Power-efficient Strategies for Sensing in Autonomous Mobile Robots, a critical requirement of I4.0 standard

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Abstract. In a production environment, there are several challenges in meeting the Industry 4.0 (I4.0) standard requirements. Energy efficiency is an essential area of focus. In the production setup, the critical and real-time control systems need to be very efficient while implementing functions, namely, accurate sensing, fast processing and precise actuation. Automated Guided vehicles (AGVs) and Automated Guided Vehicles are an integral part of modern and intelligent manufacturing systems. Power consumption in such systems is directly proportional to the performance level achieved. However, there is a need to evolve strategies to reduce power consumption and attain optimal performance. Field Programmable Gate Array (FPGA) based controller solutions can provide competent performance at optimized power consumption. The proposed work discusses the requirements of I4.0 concerning energy efficiency infrastructures for the intelligent manufacturing setup. The need to develop efficient subsystems for sensing, decision-making and actuation based on FPGA is stressed. Thus the focus is on the FPGA based power-efficient models used for sensor fusion technique in Autonomous Mobile Robots. The fundamentals of sensor fusion technique and the need to fuse sensor data for improved decision making and actuation are emphasized.

Keywords: Industry 4.0, Energy efficiency, Automated Guided Vehicles, Autonomous Mobile Robots, Smart Manufacturing, Field-programmable Gate Array, Sensor Fusion

1. Introduction

The recent manufacturing applications do range from mobile computing to cloud computing. As a result, intelligent and interconnected manufacturing systems have evolved, hence Industry 4.0. The result is that the systems are specialized as real-time systems enabling the industry to achieve new lean manufacturing levels. The prominent technologies in place are Big Data, Smart Factory concept, Cyber-physical systems, Industrial IOT and Interoperability. Big Data deals with handling massive data collected from various sources within and outside the Manufacturing industry. The analysis of massive data enables intelligent analysis of data and improved decision-making process that makes a significant and remarkable change in how the organizations or the manufacturing setups function. Smart Factory provides the seamless integration of all the processes from planning to execution, enabling improved productivity, maintenance and optimization of each at the individual process level. Cyber-physical systems aim to refine the computation, networking of each of the physical processes and employ feedback control loops to work in real-time. The decision making in the control loops involves artificial intelligence and machine learning ability. Industrial IoT stands for connecting all devices to the internet and each other across the industrial plant. It is based on cloud computing and
intelligent sensor networks. Thus an infrastructure with robust connectivity enables the smart factory to use the gathered data to manufacture, collaborate with other machines, report and learn at highly efficient rates. As a result of seamless integration of organizational data generated from interconnected cyber-physical elements sharing data across the internet for the smart manufacturing setup, intelligent machines and humans' interoperability is achieved. Interoperability enables error-free transmission and compatibility across the factory environment, achieving higher efficiency, accuracy and reliability as per the requirements of Industry 4.0. Automated Guided Vehicles (AGVs), Automatic Storage and Retrieval Systems (ASRS), Autonomous Mobile Robots (AMRs) have emerged as primary solutions for material handling applications in a modern factory environment [1-6].

Autonomous Mobile Robots is an example of the evolution of intelligent technology as per I4.0 needs. AMR senses the surrounding environment and decides its shortest navigation path, avoiding the obstacles along the path traversed. An autonomous mobile robot's objective is to find an efficient navigation route to its final destination, using the support of robust sensor networks and an accurate decision-making facility. The efficiency of the AMR is judged by the saving incurred in reduced power consumption, enhanced battery life, and the distance travelled by it. The onboard facility of intelligence provides Autonomous Mobile Robots with a vital role in a smart factory environment. AMR's have evolved over the years to provide increased flexibility, safety efficiency, higher throughput and assured fast return on investment (ROI). The intelligence level developed on intelligent mobile robots ensures that they can handle the monotonous, hazardous, and laborious, dull and dirty tasks efficiently, replacing humans. AMRs for Logistics for labour-intensive transport applications, E-commerce functions, namely, raw materials transport, sorting of received parcels for delivery and returns, inventory management, and manufacturing applications, as data-centres. Furthermore, there are research platforms for biotech and health care industry related services, Data Centers, Research and development. There is a widespread use of innovative methodologies employed for healthcare-based solutions for accurate detection of ailments or abnormal conditions in human beings and the systematic analysis of the identified problems followed by accurate diagnosis. Similar facilities are available for monitoring and up-keeping machine health conditions for effective maintenance [7-14].

In a production environment, Automation and Robotics based control systems play an essential role in implementing the objectives set for the attainment of I4.0. Hence the control system solutions need to have high performance and power-efficient characteristics. The adopted control strategy needs to be very efficient, as the accuracy and reliability expected in the robot operation are very high in autonomous applications, replacing human beings. It involves accurate sensing, fast processing and precise actuation. The current era of technological changes has been adopted at an accelerated rate to attain Industry 4.0 standards. The role and need of mobile robots in the present industrial scenario are highly challenging, as the demand for rational approaches to material handling and manipulation is fast growing. Many types of sensors may be used in a mobile robot application to gather information from the surrounding environment. The sensors, in general, possess distinct characteristics, having a unique principle of operation with a wide range of the electromagnetic spectrum, suiting the demands of various applications. A single sensor used in standalone mode provides a limited sensing range in a constrained environment and is associated with operational errors. However, many sensors’ synergistic and networked operation provides the broader perspective of the sensed environment in a mobile robot application. The high-speed performance of sensors employed in the critical control systems ensures that the response is always relevant. Since mobile robots operate in a complex, uncertain and highly dynamic environment, the rich information gathered from sensor networks can help the robot system optimize a strategy for path planning and navigation. It is also essential that how best a controller uses the sensor data tapped from a collection of sensors and fuses them provides the highly reliable and intelligently processed information for robot navigation [1-6].

1.1 Energy requirements of I4.0 standard

Energy efficiency is an important measure considered for I4.0 applications. In countries like Europe and the United States, industrial energy consumption amounts to 25% to 35% of their total energy
production. Intelligent manufacturing systems under I4.0 hence aim for power-efficient and sustainable operations. Similarly, along with the supply of electric power, its constant availability and reliability of performance are critical factors. Hence the energy efficiency and energy management are the critical needs of the I4.0 standard. Hence, innovative strategies and technologies are employed to improve energy efficiency. Management using the IoT enabled monitoring and control services to minimize the disruptions in the intelligent manufacturing setup. The objectives are here to limit energy wastage and to exercise real-time control of power consumption. It is ensured using an array of sensor nodes, monitoring the integration of energy sources across an intelligent network in the company and beyond. It is also an essential factor to improve cost-effectiveness. Thus, the steps initiated in this direction impact even abiding with the environmental regulations and exploiting alternate energy sources. The key drivers for power management functions in line with the demands of the I4.0 standard can be listed as follows:

- Need for meeting requirements in the regulatory, environmental and societal context.
- Need for efficient mechanisms for managing complexities and challenges of industrial ecosystems
- Need for awareness regarding energy management and efficiency
- Need to ensure uninterrupted operations using critical monitoring strategies based on IT-enabled services
- Need for highly reliable, optimized quality of power using intelligent decision-making functions implemented using data analytics and AI-based machine learning ability[1-6].

Intelligent manufacturing setups use intelligent energy management and metering solutions based on Industry 4.0 and IOT to continuously monitor the plant's operations, energy consumption, wastage, or energy leak. All the devices are connected to share information about production and operation status to promote energy efficiency. Wired and wireless sensor networks role is prominent in gathering the relevant data and contextual information across the plant for integrated and intelligent decision-making on energy management. The diagram in Figure 1 shows the prominent components in an environment that even supports collaborative learning [1-6].

![Figure 1. Context-Aware Framework for Collaborative Learning Environment](image)

The Physical layer comprises all the devices and the infrastructure for energy management across the plant. Sensors in standalone and networked form collect the data that help in operations, namely, characterizing the environment, setting machine parameters, monitoring machine status (idle or run), gathering maintenance status parameters, and detecting overriding conditions machine or process parameters. These are essential in estimating the power consumption profile. Localization is a process of identifying, locating, and tracking operators and the machines accurately, using a set of
beacons set up throughout the plant is ensured. Devices include all those interfacing equipment needed by the system to generate the localization data acting as the intermediate devices between sensors and the designed localization infrastructure and the internet. Communication Layer allows for accommodating any communication protocol, namely, Modbus, Profibus, Ethernet/IP, Interbus, Control Net, ZigBee, WIFI, and GPRS/3G/4G. The context-aware layer is built using both the wireless sensor network and Real-time localization using the available physical and logical infrastructure. The function, namely, collecting contextual information from sensors and the localization data from beacons, is carried out in the context layer. The management layer provides the services related to communication, logical and intelligent functions correlated with the monitored activities. Decision-making functions are invoked based on the various conditions or events that arise during the operations. Critical decision making is required for cases, namely, machine tool in jammed condition, vibration level attaining the maximum limit of defined thresholds, non-functioning Auto Toolchanger. Turning off of heating process or reducing fuel consumption efficiency can be options for overriding operating temperature conditions in a process setup. Application Layer is concerned with identifying all those events or actions in machine operating conditions, machine status and the process or the tool parameters. Social computing maximizes information functionality to improve relationships between humans and machines [1-6].

Thus the framework provides information on the energy consumption facts based on the data collection and interpretation mechanisms. Recommendation mechanisms are built based on the energy consumption patterns identified and recorded. Based on the requirements and recommendations of the energy-aware framework, the appropriate hardware platforms need to be adopted. FPGA based solutions can provide power-efficient architectures for accurate Data acquisition, decision making and precise actuation in the control loops set up for innovative manufacturing solutions. FPGA based hardware design exploits the inherent features such as reconfigurability, parallelism and competitive cost as compared with processor technology. FPGA's are widely used for real-time applications. FPGA based implementation of algorithms for sensor fusion, image processing and actuation can reduce cost as well as time. It ensures the quick prototyping of complex algorithms, simplifies verification and testing. Hence the feasibility of using FPGA/SOC based solutions for accurate sensing achieved through sensor data fusion techniques, followed by high-speed execution of control strategies, namely, obstacle detection and path planning and finally, the precise actuation for robot navigation. The sensing, processing, and actuation strategies can be implemented using an algorithm sequentially on a sophisticated controller [1-6]. The other alternative is to use multiple processor cores for distributed and parallel computing, ensuring high-speed processing. The case study of the sensor fusion process followed for Autonomous Mobile Robot is discussed further in this direction.

2. Autonomous Mobile Robot and its functionalities

The critical components used in a mobile robot are based on the key functions, namely, Perception, Decision-Making and Actuation. Perception is the built-in capability of a robot system using the appropriate sensing technologies, namely, laser scanning, stereo vision, force-torque sensing, and spectrometry, to see and perceive the environment. Internet data provides enormous data to the robot in either wired or wireless fashion as an endless array of sensors that can support perception. The decision is the action or the outcome planned based on the intelligence models designed and the environment's perceived information. Nowadays, Artificial intelligence models mimic the human brain capabilities restricting to the application demand. As a result, the robots prove to be more innovative and faster in decision making. Actuation is the process of energizing the actuating elements of the robot for motion[15-20]. The critical functionalities associated with any autonomous mobile robot are Navigation, Mapping and Localization, and Obstacle Avoidance. Robot perception of the environment and how decision-making processes are handled are crucial for a mobile robot application. The navigation plan for a mobile robot is implemented based on the data collected from various sensors. Robot perception is enhanced using a robust sensor network. The use of technologies, namely Cloud Computing, Fog Computing, and Edge Computing, enables the mobile robot to network with
intelligent systems across the plant and even remotely. Edge computing solutions mainly rely on FPGA based reconfigurable architectures. The algorithm implementation using FPGA provides significant performance as compared with CPU. Even though building FPGA compatible code, i.e. VHDL or Verilog, is complex and time-consuming, it is worth doing as it provides an actual acceleration. Hence the FPGA implementation of the Central limit theorem for Sensor Fusion is proposed.

2.1 Sensor Fusion Technology in Autonomous Mobile Robot
Among the various tasks performed by a mobile robot, the real-time object detection is a prominent one. It is a computer vision technique that helps the robot to capture, identify and locate the objects. Using the sensor fusion technique, the data is extracted from the information gathered from various sensors and treated suitably as required by the system. The robot then performs the object detection task in order to detect the object and the environment. Object detection task primarily involves capturing and identifying the objects to decide on the navigation path. The popular applications of real-time object detection are, namely, crowd controlling, self-driving cars, face recognition, and surveillance applications. The sensor fusion process yields the data, which is more accurate and dependable as compared to the data collected from a single sensor data. The process is preferred mainly to obtain noise-free and precise measurements required in a mobile robot application to achieve accurate navigation. As each sensor type has its strengths and weaknesses, the algorithm needs to determine the way the data is captured and processed to provide an accurate model. The work proposed here is based on an algorithm that combines IMU positioning and ultrasonic positioning for localization in an Autonomous Mobile Robot. Here the algorithm based on an extended Kalman filter is used to fuse the information collected from IMU and ultrasonic sensors to estimate the target position that can enable in building an accurate and stabilized localization model [15-20].

2.2 FPGA Technologies for Sensor Fusion
The FPGA board for sensor fusion is used to develop the sensor fusing algorithm and compile the program. The mobile robot sensors provide the data (position/detection of an object) from the front view, which is digital, and then sends the data back to FPGA. The interfacing code for the sensors can be written in Arduino IDE kind of platforms, which can be further implemented on FPGA. FPGA board provides the facility to interface different sensors and to implement the logic of sensor fusion process. The fusion process can be implemented either using direct fusion or the indirect fusion process. Direct fusion can be the result of fusing data from sensor types, namely, heterogeneous sensors, homogeneous sensors, soft sensors and also the sensor data history. Indirect fusion process involves data gathering from the environment along with human experiences and knowledge, apart from sensor data. The sensor fusion algorithms use standalone hardware that can be implemented on Field Programmable Gate Array (FPGA) or Application Specific Integrated Circuit (ASIC). FPGAs provide an attractive option for the fusion implementation as compared with that of an ASIC fabrication, which proves to be time consuming and an expensive alternative [15-20].

2.3 Challenges in Sensor Fusion in Real-Time Object Detection
The increasing demand for robust and precise navigation system has given rise to sensor fusion algorithms. However, choosing a suitable algorithm is the biggest challenge to achieve precise output. These algorithms mainly possess two challenges, i.e., these algorithms are computation-intensive and require hybrid but tightly coupled processing resources. Real-time sensor fusion requires high speed performance using the parallel data processing capability of systems of the type FPGA. Similarly, the processing capability needs to be robust that handles a vast amount of information and complex interrelationships in the multisensory information. The prominent requirement is that the real-time data processing needs to be achieved with the highest accuracy possible. A rise in the number of sensors used leads to more power usage when used in applications like gesture recognition and indoor navigation. Hence, the right choice of sensor interface can help bring down the power consumption. We know that multi-sensor data fusion helps to improve the system's reliability, but at the same time,
additional devices can significantly increase the overall cost of the system. During the monitoring process, similar activities can be interpreted differently by unrelated sensors. The amount of false alarms/output is relatively high. Therefore, it is required to give a higher priority to the more reliable technology. The data obtained from sensors should be merged most efficiently and analyzed for common trends and similarities. The proposed work involves studying sensor fusion techniques using specific methodologies, namely, filtering techniques like Kalman Filter and algorithmic techniques on data fusion. Further study of the real-time sensor fusion technique and applying it to a real-time-based scenario can be challenging. Work can be extended for navigation of mobile robots using sensor fusion in real-time that provides high performance and low-cost implementation [15-20].

3. Proposed Methodologies for Implementation

The discussion of methodologies for sensor fusion, namely, Kalman Filter method, Central limit theorem and Multisensory Laplacian Fusion, are covered under this section.

3.1 Sensor Data Fusion using KALMAN Filter method

The Kalman Filter method employed here is an algorithm used for sensor fusion that uses a series of measurements observed over time and computes estimates of the unknown variables. The algorithm employs basically the two steps, namely, Prediction and Correction. Here the kalman filter is used to process the data collected from the 9-axis IMU sensor to determine the mobile robot orientation. The computation of orientation using the Kalman Filter involves series of complex matrix calculations with trigonometric functions that can further be converted into scalar values. CORDIC algorithm is an hardware efficient algorithm that can be used with functions, namely, trigonometric, hyperbolic and logarithmic functions along with the eigen value estimation.

3.2 Sensor Data fusion using Central limit theorem

Here, the central limit theorem is used in mobile robots for object and range detection to avoid obstacle contact. The sensors used here are infrared and IR sensors to measure the distance from the obstacle. The technique is simple and inexpensive enabling the mobile robot to efficiently detect the obstacle as well compute the distance between the robot and obstacle.

3.3 Real-Time Multisensory Laplacian Fusion

Laplacian fusion technique is implemented using the pyramid decomposition process that utilizes the reusable memory architecture and parallel computing. Hence the fusion algorithm constructs the Laplacian pyramid for every captured image and then extracts local salience information at multiple pyramid levels. Further the extracted and fused pyramidal information is reverse transformed to reconstruct the image. It compares the pixel energy captured locally with that of the most definite and nearest pixel value, as per the choice of salient features from source images.

MATLAB is an excellent tool that enables many features for simulation but using MATLAB algorithm for ASIC or FPGA needs some additional implements and features needed to process the stream of bits. Kalman filter is entirely defined by the State-space model (assumed dynamics of the framework to be filtered) and Measurement model. Suppose a mismatch exists between model (state-space and measurement), the Kalman filter and a “real-life model”. In that case, a Kalman Filter with non-optimal characteristics and behaviour is likely got. In order to avoid this problem, other filters such as adaptive Kalman filters and robust Kalman filters can be used.

3.4 FPGA Technologies for Sensor Fusion

There are several hardware platforms based on microcontrollers, Digital Signal processors (DSPs) and FPGA, available to implement the fusion algorithms in an embedded system. The choice of the platform is mainly based on the key features, namely, performance, power consumption and the cost per chip along with the software tool support. As a result of which the system can designed meeting
the constraints in terms of incurring the lower cost of implementation as well meeting of the project deadlines timely. As ASIC devices require special foundry facilities, FPGA proves to be an attractive and natural alternative for such implementation.

FPGA's are mainly used for techniques that need high-speed processing and attain true parallelism and thereby increase the system's performance. The information obtained from the fusion of sensors is complex, and hence using the other microcontroller for prototyping would not be an appropriate choice. The sensor fusion algorithm that captures massive data and strict requirement of real-time response, FPGA's are highly recommended because it possesses high speed, complex logic control ability. FPGA also controls the interface and timing of the sensor signal acquisition, pre-processes data, and transfers the information to DSP in parallel, which may simplify the peripheral circuit and ensure the system's real-time performance.

4. Implementation of Sensor Fusion

The implementation of the Sensor data fusion can be carried out using the two possibilities discussed further using Figure 2 and Figure 3. As per the implementation shown in Figure 2.0, simulation is carried out using Matlab 2019b software to run multi-sensor data fusion algorithms. The fusion algorithm can be developed as a .m file or the simulink model for simulation in Matlab. As compared to the programming languages such as C, C++ or FORTRAN, MATLAB provides an easier and faster way of developing the codes for algorithm implementation.

There are various design options available in Matlab that can be explored to solve the problem in the proposed work and can be checked for feasibility through the simulation of the solution. For the proposed work, the workflow for sensor fusion in mobile robots can be realized by the following steps shown in Figure 4.0. The first step is selecting appropriate sensors as per the requirements of the mobile robot application, followed by the step of choosing the fusion algorithm and deciding on the selection of parameters through several iterations in the simulation process. Further, the fine-tuned algorithm can be fed to an inbuilt HDL (Hardware Description Language) coder in Matlab software, which provides the powerful functions in its HDL toolbox and generates the HDL code VHDL or Verilog as per the user's choice. Thus generated HDL code can now be simulated, synthesized and implemented on the FPGA hardware using the tools, namely, Xilinx ISE and Xilinx Vivado.
1) Data Gathering from sensors
The data from various sensors are collected and shaped into the required form. However, some of the sensors produce data/information in analogue form, and hence it has to be converted back to digital form to make it suitable for further process. DAC can be used for this process.

2) Choice of algorithm and its design
The algorithm needs to be chosen based on the proposed mobile robot application. The need is to choose an appropriate fusion algorithm to fuse multiple sensor data for the precise decision making on navigational path planning of the mobile robot in an autonomous fashion. Kalman Filter algorithm is the optimized algorithm used for the sensor fusion process in the proposed work.

3) MATLAB simulation
When the algorithm is simulated on MATLAB, it processes the data and converts it to VHDL or Verilog code. In addition, MATLAB provides various in-built tools such as HDL coder and other additional tools such as state machine charts, image processing tools and others to support the implementation.

4) FPGA implementation
When the VHDL and Verilog codes are obtained, the codes can be implemented on FPGA using XILINX or VIVADO. As per the other implementation shown in Figure 3.0, the entire fusion system is implemented on the EDGE ZYNQ SoC FPGA development board and provides the features of a single-board computer built around Xilinx 7-Series FPGA device integrated dual-core ARM Cortex-A9. Here the advantages of utilization of features from the processor logic and reconfigurable logic are exploited. The output from the Infrared sensor is analogue and must be converted to digitized form before sending it as the input to FPGA. As the ultrasonic sensor provides digital data, it can be directly interfaced with FPGA. Once both the sensors are interfaced to FPGA, the fusion of sensor data can be done either using the Central Limit Theorem or the extended Kalman Filter using the processor available on the same board along with FPGA. Thus the sensor fusion algorithm will thus be used for obstacle detection, and further deciding on the navigation path opted by the autonomous mobile robot. This implementation is very widely suitable for boosting robotic applications performance while providing accurate sensing, fast processing, and precise actuation in an absolute sense. The future scope of the proposed study is based on the use of FPGA based reconfigurable computing techniques for robotic solutions. The faculty and the students involved in the proposed research activity got excellent exposure to every research methodology step. The activity provided them with good hands-on experience and also problem-solving skills [21, 22].

5. Conclusion
Here, the focus was on I4.0 standards in developing autonomous systems, which work with better performance and better power efficiency. FPGA based services are of help in providing intelligent system solutions like Auto-guided vehicles or autonomous vehicles in a modern factory environment. The sensor fusion process is an essential process to improve the intelligence of the robot systems through accurate sensing, leading to robust decision-making and precise motion control and actuation. Thus the discussion further emphasizes the need for usage of FPGA based solutions in the sensor fusion process and also on the possible methodologies that can be employed.

Acknowledgement
The authors extend their gratitude to the management of KLE Technological University, Hubballi, Karnataka, India, for the financial support and the provision of a laboratory facility to conduct the research work under the program, Research for undergraduate( REU) at the Department of Automation and Robotics.

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