Autonomous Line-Following Vehicles: Bridging Educational Robotics and Industrial Automation

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Abstract. This article describes an autonomous vehicle model that has been developed for educational purposes, serving as a prototype, in which central aspects that are also present in industrial system navigation design are realized. The vehicle employs an Arduino Nano as a controller and three infrared sensors, each of which is independently driven. This contraption can independently navigate along a predetermined route without any human input. The finite state machine is used to control the vehicle's behavior in various track sections. It shows the implementation of rule-based decision-making at the level of embedded systems. The system employs dynamic speed operation through calibrated PWM signal values. The challenge of the precision of tracking a line with an automated and at the same time high-speed vehicle was addressed, resembling the challenge of the full-scale automated vehicle design.

Keywords: autonomous navigation; line-following robot; industrial automation; embedded systems; sensor fusion.

1 Introduction

As the Fourth Industrial Revolution ushers in automation technologies that enable smart manufacturing and logistics [1], global supply chains account for the viability of autonomous material handling machinery in optimizing productivity and reducing human staffing costs. The worldwide market for automated guided vehicles is expected to grow to $13.2 billion by 2027 [2]. E-commerce trends in online retail and the shift to responsive manufacturing systems will drive demand growth for more versatile applications. AGVs, which transport materials and components on factory floors, are guided by instructing technologies, and line-following remains the most affordable as well as the most robust in organized environments [3]. Many leading automotive assembly factories, such as BMW's and Toyota's assembly plants, have hundreds of AGVs, while Amazon's product distribution systems employ thousands of autonomous robots [4]. The ability for a general-purpose line-following robot to model the next-generation implementations of industrial robotics is due to the overlap between the sections of advanced material handling systems and the principles of our educational technology. The line-following robot serves as a synergetic stage where foundational robotics and embedded systems

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concepts can reinforce understanding of real-world autonomous technologies, illustrating that the modeling created in many entry-level automation systems can scale up to industrial systems. Industries not only employ AGVs but will also benefit from the foundational knowledge by understanding the AI sense-plan-act framework [5]. Our robot is a novice constructor's introduction into the world of automobile programming notions like the aforementioned architecture. The components of our car—building a system to sense its environment, process the senses collected, interpret the current state, implement a decision by executing rules, and control an actuator as a result—recognize the same procedures happening in these somewhat futuristic automobiles, such as a Tesla, as well. The devices that integrate all these functions from an algorithmic point can be very similar—thw car's IR sensors serve the same purpose and collect the same feedback information as the cameras and LiDARS on a real self-driving automobile; the Arduino, which eliminates the need for a computer to run the software, will be a vehicle's main computer, its electronic control unit, and so on; the way we implement decisions is through a state machine dictating the steps; the output to the input from decision-making is through an actuator motor and all the hardware, as is done in a cutting-edge automobile. Functionally, the modern autonomous car has become a highly sophisticated version of the line-follower in application. Accordingly, this paper seeks to discover and understand a line-following robot design methodology through its theoretical implications as a parallel between automotive systems and educational robotics, exploration of optimization strategies for advanced implementations, and revelation of design system tradeoffs. The next sections of this text will focus on the application of the construction and what benefits a company might find in the technology if integrated into its own systems. The first section will focus on the overall system design and discussion of applications, then optimization techniques and implementations, and finally, discussion and conclusion.

2. System architecture and design methodology

2.1. Sensor configuration

The system on the vehicle comprises 3 infrared reflectance sensors that allow for primitive perception. The two sensors on the front sides work for the line segmentation task by computing the line intensity difference on a white line (the line supposed to be followed) versus the background (black). In addition, a bumper sensor is mounted passively to sense the contact point of the start and the finish. Despite the simplicity of the system, these sensors represent a set of key perception principles that easily scale to any industrial applications. Both line sensors perform the thresholding process by computing the line-invisibility effect using the contrast between a white line and the visual background (black). It produces a machine state in the 'on' or 'off' mode, which shows whether the system is staying on the line or not, which is similar to various sophisticated industrial vehicles that apply different types of technologies for guidance, including magnetic tape, visual guidance, and laser guidance [3]. The conversion of the continuous signal into categorical data is a key principle in perception, regardless of the scale. Finally, the bumper sensor is a passive device that closes the circuit and creates the on/off switch when the vehicle runs into the contact points on the track. In fact, contact sensors are present as a part of industrial-grade systems, where they are mostly used as a safety backup solution. In modern automated guided vehicles, multiple laser range finders for obstacle mapping, usually supplemented with cameras for visual guidance, are used as the main perception system, while bumpers, or multiple-level contact sensors, are often included as a line of a last resort for helping to avoid catastrophic failures [4]. The hierarchically organized sensor system is a principle that repeats often in the previous stages of vehicle design, and the simple line-following application demonstrates it on a very basic level.

2.2 Actuator configuration

Table 1. Actuator Configuration

Component	Educational Implementation	Industrial Analogue
Left motor	PWM D9, Direction D10	AGV drive motor
Right motor	PWM D11, Direction D12	AGV drive motor
Motor driver	L298N H-bridge	Industrial motor controller
Speed control	PWM (125-175 range)	Variable frequency drive

The differential drive system, with left and right wheels that can be independently actuated, is the most prevalent form of indoor mobile robot locomotion [6]. Left and right motors are actuated via PWM on pins D9 and D11 respectively, while actuator direction is handled by control pins D10 and D12. The educational implementation is closely related to industrial implementations, as shown in Table 1, which details the actuator configuration of the prototype as well as the analogies between the prototype and AGV in terms of the actuator system. Left and right motors are the educational analogue to AGV drive motors and are responsible for providing the required torque and velocity control to propel the vehicle forward. An L298N H-bridge is used as the motor driver and is the educational analogue to industrial motor controllers, which are responsible for controlling the flow of current across the motor and direction of rotation. Velocity control is done via PWM in a calibrated range of 125 to 175 and is the educational analogue to the variable frequency drives industrial devices use to control velocity and acceleration profiles of actuators. PWM calibration, which involves determining a set of values to use for straight path and cornering moves, is an educational analogue to motion profiles used in industrial systems. A PWM of 175 is sufficient for straight path actuations, but lowering the PWM to 150 stabilizes turns. Industrial systems often optimize actuation in terms of accelerator profiles and cornering speeds to choose a compromise between speed and position accuracy [7].

2.3 Control logic

Table 2. State Machine Design

State	Sensor Condition	Action	Industrial Equivalent
a = 2	Basic line following	Reactive control	Continuous path following
a = 3	Hard left turn	Timed 1000ms turn	Intersection navigation

State	Sensor Condition	Action	Industrial Equivalent
a = 4	Right turn	Multi-step turn	Warehouse aisle turning
a = 13	Final approach	Precision alignment	Docking station approach

The finite state machine is the primary vehicle control architecture and is a common design pattern used in the industrial space. Programmable logic controllers (PLC), which underlie factory floor automation, typically run ladder logic instruction that implements state machine control schemes similar in nature to those presented in this project board [8]. The full state machine design with sensor conditions, actions, and industrial equivalent is summarized in Table 2. In the normal operating mode where both line sensors are picking up the line, state a = 2, basic line following is performed by reactive control (via the maze-in-the-skid reactive algorithm). This action is paralleled in the industrial space by continuous path following automated guided vehicles (AGV). When a hard left obstacle is detected, state a = 3, a timed 1000ms turn is performed by the vehicle. The more elaborate right hand turns requiring a multi-step turn follow in state a = 4. This timed and sequenced action is paralleled by intersection navigation in the industrial AGV space where vehicles must reliably make turns at right angles for safe operation. When the vehicle detects the finish marker (in state a = 13), a form of precision alignment is performed and is paralleled by the docking station approach routine industrial AGVs use to enable reliable material-handling operations. Reactively used turn cues followed by rapid maneuvering illustrate the concept of hybrid control schemes where a reactive system rapidly responds to conditions but may use time-based sequences to handle other situations [9]. A similar architectural design is found in the industrial AGV space where a vehicle may follow a reactive tape path by magnetic guidance but may have to perform some pre-programmed maneuvers for intersection navigation, orientation, or other complex facilities.

2.4 Speed Control Strategy

Table 3. PWM Calibration Results

PWM Value	Application	Performance Characteristic
175	Straight paths	Maximum speed
150	Standard turns	Balanced control
125	Precision maneuvers	Enhanced control
100	Fine adjustments	Maximum precision

PWM calibration revealed a key design trade-off characteristic of autonomous vehicles, namely speed versus precision. High speeds allow greater throughput and minimize transit times, but they compromise navigational precision and can cause automatic steering to lose the line when turning. The relationship of PWM settings to performance characteristics, as a result of these systematic experiments, is summarized above in Table 3. The maximum speed setting, PWM 175, is achieved at the highest performance level for straight paths with little navigational precision. Standard turns, which require a reasonable balance between navigation and physical operation, are best controlled with PWM 150. To control difficult maneuvers, the vehicle can slow down its performance with PWM 125 to maintain a predictable line to avoid line loss. The minimum performance grade, PWM 100, is reserved for fine maneuvers that put the maximum importance on navigational fidelity, such as stopping at a finish or error recovery. The use of state-dependent PWM, which selects the appropriate passage speed performance depending on the path being cleared, increases the total value derived from the vehicle as higher speeds are used where appropriate and vice versa for fine maneuvering. This use of state-dependent speed is similar to adaptive cruise control in automobiles that automatically adjust the vehicle's speed according to the road and surrounding traffic. It is also similar to dynamically changing speed in industrial AGV's that modify their speeds automatically according to their distance from waypoints and tricky pathways [10].

3. System optimization and real-world implications

3.1 Timing versus event-based control

A critical design choice was to change from sensor feedback-based to time-based turn execution. The initial strategy of counting sensor inputs incremented by detecting the white colour of the line failed as the robot may turn without activating both sensors. This highlights an interesting point: the reliability of event-based control depends on the platforms geometry and dynamics [6]. The approach of timed turns based on measured data has disadvantages. Timing-based control is based on the idea that the dynamics of the system remain the same (battery charge, friction force) [11]. In the industrial context, this is solved through a closed-loop control architecture using the encoder feedback. This is a concept used in many autonomous systems. The cars travelling through an intersection can not solely rely on time estimates or the lights but must also consistently scan the environment for lane and light signals. But it must use accurate time estimates to determine when to stop on red.

3.2 Inertia

To overcome inertia, overshooting behaviour during consecutive turns. The first turn faltered due to the fact that the car could not make the second turn as it has not stopped moving due to inertia before completing that turn [6]. This has industrial implications. Some Automated Guided Vehicles (AGVs) need to navigate heavier loads, requiring careful attention to inertia. Some industrial trucks must consider the inertia value of a vehicle when planning a stop. The correction made to slow the car and wait longer before the turn to improve reliability. In industrial systems, this is the point where systems must be designed while taking cycle time into account.

3.3 Hardware robustness

The whole experience of loss of single wheel with motor controller failure. Hardware robustness is clearly demonstrated in this exercise. In industrial systems, there is a lot of hardware switching, and in case of failure of the inverter in an AGV, production might halt for a long time [12]. In an AGV, we can easily mitigate this by building new hardware kits, but at this level of development, the efforts are in re-doing the work with the component fix. Industrial systems use various means for this. A complete understanding of reliability engineering would require some troubleshooting experience which this exercise covers well.

3.4 Educational-industrial parallel

Table 4. Educational-industrial Parallels

Educational Feature	Industrial Parallel
Infrared sensors	Camera and LIDAR sensors
Sensor fusion (ultrasonic, bumper)	Multi-sensor redundancy
Differential drive	AGV transport systems
PWM speed control	Variable frequency drives
State machine control	PLC ladder logic
Speed-precision tradeoff	Throughput vs. accuracy
Hardware troubleshooting	Reliability engineering

As seen in Table 4, the parallels identified. Infrared sensors are used for proximity detection in this educational project. These sensors perform a similar function to camera and LIDAR sensors used in full-scale autonomous vehicles. Sensor Fusion, the use of ultrasonic sensors to replace missing readings from the infrared line sensors, i.e., bumper switch is a common method used in industrial systems to mitigate the imperfections of other sensors. With differential drive, two independent control wheels on a common frame system, this educational project shows how these vehicles are the most common transport at industrial sites. PWM speed control: Arduino's capacity to control PWM outputs gives that function to most industrial electrical systems (like variable frequency drives). State machine control of the robot: Programmers at most industrial sites use PLC programming (ladder logic) to control industrial automation. The speed-precision tradeoff has an industrial significance in throughput and accuracy. Troubleshooting hardware and refurbishing is another experience that would have an impact on industrial reliability engineering. These parallels demonstrates in table 4 for the reasons provided above. The relevance of these parallels comes from the fact that the cognitive skills developed through the hands-on education project are of considerable value in both educational and industrial environments. Some crucial cognitive skills include the ability to think critically about the interactions of various system components, such as the Arduino and Arduino IDE, to identify potential troubleshooting strategies, to engage in optimization to find the best speed and precision balance for the robot, and to engage in systems thinking, which promotes an understanding of the significance of each component and its relationship to the system as a whole [5], particularly the relationship of each component to the rest of the components. The parallels between educational projects and industrial technologies are aligned with the educational query as they help to simplify the complex ideas that are present in full-scale implementations.

4. Conclusion

This paper puts forward a design and implementation of an autonomous line-following vehicle, specifically in the context of industrial applications. The project shows that the fundamental concepts behind autonomous navigation—sensors-based perception, rule-based decision making, actuators control, and systematic optimization—are ones that educational platforms and industrial AGVs and autonomous vehicles have in common. Among the main aspects that this work aims to cover are the production of a design process that focuses on the prototype learning analogy from an educational environment to real technical systems, and thus will serve as an implementable idea to project-based learning. This article maps the specific roles in a simple line-following vehicle to the industrial counterparts, which explains the foundational principles are invariable from the classroom exercises to the integrated AGV and self-driving cars. In general, the study gives the practical revelations related to speed precision trade-off in autonomous navigation and control techniques like state-dependent PWM adjustment applied to reduce the disturbance. Finally, this work has demonstrated that the debugging processes and systems-thinking abilities, which were honed through hands-on projects, have proven to be very useful tools in the engineering profession by applying them to the solution of real-world engineering problems. Such findings signify the role played by such engineering education in connecting to industrial practice. The car that students customize acquires the engineering intuition needed to design, implement, and maintain the autonomous systems present in modern industries. Upcoming works can include wheel encoders for closed-loop control and adaptive control strategies for machine learning tasks in autopiloting.

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