Smart Wearable System for Safety-Related Industrial IoT Applications

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Abstract. The Industrial Internet of Things enables the realization of modular, flexible and efficient production processes. Machines and production plants are networked over various communication channels and organize themselves in an intelligent way to create products tailored to the customer's specific needs. Highly networked system structures will evolve including the interference of humans as well as of machines. Apart from security, functional safety plays an increasingly important role in the networking of humans and machines. Especially in environments where humans interact with dangerous systems or moving in the same area as autonomous driving robots, it is very important to provide a maximum of safety. In this paper, a system solution is introduced, which detects the movement of persons, prevents collisions between autonomous driving machines and humans, and decreases the probability of potential hazards in the interaction between humans and machines, while the movement of all participants should not be restricted.

Keywords: Industrial Internet-of-Things · Safety systems · Motion detection Smart wearables

1 Introduction

According to the ideas of the industrial Internet of Things (IIoT) a factory should be based on intelligent and modular units that cooperate closely together. Production plants are able to coordinate their manufacturing process independently, while communicating with production robots at the same time, and furthermore, they are able to organize their maintenance independently and to work on logistics tasks in terms of transport vehicles. Depending on their tasks, all elements of the production are equipped with sensors and actuators and they are networked over a sophisticated IT infrastructure. More and more parts of the workflow are performed by independently acting and autonomously moving robots. Therefore the interaction between human and machine is becoming increasingly important in such production plants.

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Particularly in the area of IIoT applications, where serious accidents can happen, the focus has to be put on the safety and reliability of a plant. Potential sources of failures have to be avoided and considered and corresponding safety measures have to be taken already in the developing stage, so that such failures become controllable. The safety of human beings and environment has to be guaranteed during the entire lifespan of a plant. To minimize the risk to human beings and environment, potential hazards and dangers have to be taken into consideration and analyzed. Production processes have to be monitored and controlled by a corresponding safety system. Such safety system has to meet strict requirements in context of functional safety as they are defined, for example, in the standard IEC 61508. An introduction to safety systems, referring in particular to safety-related system-on-chips (SOC), will be given in the Sects. 2 and 3.1.

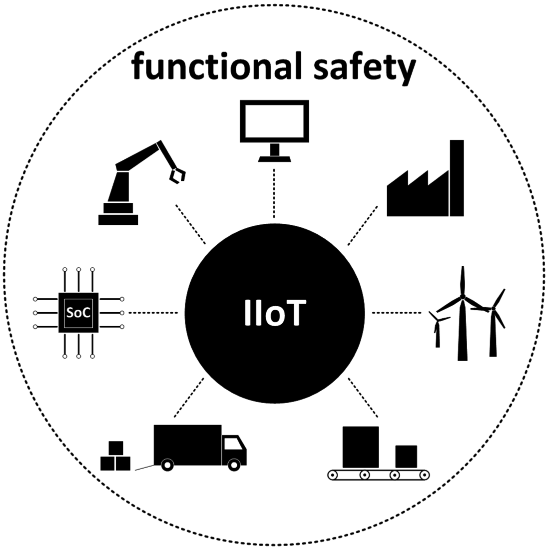

Fig. 1. IIoT and functional safety

In IIoT applications, human workers strongly interact with robots and machines. All of them take an active part in an industrial process, for example, in the same industrial hall or production line. Thereby the risk of incidents between the participants increases. To minimize this risk it is of high relevance that the robots and machines can react on human actions, for example, by detecting the motions of the human workers as early as possible and act in an appropriate and primarily safe way. In this context, several research groups and also companies around the world are currently working on robots and machines capable of interacting with humans as naturally as humans interact with each other.

However, the main focus of our research work is led on the exploration of miniaturized and safety-related systems, which can be used for smart wearables within a manufacturing plant for example. Inspired by the idea, this work presents the idea of having shoes equipped with a miniaturized and safety-related motion detection system, which can be worn by workers in an industrial environment. Such an apparently simple system requires a broad set of technical and safety-related capabilities like, safe and accurate motion detection, safe and secure wireless communication and compact size, which motivates the approach presented in this paper. To achieve this, smart shoes equipped with different kinds of sensors should capture the human walk, recognize patterns and calculate walking routes. Safe acquisition and processing of data as well as safe transmission of data and orders to the interacting robots is essential.

The main objective of this paper is a system design that provides the sensors required to analyze the position, velocity and motion data, evaluates these data and sends them to involved robots in a functional safe way. Furthermore is it able to drive the robots into a safe state in case of dangerous failure. The system size is compact and does not need any external physical connections so that it can be included into working shoes and so does not restrict the motion of the carrier but enables a maximum of flexibility to him (Fig. 1).

2 Safety Systems

Electronic safety systems should be designed and certified conforming to safety standards such as the standard IEC 61508 [2]. Therefore, several requirements on development process, and system architecture and design should be met by employing different methodologies. In this context, functional safety is playing an increasingly important role for IIoT applications, especially due to two aspects: On the one hand, processes have further been automated, machines acting autonomously, and on the other hand, the networking of plants and machinery is increasing and does not stop at factory gates. In order to reduce the risks for humans, environment and economics to an acceptable level measures have to be taken to avoid systematic errors, detect and control random failures and to reduce the risk of dangerous failures to a minimum. Therefore, a safety concept has to be created including the hazards that can be implied in a system and the hazards have to be detected by hazard and risk analyses. In order to classify the safety risk so-called Safety Integrity Levels (SILs) are used according to IEC 61508 - from SIL 1 (low) to SIL 4 (high). Depending on the risk particular measures have to be taken that serve to reduce the probability of default of the system so that the required SIL can be reached.

All the mechanisms, which are implemented for the risk reduction of a system, are together to be regarded as safety architecture of the system. The safety architecture is defined by the number of independent channels and the minimum number of properly functioning channels for error-free operation. For example, the 1oo2 architecture (one out of two) consists of two independent channels. To perform safety functions correctly, the channels are connected in such a way that one of them is sufficient for triggering the safety function [1].

The 1oo2 architecture is used for critical systems or systems with a high safety. Several specific parameters as, for example, the Probability of Failure on Demand (PFD), Hardware Fault Tolerance (HFT), Safe Failure Fraction (SFF) etc. [2] have to be met so that a high safety integrity level can be reached by safety architecture. For example, for a SIL 3 classification test coverage of 99% has to be reached. This high level of test coverage is often hard to reach when the hardware is not suitable for safety applications. In this case, integrated self-tests are used very often to reach the required test coverage. The required coverage can be reduced through the use of redundancy. If, for example, a system allows fault tolerance a fault detection of a SIL 3 system of only 90% has to be reached. A very common concept for fault tolerance is represented by the usage of 1oo2D (one out of two with diagnosis) architecture. The entire hardware - including the sensors - is provided in duplicate implying two systems that are independent of each other. The safety concept used in this work is based on a miniaturized safety system, which is developed in accordance the second edition of the standard IEC 61508. This edition was published in 2010 and introduced the term “on-chip redundancy” allowing the design of safety-related digital systems on a single silicon chip up to SIL 3. Systems which are relevant to safety-related functionality have to undergo a certification process.

Furthermore, inserting security aspects to safety architectures used in IIoT applications is of great relevance [3]. However, security is not in the focus of the present work, and will be part of future work.

3 Concept

The main idea behind the proposed approach is the design of a compact safety system, which is suitable for an implementation and use in IIoT applications in the field of functional safety. The system should be composed of an on-chip safety system and a system of different sensors. The on-chip safety system was particularly chosen because of its small size, high performance capacity and its wide range of interface. Moreover, the on-chip safety system does consist of an entire, safety-related programmable logic controller (PLC) and a communication processor on one single, compact chip. The sensor system consists of three vibration sensors to detect the motion of the carrier and a GPS sensor to measure the absolute position and the movement. Due to the integration of safety system and sensor system in one board, the whole system is very small and thus it could be used for wearable systems. Since the power supply can be provided by a battery and the communication is carried out using wireless interface (WiFi), there is no need of any physical connection between carrier and other systems.

Furthermore, due to the on-chip safety system it is possible to collect and process sensor data and operate connected actuators in a safety-related way. The connection to other systems and robots will be via WiFi. The user will be in the position to retrieve status data and he will be able to operate the connected periphery as well (Fig. 2).

The safety system complies with 1oo2D architecture as it is described in IEC 61508 [2]. This means that the safety system consists of two identical subsystems (channels) with diagnostic units. The diagnostic units continuously monitor the states of both channels and instruct them in a case of errors, in a way that the system is transferred into a pre-defined safe state. Apart from the redundant safety component, the on-chip safety system has to consist of an additional processor, which is coupled in a non-

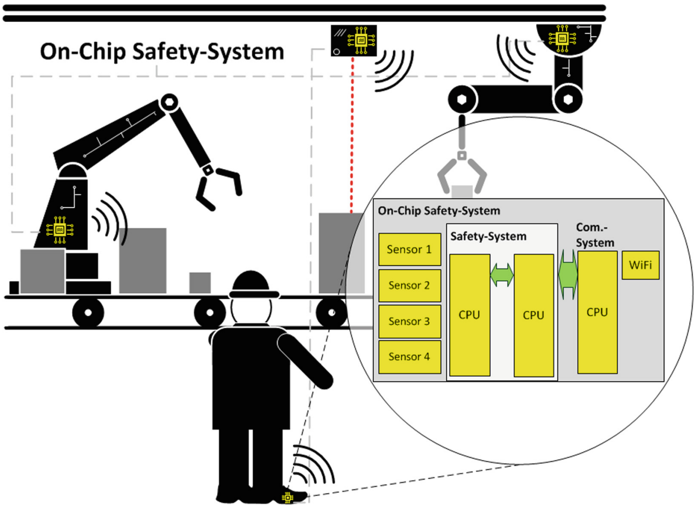

Fig. 2. Concept for smart wearable system for IIoT applications

interacting way to the 1oo2D system and serves for communication and monitoring processes.

The on-chip safety system and its architecture are described in more detail in Sect. 3.1. A description of the used sensors is given in Sect. 3.2. Furthermore, Fig. 3 shows the PCB-prototype of the implemented circuit design in this work with its main components. The size of the board is 130 mm × 75 mm, and it is supplied with 24 V which is transformed to 3.3 V and 1.8 V via the voltage regulator. Furthermore, redundant power monitoring elements are integrated in the circuit. If a voltage reduction is detected the safety chip will be reset in order to go the safe state.

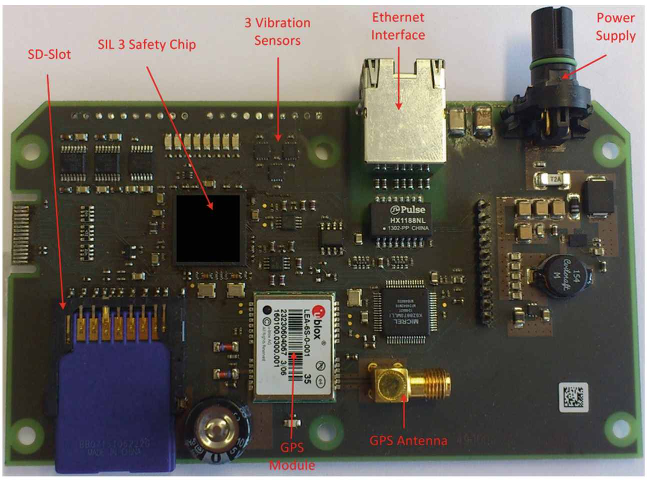

Fig. 3. Embedded safety platform

The JTAG interfaces are required for programming the chip. Further battery-operated more compact design will be part of a future work.

3.1 On-Chip Safety System

The on-chip safety system consists essentially of two main components: a safety system and a communication system. While the safety system is based on a fully redundant safety-related 1oo2D-architecture with an on-chip-diagnosis unit, the communication system is composed of a simple processor serving as a black communication channel. All three processor systems are based on 8-bit processor. Both systems are decoupled from each other to achieve a freedom of interference. Each system has own interfaces for communicating with the outside world [4].

As a safety integrity level, SIL 3 is targeted as the maximum possible SIL according to the standard IEC 61508 [2]. In order to meet SIL 3 requirements, several measures and methods are realized at coding and implementation level, such as physical placement and routing.

Safety System: The target safety system consists of two identical processor units. Each of them possesses the same technical characteristics, parameters and its own memory, and communication interfaces. The communication interfaces can be served by one of the processor units. In the following the main feature of the safety system are listed:

- on-chip SRAM data and on-chip flash program memory, for each channel
- Timers, interrupt controller and on-chip debugger
- Digital inputs, digital outputs, PWM outputs and frequency inputs
- Serial communication interfaces

Communication System: The communication processor has the same technical characteristics and parameters as the safety system. Additionally, other communication interfaces are used. The main features of the communication system are the following:

- on-chip SRAM data and on-chip flash program memory
- Digital inputs and outputs
- Timers, interrupt controller and on-chip debugger
- Extended Serial communication interfaces

Safety Measures: In the following, special architectural and safety-related features of the presented chip are summarized:

- Safety-related subsystem based on 1oo2D-architecture with on-chip diagnosis: On-chip diagnosis unit and clock monitoring unit
- Memory Protection Unit
- Watchdog and power supply monitoring interfaces
- Hardware mechanisms for decoupling both systems

3.2 Sensors

Vibration as a definition is a dynamic mechanical phenomenon in which a periodic oscillatory motion is involved around a reference point [5]. Generally, the ability of a system to withstand vibration and shock depends upon "g" level the system can withstand. In that, a sensor-accelerometer is used to measure these "g" levels.

An accelerometer is a sensor that reflects and measures the physical acceleration experienced by a movable object due to inertial forces or due to mechanical stimulation. It is comprised of a mechanic sensing element engaged with a mechanism which converts its sensed motion into an electrical output signal [6].

The mono-axial accelerometer is based on the Newtonian mechanics. A mass "M" is moving periodical attached to a spring and damped by a viscosity damping element. The stiffness of the spring is given by "k"; the coefficient of the damping element is given by "b". The acceleration "a" is then a function of mass, stiffness, viscosity and deflection x:

$$a = -\left(\frac{b}{M}\right) * \dot{x} - \left(\frac{k}{M}\right) * x \quad (1)$$

In this model the acceleration is measured just by well-known parameters and the measured deflection. So there is no need of any external references, which could otherwise be a problem for the usage in safety-related applications (Fig. 4).

In this research work three "BMA180" acceleration sensors are used, which are manufactured by Bosch Sensortec. The "BMA180" is a digital sensor for the tri-axial

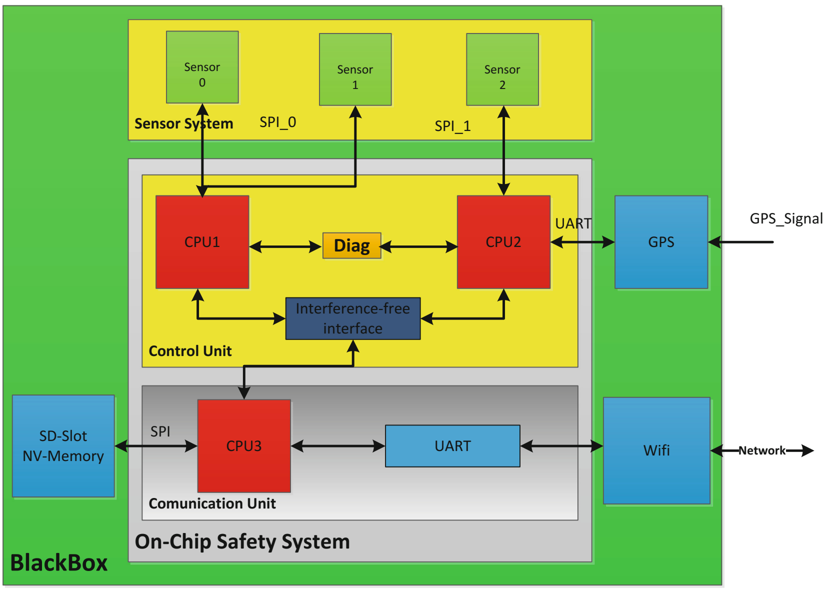

Fig. 4. Hardware black box with on-chip-safety-system and safe sensor system

measurement of static acceleration as well as dynamic acceleration. It provides a measurement range up to 16 g and can be configured in seven different measurement ranges. In addition there it provides measurement of the absolute orientation in a gravity field. The sensor is based on a two-chip assembly and the output acceleration signal is provided via 4-wire serial peripheral interface (SPI) as a digital full 14-bit.

The sensor system is based on 1oo3 safety-related architecture. Each of the three "BMA180" acceleration sensors transmits the data synchronously via SPI to the SIL3 chip, where two sensors are connected to CPU1 via SPI 0 and the third sensor is connected via SPI 1 to CPU2. Between the sensors and CPU the communication is based on master-slave principle whereby the CPU works as the master and the sensors as slaves.

For this work the 2-g mode is used for all three sensors. So the sensors have a resolution of 0.5 mg. The tilt sensing has an accuracy of 0.25°. In standard mode, the current consumption is 650 µA, and a supply voltage of 2.4 V is required [7].

The GPS module is connected via Universal Asynchronous Receiver Transmitter (UART) interface to provide the position and velocity of the carrier. This communication is not safety-related.

4 State-of-the-Art Techniques

The existing concepts of motion detection for wearable systems (shoes) by sensors are settled in the field of sports or for medical or therapeutical purpose so far.

For example R.E. Morley et al. presented in 2001 a system consisting of four pressure sensors, two temperature sensors and two humidity sensors to detect the motion of diabetes patients [8].

In the year 2004 I.P.I. Pappas et al. built a system that detects the different stages of walk by three force sensors and one gyroscope. Aim of this project is to find the best point to give an electrical stimulation and thus facilitate to walk for persons with steppage gait [9].

In 2008 Stacy Morris Bamberg et al. developed a system containing of many sensors. Amongst others velocity sensors measure the speed, gyroscope the direction, force sensors the force distribution under the foot sole and an electrical field sensor the height of the foot over the ground. However this system is not accurate enough to use it in an industrial environment. Furthermore the measurements are not functional safe in terms of IEC 61508 [10].

In the following years Stacy Morris Bamberg and her team improved this system for special application as e.g. for stroke patients [11] or to reduce the costs [12] but not for the use in industrial environments.

For the use in industrial environments safety mats equipped with pressure sensors are available [13]. These mats detect the presence of people on the sensing surface. So they can communicate with machines in order to avoid dangerous interactions between humans and machines. However, the persons can only move on predefined routes and not free in the whole industrial plant. Furthermore these mats are a barrier for some kinds of robots and the usage of heavy vehicles could damage these mats and thus lead to a malfunction of the safety system.

5 Results

First measurements were made with this system only in the right shoe. There was tried to detect different velocities and turning of the carrier in different directions. Just the x value of the vibration sensors was used to analyze the motion, because it was sufficient to detect these motions. For motions in all three dimensions as climbing stairs it is necessary to analyze the other values as well.

Figure 5 shows a comparison between walking and running. It is easy to see the different time between single steps (green lines). Also the time a step needs is shorter while the carrier is running. Combining these two parameters it is possible to determine the velocity and especially changings in the velocity of the carrier.

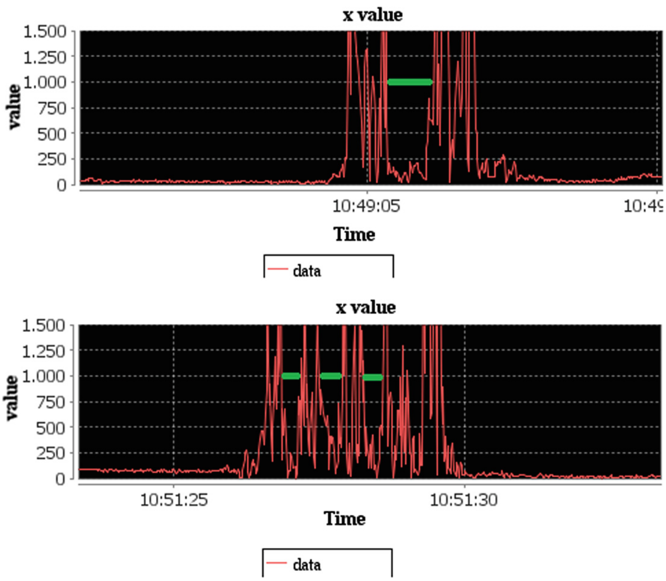

Fig. 5. Captured data of walking and running process (Color figure online)

Figure 6 shows a turn to the right in comparison to a turn to the left. The moving leads to an edge in the data while the step. The direction of this edge depends on the moving direction. A turn to the right results in a rising edge, while a turn to the left results in a falling edge. There is an edge in only one step in each data set because the system was just integrated in one shoe.

Both measurements show that it is possible to detect the most important motion patterns by this system. Due to the fact that it is possible to identify a changing in velocity and direction in real time, it is possible to predict the walking route of the carrier. This will allow avoiding collisions with autonomously driving robots and shutting down of potential source of danger for human workers.

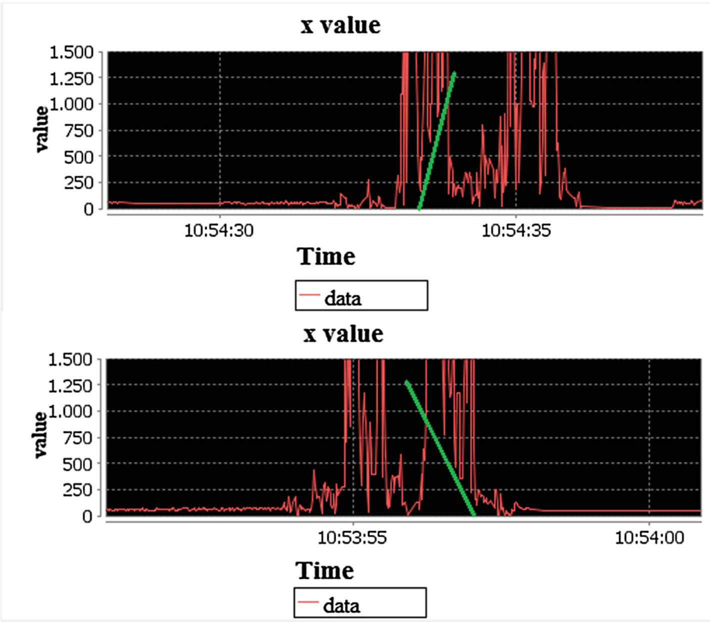

Fig. 6. Captured data of turn left and turn left process

6 Conclusion and Future Work

A compact system for detecting motion, processing data and control robots is formed. The whole system is integrated into one single board and is capable to be integrated in a normal working shoe. The system is able to meet the requirements of functional safety because of the on-chip safety system. The 1oo2 architecture and a reactionless decoupled system created by the safety and the communication system form the basis for the on-chip safety system. The sensors can detect very accurate the position, velocity and motion of the carrier and thus avoid collisions with robots or potential dangerous interactions. Furthermore, the system is capable to shut down interacting machines and so offers safety to persons working together with robots in the same industry hall or production line. The entire system is very compact. Because of its low power consumption it is possible to power it by a battery. Linked to the data transmission via WiFi, the system is mobile and thus provides a maximum flexibility to the carrier. Both parties, humans and robots, can move flexible in the whole area and are not limited by predefined routes.

Based on the flexibility and safety, there are many possible environments to use it. It is viable in all settings where people and robots move in the same area without fixed routes or processes. Another application is in the interaction between humans and potential dangerous systems such as laser or welding units. These systems could shut down autonomously if human workers enter a safety-critical area. Also it is thinkable to use it to optimize the pathways of all interacting robots dynamically in real time, which leads to less potential collisions, more safety and to time savings.

For future work the identifying of motion patterns could be improved and automated. Software could be developed that predicts the walking routes based on the recognized patterns and so guides robots on safe routes. Furthermore the system could be downsized in order to make it more comfortable to wear it the whole working day. Also the communication between several systems could be tested.

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