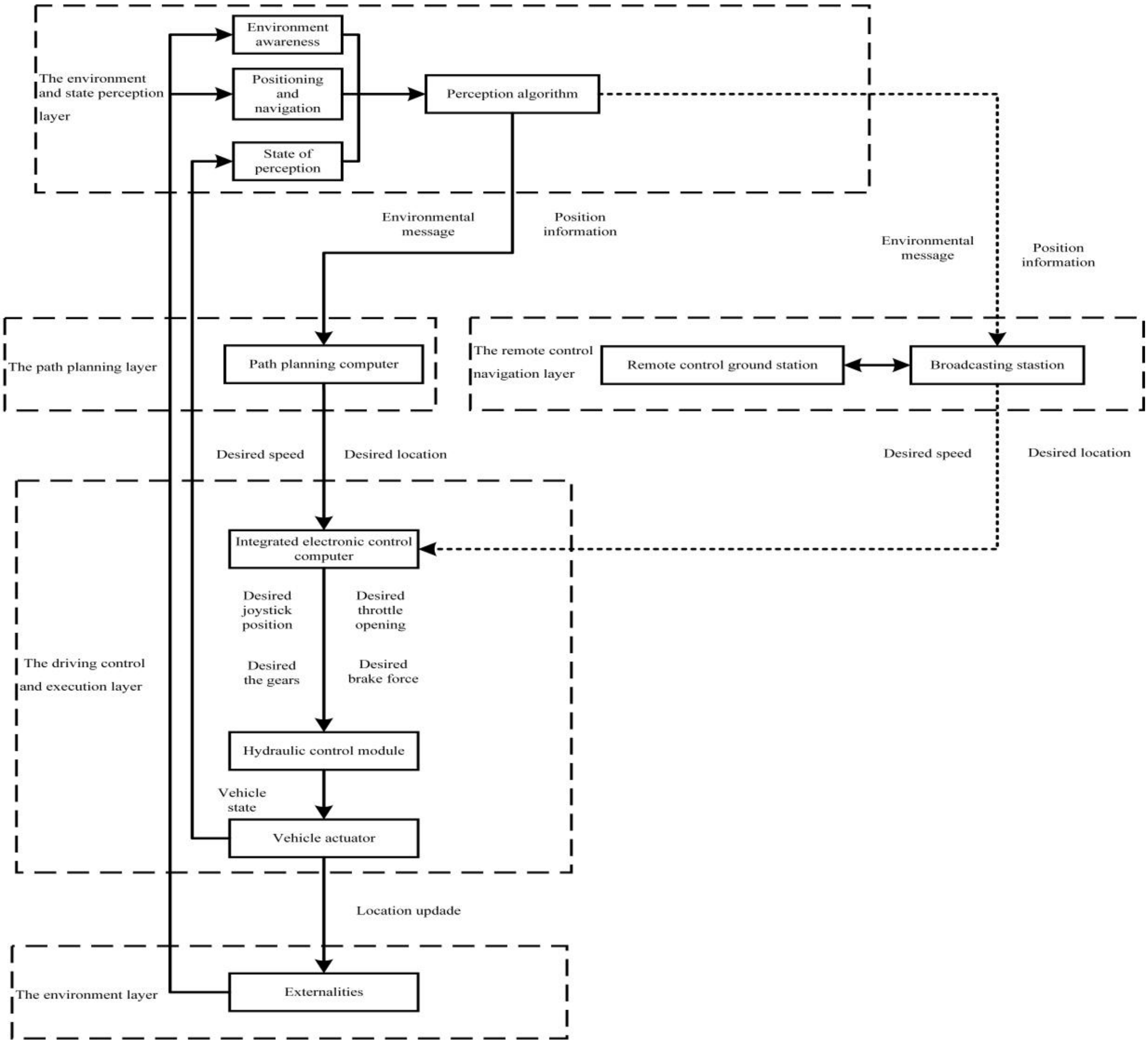

Figure 1. The vehicle control structure diagram

3. Safety System Development

3.1. Safety System Development Method

During the vehicle driving process, driving safety is not only affected by the safety performance of the vehicle itself, but also by the external environment. Based on STPA theory [4], a development method is proposed for the safety decision-making system of heavy-duty tracked unmanned vehicles in view of the autonomous driving system characteristics of the heavy-duty tracked unmanned vehicle, as shown in Figure 2.

In view of the existing functions of the autonomous driving system, we analyze control logic and control process of the unmanned vehicle, add safety strategy design and actual vehicle test steps based on the analysis process and analysis results, thus forming an iterative closed loop for the development of the autonomous driving safety system. The method is implemented in a loop of 6 steps:

1) Analyze the key control behaviors of autonomous driving;
2) Identify the hazard control behavior of autonomous driving;
3) Analyze the incentives of hazard control behavior in autonomous driving;
4) Identify potentially hazardous events;
5) Design an autonomous driving safety strategy;
6) Conduct experiments to verify the autonomous driving safety strategy.

The final effective safety strategy based on the above 6 steps is implemented in the system, which constitutes a complete safety iterative process.

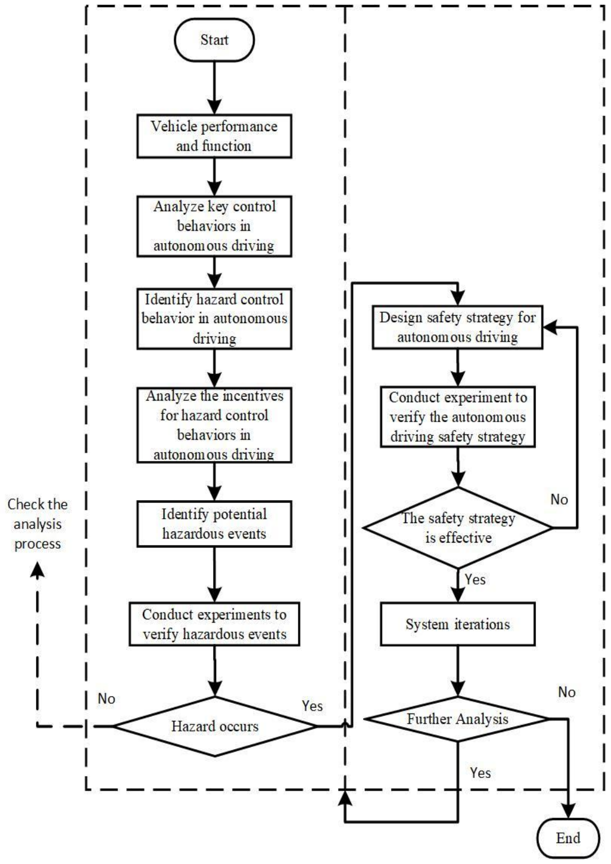

Figure 2. The development method proposed herein

3.2. Analyze the Key control Behaviors in Autonomous Driving

Through the unmanned tracked vehicle control logic diagram, analyze the key control behaviors in autonomous driving based on whether the accident occurrence is directly related to the control signal. The control logic in the diagram consists of a control logic layer and a physical behavior layer. The logic control layer includes an environment perception layer, a path planning layer, and a remote control navigation layer. It is located on the upper layer of the control logic structure [5]. The physical behavior layer includes a driving control and execution layer and an environment layer, which is located at the lower level of the control logic structure. Accidents including personal safety and property damage occur at the physical behavior layer, so the control behavior of the control logic layer against the physical behavior layer is the main way for the autonomous driving system to create impact on the physical world. If the control logic layer incorrectly implements control behavior, there is a possibility of accidents in the physical behavior layer. Therefore, the control behavior on the path where the control logic layer implements control behavior on the physical behavior layer is the key control behavior for autonomous driving. For an autonomous driving system, this path includes two control behaviors over the desired speed (K_1) and the desired position (K_2), which are combined as K.

3.3. Identification of Hazard Control Behavior in Autonomous Driving

By analyzing the key control behaviors of autonomous driving system, the hazard control behaviors are classified and transformed into identifiable models. Based on the STPA theory, the following 9 error models are proposed in view of the characteristics of heavy-duty tracked unmanned vehicles, and the model set is represented by L:

1) L_1 needs to provide the signal, but doesn't do so;
2) L_2 doesn't need to provide signal, but does so;
3) L_3 provides the correct signal, but too early;
4) L_4 provides the correct signal,, but too late;
5) The signal provided by L_5 has too long duration;
6) The signal provided by L_6 has too short duration;
7) The signal provided by L_7 has too high value;
8) The signal provided by L_8 has too low value;
9) L_9 does not need driver's manipulation, but does so.

The heavy-duty tracked unmanned vehicle is set with 5 functional states. M sets are used to indicate the sets of functional states, namely: straight driving (M_1), curved road driving (M_2), ramp driving (M_3), intersection decision (M_4), and anti-collision driving (M_5).

By Cartesian product of the sets K, L, S and M, the set of hazard control behaviors is derived and recorded as A, namely

$$A = L \times K \times M = \{(L_k \times K_i \times M_j) \mid k = 1,2,\cdots,9; i = 1,2; j = 1,2,\cdots 5\} \tag{1}$$

In the set of hazard control behaviors, not all control behaviors will trigger hazard, so hazard control behaviors need to be screened. Introduce the screening function $N = f(X)$, establish a function model for screening behaviors, and the set of hazard control behaviors after screening is $N_A = f(A)$. Use Boolean matrix method to transform the problem of hazard control behavior into a problem of constructing screening matrix. Use H to represent the Boolean matrix for screening, and the final result is expressed as:

$$N = f(A) = A \cap H \tag{2}$$

After constructing the screening matrix, the unmanned vehicle driving behavior is identified to further complete identification of hazard control behavior. This paper studies the hazardous circumstances that appear in straight autonomous driving.

3.3.1. Hazardous control behavior in straight driving

Table 1 shows the dangerous control behaviors of autonomous driving.

Table 1. Hazardous control behavior in autonomous driving

Error mode L	**Straight driving state** M_1	
	Desired speedK_1	**desired position**K_2
Required, bot does not provide L_1	0	1
Not required, but provide L_2	0	1
L_3 provides the signal too early	0	0
L_4 provides the signal too late	0	0
Duration is too long L_5	0	0
Duration is too short L_6	0	0
The signal provided by L_7 has too high value	0	0
The signal provided by L_8 has too low value	0	0
The driver mistakenly provides L_9	0	1

3.3.2. Identification of hazardous events

Use the unsafe control content and cause in the above analysis as the basis to establish a potentially hazardous event. It is clear that the accident is the collision of the unmanned tracked vehicle with obstacles such as pedestrians, trees or other vehicles, causing casualties or economic losses. The hazardous behavior generated in the system is the movement of the unmanned tracked vehicle that causes the accident, which is caused by unsafe control behaviors. According to the definition of hazardous events, system hazards DZ caused by unsafe control behaviors and accidents AZ due to driving environment factors can be described using an ordered array (RZ, DZ, AZ), and safety constraint CZ is proposed. According to the above description, construct hazardous events under straight driving, as shown in the table 2.

Table 2. Autonomous driving function accidents, system hazards, and safety constraints

Hazard control behavior	**Set safety constraint conditions**	**Hazardous circumstances for autonomous driving system**	**Accident**
(M_1, K_2, L_1)	When $CZ1$ drives in a straight line, monitor the obstacles in front of the vehicle and on both sides of the road in real time, and brake in time when the distance to the obstacle is too small.	When there are obstacles in front or on both sides of $DZ1$, normal avoidance is impossible.	$AZ1$ unmanned vehicle collision accident
(M_1, K_2, L_2)	$CZ2$ sets emergency braking trigger program	$DZ2$ unmanned vehicle mistakenly plans the driving path	$AZ2$ unmanned vehicle is out of control and an accident occurs
(M_1, K_2, L_9)	$CZ3$ sets misoperation alarm	$DZ3$ has hazard	$AZ3$ unmanned vehicle temporarily loses control or has accidents

4. Safety Strategy Design and Verification

4.1. Safety Strategy Design

This paper takes the hazardous situation as the basis for designing the safety strategy, with the circumstance where $DZ1$ has obstacles that cannot be normally avoided in front or on both sides as an example. The function of this safety strategy is to detect in real time whether there are obstacles affecting the driving in front and on both sides of the vehicle during the straight driving of the unmanned tracked vehicle. If obstacle exists and affects normal driving, transfer to the emergency braking state, separate the main clutch and set the brake to avoid collision. Its work flow is shown in Figure 3.

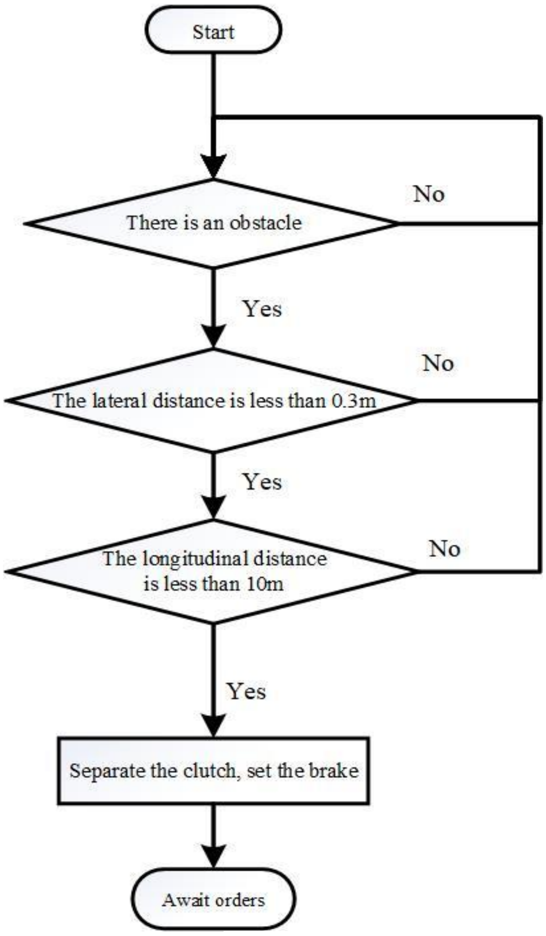

Figure 3. Strategy process under emergency braking state

4.2. Safety Policy Verification

The safety strategy was verified by simulation experiments, finding that it took 6.7s from adoption of braking avoidance measures when circumstances occur to the lifting of hazard. The braking distance was 6.8m, and the speed was reduced from 6.8km/h to 0km/h. The experimental results are shown in Figure 4. In the real vehicle verification, it took 6.4s from adoption of braking avoidance measures when circumstances occur to the lifting of hazard, and the braking distance was 6.6m.The experimental results are shown in Figure 5.

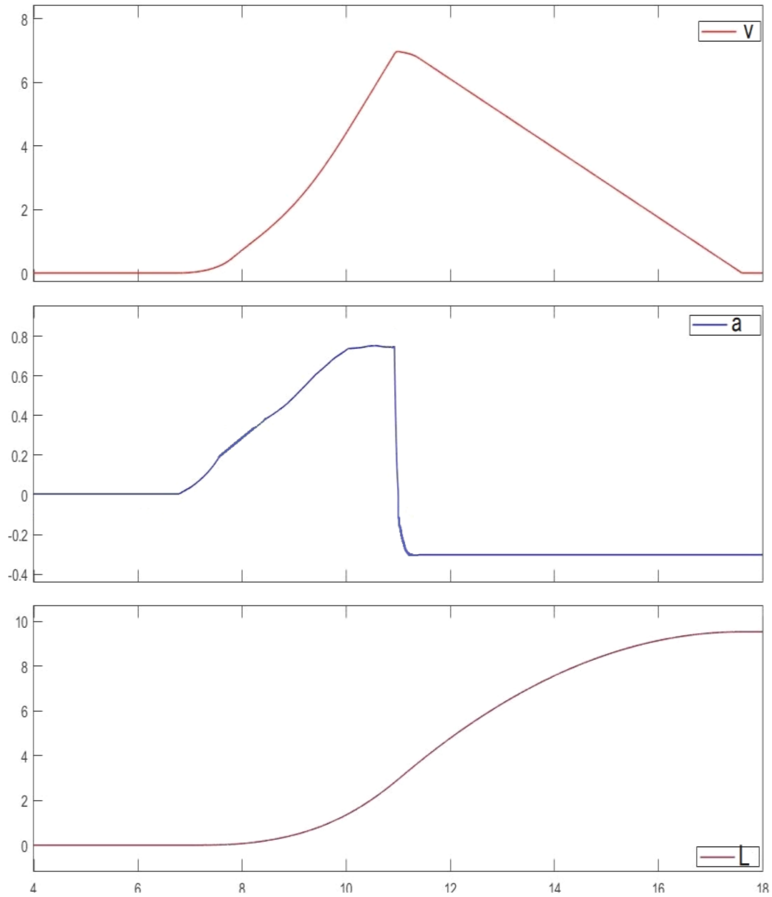

Figure 4. Simulation verification results

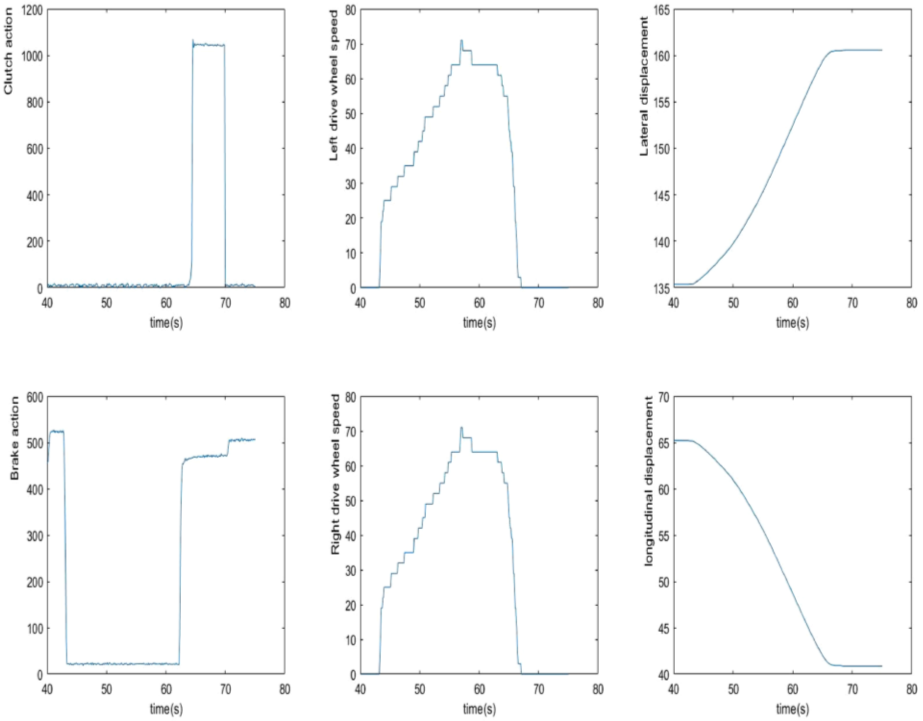

Figure 5. Real vehicle verification results

The above test results show that after the application of safety strategy in unmanned tracked vehicle, the vehicle detects hazardous situations in time and avoids collisions with obstacles. The proposed safety strategy effectively avoids collisions.

5. Conclusion and Outlook

This paper puts forward a STPA theory-based safety system development method by studying the safety issues of autonomous driving systems. Through the three links of hazardous situation analysis, safety strategy design and simulation and real vehicle verification, an iterative development method is formed for closed-loop safety system. In view of the characteristics of unmanned tracked vehicle, control architecture is established for different functional states, and unsafe control behaviors under different error modes are analyzed. Safety strategy is proposed for one of the functional states. The safety strategy is analyzed through model simulation and compared with the real vehicle test to verify reliability of the safety strategy.

The research also has major limitations: ① The safety analysis process mainly depends on the experience and domain knowledge of the personnel, and screening based on objective reality is required; ② The analysis process lacks standardized procedures. In subsequent studies, we will standardize the analysis procedures and further investigate the quantitative safety analysis methods.

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