[1] Waseem Iqbal
[2] Samer Telawi
[3] Josef Börcsök

Implementation of a Safe Intrusion Detection System for Automated Door Applications Using a Safe System-on-Chip

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Abstract: - This paper proposes a systematic approach to design a safety-related intruder detection system for automated door operations for different areas of application. The implementation of the proposed safety control system according to IEC 61508 is addressed to accomplish the safety requirements of the intruder detection system. The redundancy schemes of the sensing elements and controller units with diagnostic capabilities are demonstrated in prototyping the safe operation of train doors. Different orientations of sensing elements are crucial for the detection of intruders with specific requirements. The control algorithm of the safety-related system is illustrated in form of a control flowchart. The timing diagrams elaborate results of different scenarios. The control efficiency of a safety system-on- chip as a controller to perform safety requirements is established with the help of a prototype. The prototype demonstrates high precision, safety, and reliability with the advantages of low cost and high added value.

Keywords: Intrusion detection; Automated door operation; Safety-related system; Redundancy.

I. INTRODUCTION

Technological development in computerized systems is ubiquitous in recent decades. It has pervaded human lives in various forms. The application of embedded technologies imparts an intrinsic complexity to it. This complexity is predominant in almost all phases of designing, developing, and assessing these applications. The magnitude of this complexity is accumulating in unison with the evolution and the advent of cutting-edge technologies. Safety applications implemented through embedded systems have improved the reliability and operability of equipment, processes, and systems.

Active and passive automatic operation of a door is used in multiple commercial and non-commercial applications based on the technology of sensors to detect intruding objects [1]. Biometric-based automatic operation of door access control is significantly in use in public and private areas where the security of premises and authentication of intruders are primary objectives [2]. The deployment of a processor-based system to control the safe automatic operation of doors as a processor-based prototype system [3]. The aforementioned schemes of door operation do not address the failure scenarios of the detection sensors, cameras, and microcontroller unit. The camera-based monitoring of intrusion requires an optimum angle for the operator's attention to perform a safe operation of doors. With the help of a different combination of pneumatic, hydraulic, mechanical, and/or electrical equipment, the manual or automatic operation of the computerized door applications remain a potential danger for intruders through the doors.

This paper presents the context of this work in the background section and discusses earlier research in the related work section. A general concept of the safety-related system is explained in the design concept section of this paper. This concept of a safety-related system is designed in the system design section and implemented in the prototype demonstration section that discusses the train door operation using redundant detection sensors and safety system-on-chip as a prototype. This prototype consists of a redundant fail-safe infrared sensor for the detection of an intruder, an internally developed safe-system-on-chip (SSoC) [4] with diagnostic capabilities to execute control logic, and a stepper motor-based mechanism to demonstrate the operation of train doors. The results of this prototype are illustrated in the results section. The conclusion section addresses the potential application areas of this concept.

II. BACKGROUND

The pervasiveness of processor-based decision-making on outcomes of electronic sensing equipment poses multiple safety challenges directly and indirectly to human lives. A review of the following events reinforces this proposition:

[1, 2, 3] ICAS, Institute for Computer Architecture and System Programming, University of Kassel, Kassel, Germany
Email: [1]waseem.iqbal89@icloud.com, [2] samer.telawi@uni-kassel.de, [3]j.boercsoek@uni-kassel.de

- Detection sensor malfunction: Multiple incidents occurred in India where passengers were dragged to death or severe injuries as they were trapped in metro-train doors. In these incidents, it was found that the detection sensors failed to detect intruders through the doors [5], [6].

- Ineffective Camera-based decision-making: Rail Accident Investigation Branch (RAIB) has investigated multiple incidents where passengers were trapped in train doors and dragged at different stations in London. The camera-based decision-making was found ineffective in identifying objects when the detection system of sensors did not detect intruding objects [7].

These incidents emphasize the importance of the selection of detection systems and their applications through structured and robust control. IEC-61508 recommends standard hardware and software safety-related practices.

III. Related Work

This section is mostly concerned with the earlier research projects. This does, however, include research on the use of controller-based multiple approaches in designing door control systems. It is important to note that few studies have attempted to develop safety-related features for these systems.

An effort to design a fuzzy controller-based door system is discussed by Sümbül, Coskun, and Tasdemir [8]. The system controls the door opening speed by monitoring the walking speed of the intruder and the distance between the intruder and the door. The sensors detect the input variables, which are fuzzified using the aforementioned model. The output fuzzy function is then created using basic if-else rules and other simple fuzzy set operations and using the predefined criteria, the output variable for Door Opening Speed is acquired. However, when the detection sensors fail, the overall system does not have decision-making attributes as it relies on rules programmed to operate.

Embedded camera-based monitoring of intrusion is implemented on a DSP platform to design a prototype of door control systems by Yang, Lai, Sheu, and Chen [1]. By using facial detection, the system may first recognize a target as an intruder. It can then evaluate the trajectory of the target's route to determine whether or not the intruder intends to open the door, in which case the door can be controlled appropriately. The system is proposed for feature detection to operate, whereas in practical scenarios facial features are not readily available for camera-based detection. Supervised intruders such as children, pets, or disabled people would be at risk of getting injured or stranded when the camera fails to detect them.

A relatively simple approach is implemented and discussed by Lihong and Jianxin [3] through a microcontroller-based decision- making system for safe and reliable door operation by using infrared detection sensors. The system proposes an open loop system of infrared detection sensors, a microcontroller, and a stepper motor to demonstrate the door control and operation system. This prototype does not address the safe operation of the door control when the detection sensors fail or when an intruder is stranded between the door and the microcontroller fails. A safe and redundant sensor-based measurement approach with an SSoC platform is demonstrated by Telawi, Hayek, and Börcsök [9]. The addition of a manual switch does not guarantee the safety of the intruder through the door as it requires an individual to take an action.

A demonstration of the door control system design is presented by Zubrzycki [10] to demonstrate a cost-effective alternative solution to the Vapor Rail controller. The door operation is implemented with the help of a single microcontroller and an H-Bridge. The proposed solution adds value to the monitoring of door reliable functionality. The prototype focuses on the detection of faults of overcurrent, obstruction, voltage fluctuations, door misalignment, and door velocity changes. The optical encoders and sensors are powered up by the microcontroller. The failure of the microcontroller disrupts the whole operation and poses a potential danger to intruders. Therefore, the idea of deployment of a redundant SSoC platform ensures the reliability and availability of the operation [11], [12].

IV. Design Concept

A redundancy of sensing elements and controllers is proposed to design a safety-related system for intruder detection and operation of door control. The redundancy of sensing elements can be achieved as discrete homogenous or heterogenous components [12]. The redundancy of the logic controllers or solvers can be established with the help of a safety system-on-chip. This redundancy of logic controllers plays an important role to implement diagnostic capabilities [13] for intruder sensing elements. Both controllers update each other on the

status of intruder sensing elements. Only one controller controls or drive the door control operations based on the exchanged data of both controllers, whereas the other controller gets the exact status update. The active control is switched from one controller to the other when a fault occurs on the active controller. The proposed design concept is illustrated in Fig. .

This scheme of control prevents complete system failure and implements intruder safety when one controller or both sensing elements become dysfunctional. Controller A (B) receives the sensor B (A) status data from controller B (A) and compares that data with the status data of sensor A (B), it imparts the diagnostics capability of sensing elements to the system. The auxiliary inputs may include manual opening or closing commands, door open or close status, emergency activation commands, and the running status of the train in case of train door applications. Whereas auxiliary outputs may include failure status alarms of intrusion detection sensors, controller faults, and door open or close status.

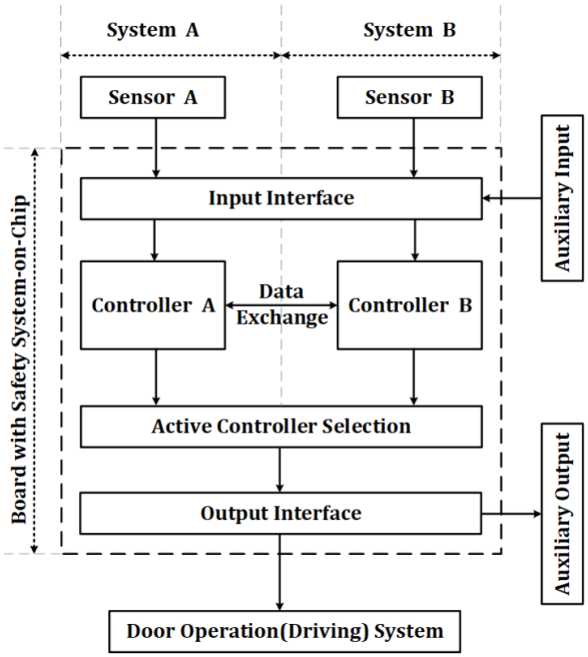

Fig. 1. A proposed scheme for the safety-related intrusion detection system.

V. SYSTEM DESIGN

The overall system controls the operation of opening and closing the doors. It achieves the safety of the intruder with the help of intrusion detection sensors. This section discusses the type of intrusion detection sensors, and the importance of their orientation. It also includes an algorithmic strategy to devise software control to execute a safety-related door operation system. The proposed algorithm can be adapted to specific requirements in different scenarios.

5.1 Detection sensors and orientation scenarios

The first and foremost step in safety-related system design is the selection of intrusion detection sensors. This selection involves criteria based on working principle, technology, target detection objects, and the type of output signals.

It is important to monitor the operational/active status of the intrusion detection sensors during the process of execution of door operation. This criterion can be accomplished by deploying sensors with Normally Close (NC) contact output as it interrupts the loop power upon intrusion detection, or it indicates a wire-break of the loop in case of sensor failure. This feature of sensors is illustrated in Fig. . The output of the detection sensor can be either sourcing or sinking output based on PNP and NPN switching transistors respectively. This feature has to be carefully selected in accordance with the input interface of the controller board. Sensors are generally categorized based on their detection principle and the technologies involved. Inductive, capacitive, ultrasonic, and photoelectric sensors are the notable non-touch type of sensor examples to detect objects in their vicinity. The selection of sensors is

specific to the requirements of the applications. However, photoelectric sensors are an appropriate choice for the detection of objects and humans through automated doors as inductive and capacitive sensors perform better when an object is required to be detected in the proximity of millimetres. Ultrasonic sensors are appropriate where the detection of liquids, fluids, and viscous material is required.

Photoelectric sensors toggle their output when there is a change in the intensity of light at the receiver end. The causes of change in the intensity of light are obstruction between emitter and receiver, misalignment of emitter and receiver, and a component failure. Photoelectric sensors are available in different setups of emitter-receiver and emitter-receiver reflector. Similarly, these photoelectric sensors are commercially available in multiple shapes and sizes such as

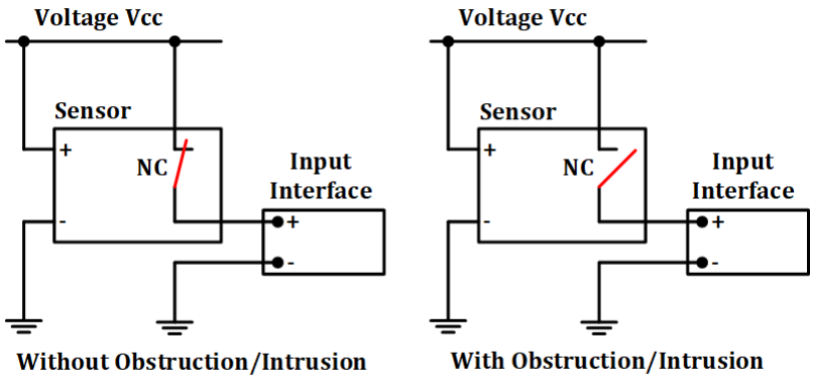

Fig. 2. Sensor output illustration with and without intrusion detection.

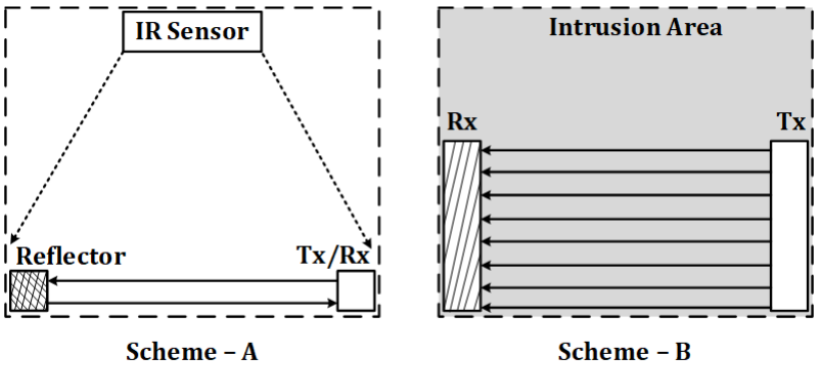

Fig. 3. A redundant combination of intrusion detection sensors with different orientation schemes for double-leaf door operation (Front view).

single through-beam and multiple through-beams pairs also known as light curtains or barriers, or grids.

The orientation of the intrusion detection sensors is another important factor in designing a safety-related system. It involves the number of door leaves and the required coverage area of the intrusion. The proposed scheme of the orientation of intrusion detection sensors for safe double-leaf door operation is illustrated in Fig. .

Scheme - A corresponds to a heterogeneous redundant combination of intrusion detection sensors for dual-door operation. The infrared sensor covers the vertical space and the emitter-receiver reflector pair covers the lower horizontal space of the intrusion area. Scheme - B corresponds to a homogenous redundant combination of two vertically mounted pairs of light curtains to cover an almost three fourths horizontal area of intrusion. These light curtains are commercially available to cover the full area of intrusion. Scheme - C and D are a few possible instances to cover the intrusion area for single-leaf door operation. These angular orientations are depicted in Fig. which are specific to different detection applications.

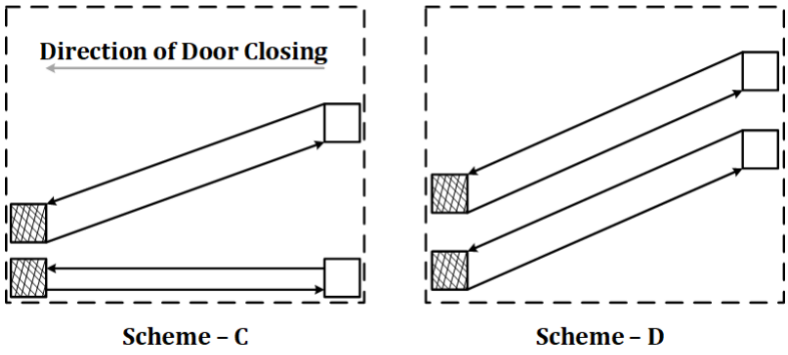

Fig. 4. A redundant combination of intrusion detection sensors with different orientation schemes for single-leaf door operation (Front view).

5.2 Software algorithm

The software of a safety-related system for door operation is critical in the design process as it controls the door opening and closing operation. The aim of this design phase is to devise an algorithm that drives the door operation safely in all possible scenarios that could jeopardize human safety. In the case of train door applications, when the train is not moving, the closing of the door could pose a potential danger to the intruder's safety if the intrusion is undetected.

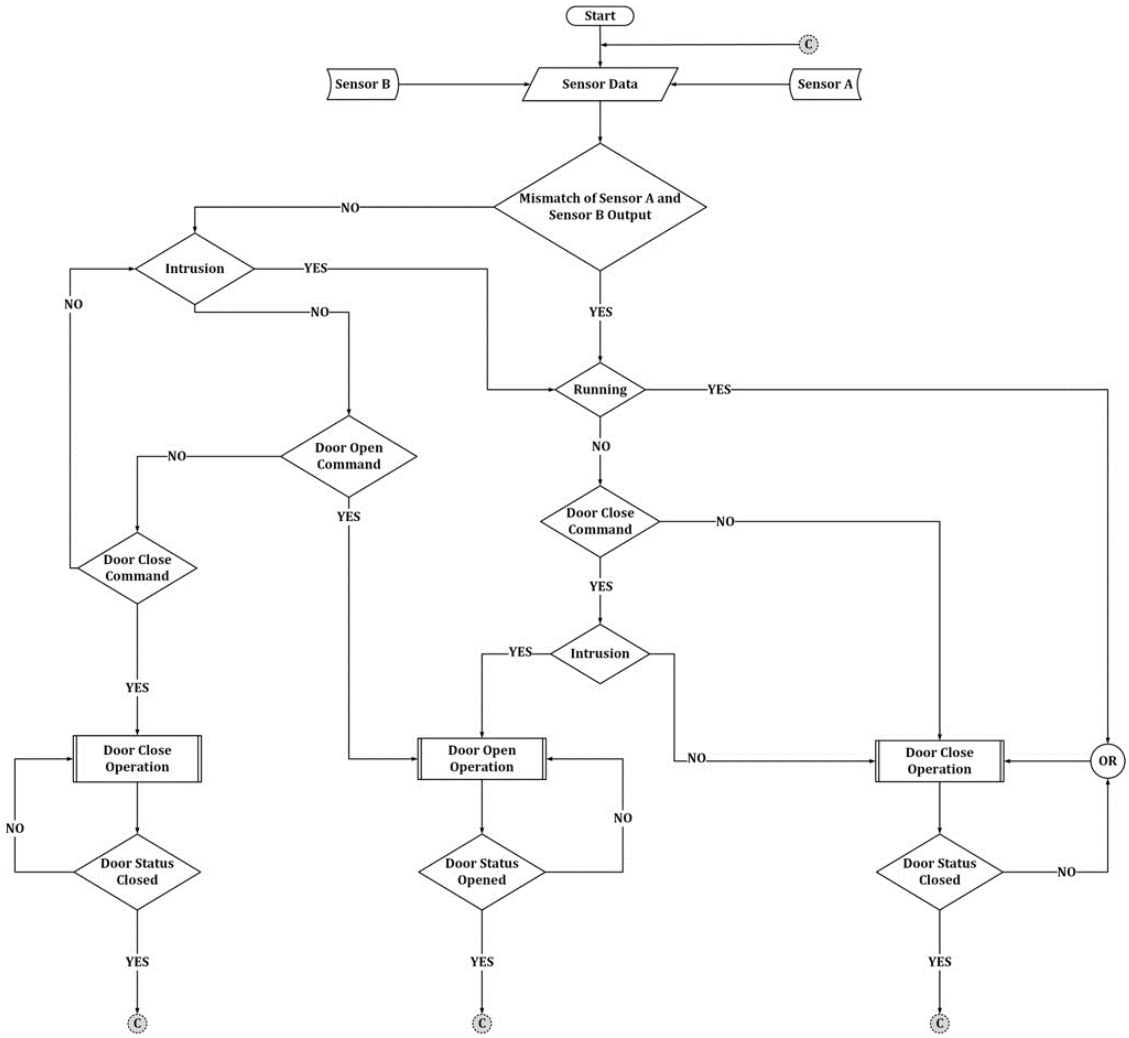

Fig. 5. Control algorithm for software designing of the door operation.

Similarly, when the train is moving, the opening of the door is a potentially dangerous situation for the passenger. This control focuses on the output status of redundant detection sensors — if there exists a mismatch or discrepancy between the output of two sensors, this scenario confers either the failure of one of the two detection sensors or detection by one of the two detection sensors or a failure of the second controller. In such a situation, the running status of a train decides the control action of door operation to keep the intruder in a safe condition as illustrated by the control flowchart in Fig. . It is important for the safety of the passenger to supersede the close command (automatic or manual) when the train is not in motion and an intrusion is detected.

VI. PROTOTYPE DEMONSTRATION

A prototype of a safety-related system for automated door operation proposed in the design concept section and designed in the system design section is implemented to demonstrate its effectiveness in maintaining a safe situation for intruders through the train doors. The components used to demonstrate the prototype are tabulated in Table I.

6.1 Light barrier as intruder detection sensors

Redundant high-resolution light barriers or grids are used for the detection of intruders and obstructions through the door. These light barriers consist of a set of emitters and receivers of modulated infrared light with 950 nm wavelength. These light barriers are positioned in a vertical parallel fashion according to scheme - B in Fig. and illustrated in Fig.. The output of the light barrier is a switching output of less than 3 Hz from the emitter side.

Table I: Components of the prototype demonstration.

Subsystem of the prototype	Subsystem details	
	Description	Component
Detection sensor	Infra-Red (IRED) light grid	AL2109-P- 1820/25/49/76a/143 [14]
Logic controller	Safety System-on-Chip (SSoC)	Redundant Safety Chip Unit (ReSCU) -V1 [15]
Open/Close status sensor	Inductive reed switch sensor	NBB2-V3-NBB2-V3-E2-3G-3D [16]
Door driving assembly	Motor driver	SIDOOR ATE530S [17]
	DC motor	SIDOOR MDG3 R [18]

This switching output is used in series with a circuit of 24 VDC to generate a constant output signal such as a Normally Closed (NC) contact as illustrated in Fig. 2. Sensor output illustration with and without intrusion detection.. It breaks the circuit when the light beam is obstructed from the emitter to the receiver which caters to the situation of intrusion, obstruction, failure, and breakdown of the light barrier. This light barrier uses a dynamic control of beam crossover by turning 61 to 135 beams ON based on the detection gap or width. The detection width can be chosen according to the door widths or requirements between 100 mm to 3500 mm. The detection height corresponds to the monitoring height of the light barrier which is 1800 mm.

6.2 Safety system on chip as logic controller

Light barriers as detection sensors are connected to the input interface of the SSoC board through a voltage shifter. The SSoC is programmable with a C/C++ language through a suitable debugger. Each CPU of the safety chip accesses the output of a light grid. Both CPUs of the safety chip exchange the output status of their respective light grids over the communication interface between them. The master CPU directs the motor drive to control the door operation according to the control design in Fig. . The running or in motion status of the train dictates different controls of the door operation and is simulated as a digital input by a push-button. The standby CPU executes the same algorithm as that of the master CPU at the same time except for the output by the standby CPU is logical AND with the alarm status of the master CPU.

6.3 Door driving system

The door operation is controlled through a mechanical setup driven by a DC motor and a motor driver detail tabulated in Table I. The output of the controller is connected to the motor driver through the output interface of the SSoC board. The close or open output defines the direction of rotation of the motor to close or open the doors.

VII. RESULTS

The results of the prototype demonstration are combined in form of timing diagrams in Fig. 7. Whenever there is a discrepancy, or a mismatch exists between the output sensors,

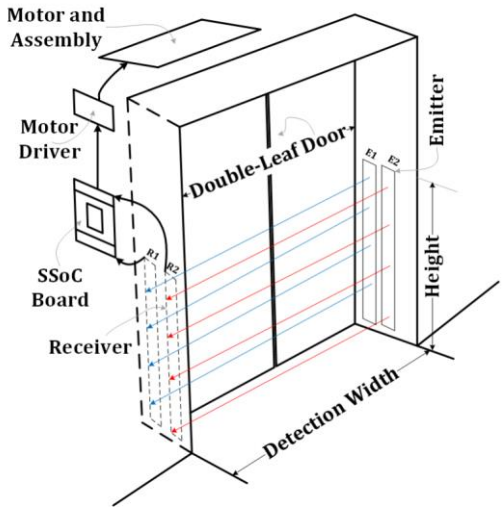

Fig. 6. An illustration of the prototype of door operation setup.

the control takes action that is safe for intruders —opening the door in case of the stationary status of the train, closing the door in case of the running of the train, and maintaining the open or closed status of the door until the discrepancy between the two outputs of redundant light barriers exists. Whenever both light barriers detect an intrusion, the control executes the corresponding operation of the door control based on the running status of the train. Open and close output signals are the input signals to the motor driver to control the direction of rotation of the motor.

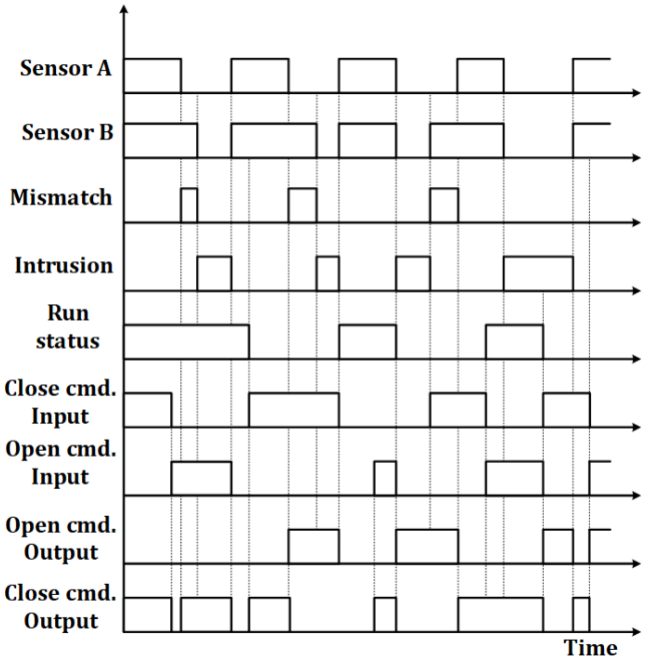

Fig. 7. Illustration of the door operation by time diagrams.

VIII. CONCLUSION

The proposed concept of redundancy is generic in nature and can be adapted to different technology specific to different applications such as in trains, trams, loading docks, and secure premises. The implementation of a safety-related prototype system for train door applications demonstrates the effectiveness of the concept of redundancy at the detection sensor and controller level. The SSoC board-based controller exhibits efficient prototyping with safety-related features for automated door applications. The selection and orientation of the detection sensor impart safety to the door operation with optimum area coverage and loop monitoring. The system design with the proposed safety controls exhibited a reliable response with different speeds of intruders.

Further improvements in the prototype include door alignment monitoring, running status based on train speed monitoring, and variable speed of train door closing and opening operation with the proposed concept.

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