Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnline CONFERENCE PAPER ARCHIVE

IFAC PapersOnLine 58-4 (2024) 150–155

Safe and Fault Tolerant Control of Industrial Differential Drive Vehicles

Vito Andrea Racanelli * **Saverio Mascolo** *

* *Polytechnic University of Bari, Bari, Italy e-mail: {vitoandrea.racanelli, saverio.mascolo}@poliba.it*

Abstract: Differential drive vehicles are an integral of industrial operations, where precise control is essential for safety and efficiency. These vehicles often employ encoders for precise maneuvering through closed-loop control. In this scenario, system failures can result in uncontrolled movements, posing significant risks to human operators.

To address this issue, this paper proposes a robust and fail-safe controller model that ensures vehicle safety, even in the face of multiple failure scenarios. The proposed model provides a comprehensive solution to address various potential problems encountered in industrial environments.

Based on fault tolerance and control theory principles, our model incorporates innovative strategies to mitigate encoder failures, sensor malfunctions, and other related system faults. The design and performance of the controller are thoroughly analyzed to demonstrate its effectiveness in preventing catastrophic failures in industrial environments.

1. INTRODUCTION

Manufacturing and logistic enterprises employ vehicles for the execution of tasks and the movement of loads. Depending on the scope of use, the weight of these vehicles can range from a few hundred kilograms to tenths of tonnes. Consequently, during maneuvers, these vehicles can pose significant risks to human operators.

While the overwhelming majority of incidents involving these vehicles result from operator distraction or imprudence, a small percentage is attributable to the failure of sensors, actuators, or the control system mounted on them [OSHA (2023)]. The European Union Directive 2006/42/EC [htt (2006)] and lower-level international regulations (e.g., UNI 280) establish mandatory minimum safety requirements that manufacturers of such machinery must adhere to.

The required level of safety for these vehicles is directly proportional to the vehicle's inherent danger. The greater the potential damage a vehicle failure can cause, the higher the likelihood of such failure, and the higher the required degree of safety for the vehicle. The Safety Integrity Level (SIL), as defined by [IEC (2010)], serves as a measure of the safety system's performance in terms of the probability of failure on demand (PFD). There are four distinct safety integrity levels: SIL 1, SIL 2, SIL 3, and SIL 4. A higher SIL corresponds to a higher associated safety level and a lower probability of system malfunction. Generally, as the SIL level increases, so do installation and maintenance costs, as well as system complexity. Designers of vehicles utilized in industrial settings must consider the mandated safety levels throughout the design phases, striving to minimize, to the greatest possible extent, any reduction of the vehicle's functionalities.

Vehicles employed in industrial environments are predominantly electrically powered and are controlled open-loop, that is, the operator's control action (e.g., via a joystick, lever, or pedal) affects the motor drive signal. This approach reveals sub-optimal when looking at the maneuverability of such vehicles. For instance, a vehicle operating in an open-loop system may exhibit vastly different behaviors with the same control signal on an incline versus a decline. To address this issue, it is necessary to implement a feedback-controlled speed system, which can be realized by using speed sensors (e.g., encoders) and well-established PID controllers [Astrom (1995)]. While the implementation process may be relatively straightforward, ensuring its secure implementation is nontrivial. As the number of components within a control system increases, so does the probability of failures. Therefore, it is crucial to design the system having a deep understanding of the potential risks of failures so that proper countermeasures can be designed [Koren and Krishna (2020) and Isermann (2005)]. The literature on fault-tolerant speed control systems is rich. Bourogaoui et al. (2016) provides a comprehensive overview by examining various sectors employing speed control systems. Despite considerable research efforts directed toward the development of increasingly fault-tolerant methodologies, past researchers have not placed significant emphasis on sensor failures, particularly those related to rotary speed measurements.

Tabbache et al. (2012) addresses the detection of sensor faults in the context of a reconfigurable direct torque control system applied to an electric vehicle powered by an induction motor. It focuses on identifying faults in current, voltage, and speed sensors, which are then followed by the implementation of post-fault-tolerant control measures to ensure the continuous operation of the vehicle. Based on the posterior reliability voting algorithm, the methodology proposed by Fan and Zou (2012) can discern the intact state of an encoder and subsequently recalibrate the weights associated with the velocity derived from the encoder and the estimated velocity based on a Model-Based

2405-8963 Copyright © 2024 The Authors. This is an open access article under the CC BY-NC-ND license.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2024.07.209

Adaptive Structure. In Zidani et al. (2007) fuzzy logic is proposed for detecting and diagnosing motor state. Tang et al. (2021) presented an active fault-tolerant control approach for 4WDW electric vehicles, employing an unmatched disturbance observer, adaptive sliding mode control, and fault-tolerant allocation to enhance stability and tracking performance in the presence of actuator faults, validated through hardware-in-the-loop simulations. The paper proposes a robust and fail-safe controller model that ensures continued vehicle safety, even in the face of multiple failure scenarios.

This paper is structured as follows: Section 2 introduces differential drive vehicles and provides an overview of the safety control system. Section 3 outlines the fault scenarios considered in the system. In Section 4, the mathematical modeling of the control system is outlined. The experiments and results obtained from the validation of the control system are presented in Section 5. Finally, Section 6 concludes the paper.

2. A DIFFERENTIAL DRIVE VEHICLE

Differential drive vehicles are a category of mobile platforms primarily employed in industrial settings that enhance maneuverability when compared with the conventional Ackermann kinematics. The fundamental mechanics of differential drive vehicles involve two (or more) independently driven wheels. Two or more motors allow the rotational speed of each wheel to be independently set, enabling the execution of precise maneuvers, including forward and backward movement, pivot turns, and complex curves (see Fig. 3). A forklift is a prime example of a differential drive vehicle used in warehouses and factories, where its capacity for intricate movements makes it invaluable for lifting and transporting heavy loads.

Central to the distinctive capabilities of differential drive vehicles is their steering mechanism, which is realized by the possibility of setting different speeds for each wheel using one electric motor for each wheel. For instance, to initiate a right turn, the left wheel accelerates while the right one decelerates, causing the vehicle to pivot around its central axis. This results in exceptional agility and accuracy, making these vehicles suitable for applications demanding precise control in constrained spaces and uneven terrains.

A common practice in differential drive vehicles to obtain precise speed control and navigation is to use encoders on each wheel to allow closed-loop control of the speed. These encoders provide real-time feedback on the wheel rotation speed and position. However, it is of the utmost importance to consider that these encoders are susceptible to failures, such as signal loss or sensor malfunctions, potentially leading to a risky uncontrolled vehicle.

Therefore, despite their advantages, these vehicles present specific technical challenges in terms of safety and reliability. Ensuring the dependable operation of these vehicles, even in the face of sensor and encoder issues, asks for advanced fault-tolerant control models and safety measures which is what this paper focuses on.

2.1 A Safe Control system

In order to operate a safe feedback control of the left and right wheels in a differential drive vehicle, we propose the four-state machine depicted in Fig. 1.

The starting state is the *IDLE* state, wherein the machine is expected to remain stationary while the controller awaits commands from the operator.

Following the operator's issuance of commands, the machine changes to the *ARMED* state, where a meticulous test on the encoder's functionality must be executed. If the test is successful, then the machine is allowed to enter the *MOVING* state; otherwise, the machine enters the *FAIL* state.

The *MOVING* state is characterized by the controller's nominal operation, involving also real-time analysis of sensor data to identify potential failure conditions. The controller stays in this state until the operator issues further commands or until a system failure is detected.

Upon the detection of a failure, the *FAIL* state is entered by the controller, which is a secure mode. This failure may happen during the encoder test at the startup time or when the machine operates in the *MOVING* state. When in the *FAIL* state, all outputs to motor drivers are restrained, thereby cutting power and stopping any movement. Upon the operator's release of commands, the controller gracefully reverts to the *IDLE* state, providing a mechanism for resetting false positive detections.

In case the detected failure is authentic, upon the operator's subsequent command issuance in the *ARMED* state, the startup test failure ensues, compelling the controller to return to the *FAIL* state. If the fault detected is authentic, the next command issued by the operator in the *ARMED* state will cause the startup test to fail, forcing the controller to return to the *FAIL* state.

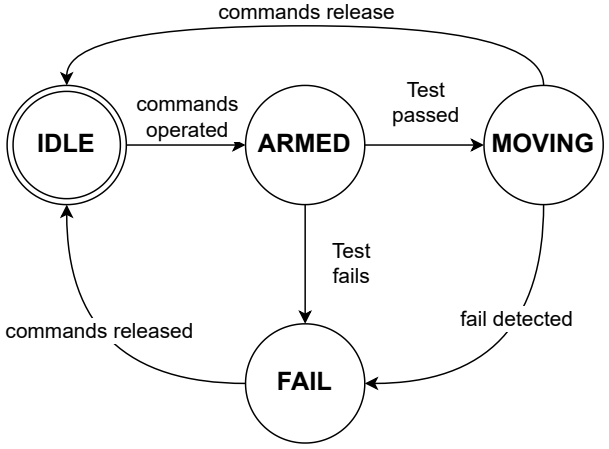

Fig. 1. The proposed state machine to operate a safe controller

3. FAULT SCENARIOS

This section examines different types of faults that are potentially harmful to the safe operation of the vehicle. A detailed enumeration of different fault types is provided, each characterised by different degrees of severity and frequency. Some of these faults are highly critical and require

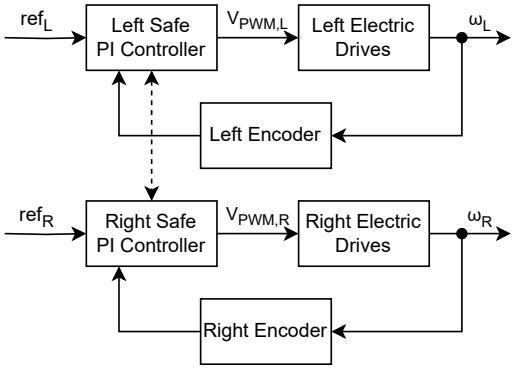

Fig. 2. Block diagram of a safe control system for a differential drive vehicle

a rapid response from the controller, while others are less severe and can be managed with controller adjustments. It should be noted that the frequency of their occurrence jeopardises the efficiency of the system.

3.1 Sensor Faults

Potential faults that can affect incremental encoders include mechanical, electronic and optical faults.

In this manuscript, we have simplified their classification into three distinct categories:

Encoder detachment. These types of failure are referred to as $\Delta E_{1,L}$ and $\Delta E_{1,R}$, and involve the Left or Right Encoder becoming detached, which occurs when the encoder's connection to the shaft becomes loose, causing the encoder to shift along the axis to, in the most extreme scenario, completely detachment. While this failure is very serious, its likelihood of occurring is quite low. This can result in either a zero value or a fluctuating value in the speed measurements.

Encoder stuck. The encoder may become stuck, which is identified as faults $\Delta E_{2,L}$ and $\Delta E_{2,R}$. This fault is very serious and happens frequently. It can manifest as either an electrical or mechanical issue, causing the speed measurements to remain at a constant value.

Generic encoder failure. The last type of encoder failure we consider is the generic encoder failure, labeled as $\Delta E_{3,L}$ and $\Delta E_{3,R}$. This type of failure can be either electrical or mechanical. It is characterized by a high level of severity and a low frequency of occurrence. This type of failure results in random speed measurements.

3.2 Actuator Faults

Both the electric drives can fail. Drives faults considered are:

Motor detachment. This occurs when a motor is disconnected from the electric driver that acts as a power source. The severity and frequency of its occurrence are low. It is denoted as ΔM_L and ΔM_R.

Driver shorts. This situation arises when two channels on the H-bridge become shorted in a manner that allows current to pass to the motor, resulting in the motor being short-circuited to the power supply voltage. The severity of this failure is very high and its frequency is rare. It is denoted as ΔSC_L and ΔSC_R.

Driver broken. This situation occurs when two channels of the H-bridge are shorted in a way that allows current to pass to the motor, resulting in the motor being short-circuited to the supply voltage. The severity of this fault is very high and its frequency is rare. It is referred to as ΔDB_L and ΔDB_R.

3.3 Safety requirements

The safety requirements are outlined in this subsection, and the fault detection time T_D, for the corresponding failures, is defined as multiple of the control sampling time T_s.

Fault	Severity	Occurency	Detection time
$\Delta E_{1,L}$,$\Delta E_{1,R}$	Very high	Low	$T_D < 50T_s$
$\Delta E_{2,L}$,$\Delta E_{2,R}$	Very high	Medium	$T_D < 150T_s$
$\Delta E_{3,L}$,$\Delta E_{3,R}$	High	Low	$T_D < 150T_s$
ΔM_L,ΔM_R	Low	Low	$T_D < 50T_s$
ΔSC_L,ΔSC_R	Very high	Very Low	$T_D < 50T_s$
ΔDB_L,ΔDB_R	Low	Low	$T_D < 50T_s$

Table 1. Considered faults

False detections: The number of false positives must be kept as low as possible to avoid the vehicles becoming unusable. We have required that the minimum time between consecutive false positives should be less than 360,000 samples (approximately 1 hour). In the event of a false positive detection, the controller will push the machine into the *FAIL* state, easily re-set by the operator by releasing the commands to activate the machine and run the startup test again. The detection will be either confirmed (correct detection) or refuted (false positive).

Missed detections: All faults should be detected.

Safe state behavior: An essential feature is to define a policy regarding the controller's behavior in the event of fault detection. In case of a failure, the controller must promptly bring the speed of both motors to zero. This is achieved by reducing to zero the power supplied to both motors and, if available on the vehicle, engaging the brakes.

4. SYSTEM MODEL

4.1 The electrical drives model

The DC Motor can be modelled as a second-order system [Franklin et al. (2015)]:

$$G_M(s) = \frac{\dot{\Theta}(s)}{V(s)} = \frac{K_t}{(Js+b)(Ls+R)+K_tK_e} \qquad (1)$$

where: V is the voltage source, $\dot{\Theta}$ is the speed of the shaft, J is the moment of inertia of the rotor, b is the motor viscous friction constant, K_e is the electromotive force constant, K_t is the motor torque constant, R is the electric resistance and L is the inductance of the motor.

The gearbox is a mechanical device used to transmit power and change the speed and the torque between the motor shaft and the load shaft. In the context of our research, the

complexities associated with its dynamic behaviors have been deliberately omitted. Consequently, for the analytical framework of our study, we construe the gearbox as an idealized kinematic model characterized by a constant gain called gear-ratio.

$$K_r = \frac{R_M}{R_L} \tag{2}$$

where: R_M is the radius of the motor gear and R_L is the radius of the load gear.

The driver for a DC motor is an electronic device that controls the motor's speed, direction, and other parameters. It provides power and control signals to operate the motor effectively.

$$V = \frac{V_{PWM}}{\gamma} V_{cc} \tag{3}$$

where: V_{PWM} is the voltage control action expressed in Pulse With Modulation (PWM) units, γ is the digital resolution of the driver expressed in PWM and V_{CC} is the supplied voltage of the system.

Combining 1, 2 and 3 the motor drives can be written as:

$$G_P(s) = \frac{\dot{\Theta}(s)}{V_{PWM}(s)} = \frac{K}{(Js+b)(Ls+R) + K_t K_e} \tag{4}$$

where:

$$K = \frac{K_t K_r V_{cc}}{\gamma} \tag{5}$$

For simplicity, we can end our modeling here without considering friction, saturation effects, etc. As we will discuss further in the controller description, the verification of the deviation from the nominal model to the actual plant occurs only during the *MOVING* state, so the effects of friction are negligible in this scenario. The same is true for uncertainty or parametric variation, as the check of the deviation from the nominal to the actual plant is done by evaluating whether the absolute error is below a certain threshold. Failure of this check could indicate either a real fault or a false detection caused by excessive parametric variation. In the case of a false positive, it wouldn't be a problem for our application, but rather a maintenance indicator.

4.2 Differential drive vehicle model

The kinematics of a differential drive vehicle can be modelled as follow [Siegwart et al. (2011)]:

$$v_c = \frac{r(\omega_R + \omega_L)}{2} \quad \omega_c = \frac{r(\omega_R - \omega_L)}{L} \tag{6}$$

where: v_c is the linear speed of the vehicle, ω_c is the rotational speed of the vehicle, r is the radius of the wheels, L is the distance between the center of the wheels and ω_i with $i = L, R$ is the rotational speed of the wheels, respectively left and right.

4.3 Sensor

For our system, we have chosen differential incremental encoders as the speed sensors. Unlike absolute encoders, incremental encoders do not provide information about the absolute position of the rotor to which they are attached. However, this is not a problem since our control objective is velocity rather than absolute position.

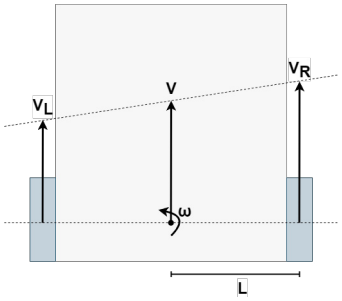

Fig. 3. Scheme of differential drive vehicle kinematics

An incremental encoder consists of a disk divided into N slots. A light-emitting diode (LED) and a photodiode are positioned on the sides of the encoder disk. As the disk rotates, interrupting the light emitted by the LED, the sensor transmits a signal containing information about the shaft's positional change. These impulses form a square wave. The longer the period of this wave, the lower the rotational speed of the motor shaft. Conversely, a higher frequency of impulses represents a higher speed. This square wave signal is transmitted as a dual signal on two channels (denoted ch=A,B) that are phase-shifted by $\pi/2$ radians, allowing us to determine the direction of rotation.

While the instantaneous speed cannot be determined with encoders, the average speed within an observation time ΔT can be calculated by counting the number of rising and falling edges using the formula:

$$N_{ch} = \sum_{k=1}^{K} \frac{|V_{ch}(k) - V_{ch}(k-1)|}{V_{enc}} \tag{7}$$

Normalized with respect to the encoder's supply voltage V_{enc}, this formula allows to determine the number of edges within a time ΔT, where K represents the number of samples acquired during the observation. This computation is performed for both channels A and B. In addition, V_{ch} denotes the voltage of the channel.

The rotational speed of the encoder is expressed as:

$$\omega_{ch} = \frac{2\pi}{4PPR} \frac{N_{ch}}{\Delta T} \tag{8}$$

Here, Pulses Per Revolution (PPR) represents the encoder resolution, quantified as the number of impulses per revolution of the encoder disk. The denominator of the rotational speed of the encoder is multiplied by 4 times the PPR because quadrature decoding doubles the count for each state change of both channel A and B, resulting in 4 times the count for each pulse or period.

4.4 Controller

The vehicle controller operates within a state machine, as described in the section 2.1. The controller is implemented with a sampling frequency of 100Hz, and it starts in the *IDLE* state.

The condition for moving from *IDLE* to *ARMED* is that $r_L \neq 0 \vee r_R \neq 0$. It is evident that, as with industrial vehicles, safety regulations require measures to prevent accidental activation of the vehicle. Due to paper length constraints, these details are omitted. Therefore, we only consider the reference resulting from the operator's action.

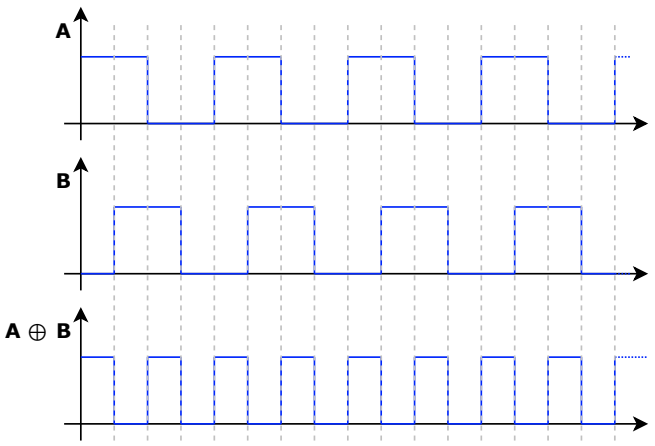

Fig. 4. Representation of signals originating from channels A and B of the encoder. The third plot depicts the outcome derived from the exclusive OR (XOR) operation applied to these channels ($A \oplus B$).

In the *ARMED* state, the system performs a pre-departure check of the encoder and motor functionality. This test leverages the backlash within the gearbox [Nordin and Gutman (2002)]. Regulations dictate that the vehicle cannot be activated without the explicit intention of the operator. Typically, a test involving motor activation would violate this requirement. However, by utilizing the backlash within the gearbox, it is possible to conduct a micro-actuation on the motor shaft that is not transmitted to the wheel.

Algorithm 1 Algorithm of the start test

$direction \leftarrow 0$ ▷ $0 = CCW, 1 = CW$
`test procedure:`
$actuateMotorsForTest(direction)$
while test is running **do** recordEncodersData()
end while
$N_A, N_B \leftarrow countPulseCh(A, B)$ ▷ Eq. 7
$\omega_A, \omega_B \leftarrow computeSpeedCh(A, B)$ ▷ Eq. 8
$AB \leftarrow computeXORChannels()$
$\omega_{AB} \leftarrow computeSpeedCh(AB)$
$C_1 \leftarrow N_A - (N_A \mod 2) == N_B - (N_B \mod 2)$
$C_2 \leftarrow \omega_A == \omega_B$
$C_3 \leftarrow \omega_{AB} == 2\omega_A$
if $C_1 \wedge C_2 \wedge C_3$ **then** ▷ Test passed
  $testPassed \leftarrow 1$
else if direction is 0 **then**
  $direction \leftarrow 1$ ▷ Retry changing direction
  `goto test procedure`
else
  $testPassed \leftarrow 0$
end if

The motor is driven with a very low pulse width modulation (PWM) value, insufficient to move the vehicle but sufficient to rotate the motor shaft freely within the backlash zone. If, during this operation, waveform edges aligned with the model are detected, the test is considered successful.

If no waveform edge is detected at the encoder input, the test is repeated by activating the motor in the opposite direction, since the gear attached to the motor shaft might be in contact with the gear attached to the driving wheel. If this operation detects waveform edges that match the model, the test is considered successful. Otherwise, if none are detected, the test is deemed definitively failed, indicating a possible disconnection of the encoder or a broken motor driver. The controller prevents the vehicle from moving, signals the malfunction, and pushes the machine into the *FAIL* state.

Specifically, we check equation (9) to make sure that the number of edges detected on both channels, if even, is the same. In the case of an odd number of edges on one channel, we subtract 1.

$$N_A - (N_A \mod 2) = N_B - (N_B \mod 2) \tag{9}$$

After confirming this, we make sure that the detected speed is the same for both channels of the encoder. If this speed corresponds, it will be the measured rotational velocity: $\omega_A = \omega_B \triangleq \omega$.

Confirming that the number of edges and the velocity are the same on both channels is not enough to ensure safety. One of the two channels (or both) could show anomalous behavior and manage to overcome the first two checks. Therefore, we proceed to perform an XOR operation between the two channels ($A \oplus B$) and calculate the measured velocity ($\omega_{A \oplus B}$). By performing the XOR operation, if the signals are correct, we double the signal frequency. If there are no problems with the encoder, we must verify that: $\omega_{A \oplus B} = 2\omega$.

If a higher-than-expected speed is detected during the test, the test will stop and fail. This could indicate a short circuit in the motor driver. The controller prevents the vehicle from moving, signals the failure, and puts the machine in the *FAIL* state.

If the test is successful, the controller enters the *MOVING* state. In this state, the PI controller operates normally, adjusting the motor speed to the required setpoint. During this state, the motor current consumption and speed measurements from the encoder are monitored. If the data deviates from the model, a fault is detected, and the machine enters the *FAIL* state. Real-time analysis of the sensor data verifies that the difference between the sensor estimate and the actual value is always below a certain threshold.

Finally, in the *FAIL* state, motor activation is inhibited, preventing any movement of the machine.

The PI controllers for both motors, although operating independently, communicate with each other when they detect a fault. When one controller detects a failure, it communicates this information to the other controller, and both simultaneously enter the *FAIL* state.

5. EXPERIMENTS AND RESULTS

This section describes the experimental validation of the proposed fault detection system. To assess the vehicle dynamics, it is assumed that the operator follows the trajectory shown in Figure 5. Moving along this trajectory, it is possible to experiment with right and left movements. Moreover, the experiment has focused on the forward

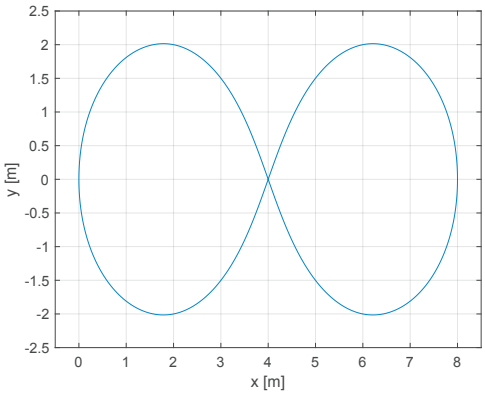

Fig. 5. Vehicle trajectory considered in the experiment

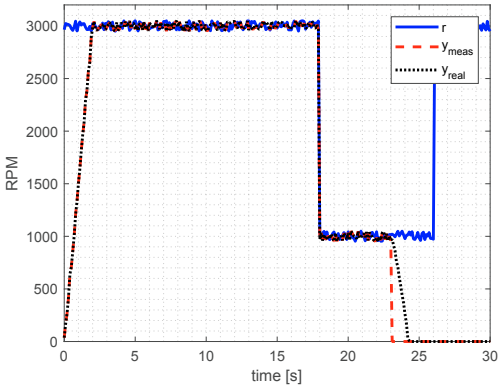

Fig. 6. Excerpt of a experiment with fault injection.

movement along this trajectory since the backward movement along the same trajectory does not add any further insight.

In the experimental setup, we have employed 24V DC motors. Hall effect differential encoders were mounted on the motor shafts. We utilized a custom control board with a Microchip microprocessor and a custom power driver capable of working with motors up to 2kW. The experiments lasts for 5 minutes.

Failures should be detected and managed according to the requirements specified in Section 3.3. To execute the validation, random failures have been injected during the experiment. These experiments were repeated 100 times to exhaustively validate the safety system.

Figure 6 shows an excerpt of an experiment. It shows the speed set point (blue solid line), the speed measured by the encoder (Dashed red curve) and the actual speed (dotted black curve). At the beginning of the experiment, there is a short transient period after which the motor stabilizes at the reference speed. At t=23s, a fault is injected that is detected a few milliseconds later, leading the motor into a quiescent safe state.

6. CONCLUSION

This paper contributes to the field of industrial operations by addressing the challenge of ensuring safe operation of differential drive vehicles in the presence of encoder failures and sensor malfunctions, which would cause control system failure and pose significant risks to human operators.

The proposed safe control system has been developed by combining principles of fault tolerance and control theory and has been tested in simulation and real industrial settings. Experiments have shown the effectiveness of the proposed fault detection system in the presence of component faults.

ACKNOWLEDGEMENTS

This work has been partially funded by Quavlive S.r.l.

REFERENCES

(2006). Directive 2006/42/ec of the european parliament and of the council of 17 may 2006 on machinery, and amending directive 95/16/ec (recast) (text with eea relevance).

(2010). International electrotechnical commision, iec 61508-1, functional safety of electrical/electronic/ programmable electronic safety-related systems.

Astrom, K. (1995). Pid controllers-theory. *Design and Tuning*.

Bourogaoui, M., Sethom, H.B.A., and Belkhodja, I.S. (2016). Speed/position sensor fault tolerant control in adjustable speed drives–a review. *ISA transactions*, 64, 269–284.

Fan, S. and Zou, J. (2012). Sensor fault detection and fault tolerant control of induction motor drivers for electric vehicles. In *Proceedings of the 7th International Power Electronics and Motion Control Conference*, volume 2, 1306–1309. IEEE.

Franklin, G.F., Powell, J.D., and Emami-Naeini, A. (2015). *Feedback control of dynamic systems*, volume 33. Pearson London.

Isermann, R. (2005). *Fault-diagnosis systems: an introduction from fault detection to fault tolerance*. Springer Science & Business Media.

Koren, I. and Krishna, C.M. (2020). *Fault-tolerant systems*. Morgan Kaufmann.

Nordin, M. and Gutman, P.O. (2002). Controlling mechanical systems with backlash—a survey. *Automatica*, 38(10), 1633–1649.

OSHA (2023). Occupational safety and health administration - fatality inspection data. `https://www.osha.gov/fatalities`.

Siegwart, R., Nourbakhsh, I.R., and Scaramuzza, D. (2011). *Introduction to autonomous mobile robots*. MIT press.

Tabbache, B., Benbouzid, M., Kheloui, A., and Bourgeot, J.M. (2012). Dsp-based sensor fault detection and post fault-tolerant control of an induction motor-based electric vehicle. *International Journal of Vehicular Technology*, 2012.

Tang, H., Chen, Y., and Zhou, A. (2021). Actuator fault-tolerant control for four-wheel-drive-by-wire electric vehicle. *IEEE transactions on transportation electrification*, 8(2), 2361–2373.

Zidani, F., Diallo, D., Benbouzid, M., and Berthelot, E. (2007). Diagnosis of speed sensor failure in induction motor drive. In *2007 IEEE international electric machines & drives conference*, volume 2, 1680–1684. IEEE.