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THE APPLICATION OF ENERGY HARVESTING SYSTEMS IN PRODUCTION LOGISTICS

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Nowadays, within the framework of Industry 4.0, devices that consume little energy and are capable of taking over the data collection and measurement tasks of PLCs are increasingly being integrated into manufacturing and logistics processes. The emergence of IoT devices enables a level of data collection that allows more accurate forecasting and planning in the field of logistics through data processing and analysis. However, these devices are typically powered either by the mains or by dry cells/batteries. The cost of installing a mains power supply is high, while replacing or charging power sources integrated into local devices can be problematic. Advances in electronics are also driving IoT devices towards ever lower energy consumption, therefore energy harvesting solutions may be a realistic option for recharging batteries. In this publication, we define the conditions for the application of these solutions, taking into account the characteristics of manufacturing and logistics processes. Furthermore, we illustrate the potential of their introduction through a fictional example.

Keywords: IoT, energy harvesting, production logistics

1. Introduction

There are numerous sensors and data collection devices available today in the field of production logistics. With the introduction of Industry 4.0, the number of smart devices is also increasing. During the manufacturing process, it is essential to track and monitor raw materials, semi-finished and finished products. However, this requires an increasing number of devices that rely on some form of power source [1]. Older sensors had to be wired for power, but today more and more devices operate on their own power sources. These devices allow flexible placement and dynamic reallocation when required by the flexible manufacturing process [2]. New technologies are increasingly energy-efficient, but depending on usage, charging or replacing power sources is unavoidable from time to time. This causes downtime; therefore backup devices must be provided. The period between two charges can be increased, or external charging can be replaced by energy harvesting solutions that collect energy that would otherwise be lost in a given environment and use it to charge the devices [3].

In this publication, we examine these solutions from the perspective of production logistics. We review the possible energy sources and the energy harvesting solutions that can be used to collect them.

2. Sensors, data collection and identification devices in production logistics

Although a number of sensors and data collection devices can be used to measure logistics data, it is necessary to examine which devices are suitable for the application of energy harvesting solutions. Passage detection photocells and color or shape recognition cameras primarily control the product route and are suitable for detecting rejects [4]. These sensors are connected to various motors and control devices; therefore their power supply is provided by the mains. Cameras have high energy requirements, so using their own power source is not efficient.

Product identification is still carried out using barcodes or 2D codes. Modern barcode readers also use cameras to read the identification, which allows the use of error correction and image analysis algorithms, enabling them to read even slightly damaged barcodes. Deep learning artificial intelligence models, which are becoming increasingly widespread today, are capable of recognizing even severely damaged identifiers [5]. There are low-energy cameras integrated into IoT systems, but their energy consumption is still relatively high.

One of the more modern identification solutions is RFID, which uses radio waves with lower energy requirements for reading. The tags are more expensive

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than barcodes, but they do not require a direct line of sight for reading. This is mainly applicable in places where mass reading is required, and it is not possible to position individual products in such a way that the barcode can be read from each one. Although RFID solutions do not guarantee 100% reading, accuracy individual reading is ensured in the production process when the unit load is broken down [6]. There are semi-active RFIDs that can measure temperature and humidity and transmit this data to the reader during reading [7]. This solution is less commonly used in production, as this type of data is not required for individual products.

When performing warehousing and transport tasks with forklifts and AGVs, it may be necessary to know the position of the transport equipment. This information can be used mainly for collision detection in automatic transport equipment and as a data source for route optimization tasks. In the case of human machine interactions, it is also important to know the position of the workers. RTLS systems are used to determine positions within buildings and factory units [8]. In this solution, an active RTLS tag periodically transmits its ID to antennas located in its vicinity, which determine the exact position of the device in space based on the principle of trilateration. RTLS systems are complex solutions with dedicated servers and high acquisition costs. However, the tags have their own power source, which needs to be replaced or recharged from time to time [9]. The maintenance time must be scheduled so as not to interfere with production processes, or a replacement device must be provided for the given period.

3. Applicable energy harvesting solutions

In a broader sense, energy harvesting systems also include naturally occurring green energies such as solar, wind and wave energy, as well as the energy recovered during braking in electric vehicles. This publication reviews solutions in the narrower sense that are suitable for powering logistics equipment in a production line or production chain.

3.1. Light energy

The use of light energy has already gained ground in many areas of life. The vast majority of solutions are based on the use of outdoor light energy, typically sunlight. Solar cells made of semiconductor materials convert incoming light into electrical energy, which is stored in batteries or other energy storage systems until it is used. Although much less energy is emitted inside buildings, it can be used to power low-consumption devices. In this case, light from outside or artificial lighting is collected and utilized [10].

3.2. Thermal energy

Energy can be obtained from the temperature difference between two media at different temperatures. The more common devices generate energy by layering semiconductor materials in a "sandwich-like" manner. The underlying physical principle is the Seebeck effect. The two sides with different temperatures increase in direct proportion to the size of the surface and the temperature difference. Efficiency is reduced by heat diffusion in the surrounding air or liquid, which tends to equalize the temperature difference. A prerequisite is that the two surfaces have a relatively stable temperature difference [11]. There are also non-semiconductor-based energy collectors. These contain materials that undergo a change in state when exposed to heat, generating electrical energy in the process. They are used in cases where semiconductor technology cannot be exploited, i.e. when the temperature changes cyclically [12].

3.3. Energy from radio waves

The amount of "electrosmog," or radiofrequency waves generated by electrical equipment, is increasing in our environment. These can originate from Bluetooth devices, WiFi used for the internet, or GSM mobile networks [13]. Unused energy from these radio sources can be captured with a suitable antenna and converted into electrical current. The amount of energy that can be extracted can be determined using the Friis transmission equation, according to the given environmental parameters. The formula includes the parameters of the transmitting antenna (power, gain, directivity), distance, and wavelength [14].

3.4. Kinetic energy

Kinetic energies include energies derived from various types of motion, vibration and shaking. Depending on the type of motion and its temporal progression, various technologies can be used to optimally convert kinetic energy into electrical energy. Periodically repeating types of motion, such as vibrations caused by the rotation of a motor, can be collected using devices that operate on the principle of electromagnetic induction. In these devices, the movement of a magnet relative to the surrounding coil induces a current in the coil according to Faraday's law. The energy generated depends on the strength of the magnet, the material and number of turns of the coil, and the degree of displacement. Displacements caused by pressure changes, such as the passage of loads over a surface, can be utilized with devices operating on the piezoelectric or capacitive principle, which are sensitive to pressure changes [15]. Piezoelectric solutions use a special semiconductor material that generates electrical voltage when pressure is applied. The magnitude of the voltage depends on the size of the surface and the degree of pressure change. In devices operating on the capacitive principle, there is a dielectric between two electrodes, and usable electrical energy is generated by the displacement of the surfaces relative to each other.

Table 1: Typical energy densities for different energy sources [17]

Energy source	Energy density
Internal light	10 … 100 μW/cm^2
Heat	10 μW/cm^2 … 10 mW/cm^2
Radio waves	0.001 … 0.9 μW/cm^2
Kinetic	200 … 1000 μW/cm^2

3.5. Complex energy harvesting systems

The collection of individual energy sources can also be achieved using integrated devices capable of collecting multiple forms of energy. In this case, an energy collection device does not use only one type of source. Their advantage is that they require less space, but their disadvantage is that they are not as efficient as dedicated solutions. For example, there are devices that collect indoor light energy and electromagnetic wave energy simultaneously [16].

3.6. Comparison of energy harvesting systems

Before examining the areas of application, it is worth describing the energy that can be collected with each technology. Of course, the amount of energy produced depends on many factors, but approximate orders of magnitude can be used to decide which solution is suitable for supplementing the power supply of which devices. *Table 1* summarizes the typical energy densities associated with different types of harvestable energy. Since different technologies can capture and convert different amounts of energy, and the amount of energy collected also depends on environmental parameters, we have indicated the typical value range. The energy density of internal light and RF energy is low, but large surfaces can be created to capture these energies sources; therefore the total energy that can be obtained can reach that of heat and kinetic energy sources. As can be seen, the typical maximum energy density is only 10 mW/cm^2, so it is important to examine the area of application to determine how much energy can be collected.

In addition to the amount of energy that can be collected, the cost of the design must also be considered. Solutions for collecting radio frequencies are the simplest, as they only require an antenna, the surface area of which determines the amount of energy that can be collected. The use of internal light requires solar cells, the cost of which depends on the semiconductor and technology used. In the case of flexible solar cells, the collection surface does not have to be flat, thus increasing the number of possible applications. It is important that energy collection does not reduce the amount of light required for work. The use of thermal energy is highly situation-dependent, the cost of the equipment is similar to that of light energy, but its applications are more limited. Kinetic energy collectors are the most complex systems, so their specific cost is the highest. However, they can be used in many places, so the total energy may be sufficient to support the energy supply of sensors and IoT devices [18],[19].

4. Possibilities for the use of energy harvesting in production logistics

In order to use the energy sources described above, it is necessary to examine the areas in which they can be applied effectively. Since the energy that can be extracted is not constant and is not sufficient to power more serious devices, it is most suitable for low-power IoT devices and sensors. From a logistics perspective, energy harvesting solutions can be used to supplement the power supply of positioning devices, devices used to track the quantity of materials and products in warehouses, and devices used to measure and record environmental parameters that are important for quality assurance. Sensor data are required for inventory monitoring and for forecasting maintenance tasks. Thanks to the internet connection, data from IoT devices can be collected remotely, allowing large databases to be built that can be used to support forecasts and analyses. In addition to statistical calculations, so-called Big Data analyses can help in the planning of manufacturing and logistics processes, and these processes can be improved based on feedback from the collected data. The devices used in logistics processes can utilize the energy generated by vibrations, accelerations and weight changes during material handling. These are kinetic energy sources, so the energy harvesting solutions used can be based on the principle of electromagnetic induction, piezoelectric or capacitive. During the movement and operation of forklifts and AGVs, the magnets in the compact energy collectors mounted on them induce a current of varying intensity and non-periodic timing. To utilize this, for example to supplement the power supply of an RTLS tag, an intermediate energy storage device is required, which can be a high-capacity capacitor that smooths out irregularities. The tag's power source can then be charged by inserting an appropriate circuit. When pallets and materials are moved, piezoelectric cells on the forklift fork or AGV surface can collect the pressure changes resulting from the weight changes. It is also advisable to store the generated energy in a capacitor before use, because the amount of energy generated varies depending on the material handling task and the weight moved.

The energy generated by changes in the weight of stored products and materials during movement on warehouse shelves and in intermediate storage facilities can be utilized by piezoelectric energy harvesters. As these provide relatively little energy in relation to the size of the storage space, they can only be used to a limited extent for energy production.

Indoor light and radio waves can be utilized throughout the entire production area. In the case of radio waves, however, care must be taken to ensure that energy collection does not interfere with their original communication function. Antennas that are too large can cause shadowing and interference, which, for example, can disrupt Wi-Fi communication and reduce bandwidth due to frequent packet retransmissions caused by errors. Light-based energy collectors can be placed on top of equipment and machines where lighting is not essential, so that the light reaching them can be utilized. In addition to lighting, other light sources generated during production can also be utilized. In a welding plant, for example, the ultraviolet radiation emitted can be captured and used to power sensors. As this is not a continuous source, temporary storage is also necessary in this case.

Vibration is generated during the use of many tools and pieces of equipment in manufacturing processes. The intensity and temporal course naturally depend on the operations performed by the given production unit, the parameters of the manufactured product and the technology applied. It is evident that there is a significant difference between the equipment used to manufacture paper products and the equipment used in an automotive factory in terms of the energy used and the recyclable energy generated. The use of kinetic energy can be efficient; for example, consider the vibration of high-performance engines, the vibrations and movements resulting from the operation of presses. These can be converted into electrical energy, but the manufacturing technology applied may also require customized energy collection solutions. Energy harvesting devices available on the market cannot necessarily be integrated into the production process without modification. In such cases, custom-designed solutions can be developed that are best suited to the machine in question. For operations that generate large amounts of waste heat, energy collection solutions based on the Seebeck effect can be used, or, if the temperature varies over time, collectors based on phase change may be suitable. For example, during production, the raw material or product must be heated in a furnace and then transported on a conveyor belt to the next operation, where cooling is required. The temperature difference between the two steps or the heat radiation emitted during the cooling of the material can be converted into electrical energy. As with kinetic energies, it is necessary to examine which solution provides optimal usable energy.

5. Application of energy harvesting solutions through a fictional example

5.1. Presentation of a fictitious manufacturing and logistics process

The fictional company is an automotive supplier that processes steel sheets for the manufacture of car body parts. The factory has several production lines, and the workers and forklifts used for material handling are equipped with RTLS tags so that their positions in the factory can be tracked in real time. In the factory's raw material warehouse, steel sheets of different qualities, thicknesses and sizes arrive on pallets from the supplier. Raw materials with the same properties are always placed in specific locations in the warehouse. For production, the forklift operator places a pallet in the intermediate storage area, where the fastening straps are removed before use, and then the sheets are placed in another intermediate storage area, from which a robot places them in the pressing equipment during production. After pressing, a conveyor belt transports the sheets to the next pressing station, where further processing takes place. Several of these production lines operate in parallel, and depending on the end product to be manufactured, the product at the end of the production line may be a finished product, which is immediately transferred to the finished product warehouse. There are also manufactured components that are welded together after pressing, so they undergo another work process to become a finished product.

The semi-finished, already pressed products consisting of several components are transported by forklift from the end of the production line to the welding line, at the end of which the finished product is produced according to the specific finished product to be manufactured. At the beginning of the line, the semi-finished products to be welded are collected in individual storage containers, lifted into the welding machine by robots, and positioned. After welding, the finished product is placed on a pallet and transported by forklift to the finished product warehouse. The finished product is delivered from the warehouse to the customer by truck.

5.2. Sensors and data collectors used

As mentioned in the presentation, forklifts and workers were equipped with RTLS tags, which enable real-time positioning. Upon arrival at the raw material warehouse, each pallet is assigned a unique identifier, to which the raw material data, quantity, and receipt data are linked. An RFID tag is attached to the pallet and linked to the unique identifier. This RFID tag is used for identification within the factory premises. This makes it possible to track the location of the pallet and the raw materials it carries.

Stock changes are recorded during transport to production using an IoT RFID reader located on the forklift. This device transmits the pallet ID via the network, and the ID of the pallet delivered to production is recorded in the logistics system running on the server. The in-process storage facilities also use IoT devices to detect the received pallet and transmit the data to the central server.

In the storage area accessible to robots, a sensor monitoring the robot's movement and a built-in scale detect changes in stock. Following pressing, an optical inspection device examines the semi-finished or finished product to ensure that it complies with the parameters recorded during production. The image of the product is also stored for quality assurance purposes, and a Go/NoGo signal is sent to an IoT device as a result of the inspection. If the product is compliant, it is assigned a unique barcode by an automatic machine, which is also recorded in the central system. If the product is defective, the IoT device directs it to a separate route where it is inspected by a human operator. Other tests are also required at the end of the welding line. The result of each test is also a Go/NoGo signal, which determines whether the product can proceed or requires human inspection. The pallets of semi-finished and finished products are also assigned an RFID tag, and products that meet the quality requirements are recorded in the central system.

The forklift also reads this tag during transport, and when the goods arrive at the warehouse, a reader installed at the storage location records the storage event in the system. During delivery, the IoT device on the forklift used for storage reads the RFID tag and records the delivery event.

5.3. Examination of the use of energy harvesting devices

In the factory described above, numerous devices require a power supply. The RTLS tags on the forklifts and workers contain batteries and can be charged via a USB-C connector. The IoT devices also contain a rechargeable power source. An energy harvesting solution based on the principle of electromagnetic induction is recommended for the forklifts to utilize the energy generated by their movements. Although it does not provide a complete power supply, it can increase the time between charges. For workers, a special energy harvester developed for wearable devices can be paired with the forklift, which is worn on the arm and uses the movements made during work to collect energy.

The RFID readers installed in the storage areas can be powered from the mains, and there is no significant energy loss that could be utilized, as there is no movement or temperature difference. The collection of RF and light energy is not efficient due to the design of the warehouse. Radio waves are shielded by the metal structure, while light is shielded by the warehouse itself and the stored raw materials or finished products. The quality control cameras are also powered by the mains, and due to the large amount of data processing, their energy requirements are high, so the use of energy obtained from the environment is irrelevant.

The vibrations generated by the pressers during operation and light from the environment can be used to supplement the power supply of IoT devices and sensors used on the production lines. Electromagnetic induction devices placed on the side of the press machines must be specially designed for the specific equipment in order to convert the large range of motion as efficiently as possible. The solution requires a device that operates on a linear principle, where the magnet does not move inside the coil. Such devices are available on the market, but not in the appropriate size, so a custom-made solution is required. Indoor light-collecting cells can be placed on surfaces where lighting allows. A significant amount of energy can be collected by covering a relatively large area. It is advisable to combine these into a common storage device, which is no longer a high-capacity capacitor, but a high-capacity battery connected to it. The electrical energy stored in this device can be used to power sensors and IoT devices.

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