IIoT based efficiency monitoring of a pick and place robot

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Abstract
The Industrial Internet of Thing (IIoT) approach to an Industry plant design devises a comprehensive interconnection of the system components, from sections up to single devices, in order to get a general and punctual understanding of the process. Such a network, mostly based on Ethernet basic layers, when properly conceived, should be able to add relevant value to the plant operation, thus giving a relevant contribution to the Industry 4.0 perspective. This paper shows how, within the IIoT frame topics, the plant efficiency e.g. can be addressed and bring relevant improvement. The reason is that variables directly related to the energy consumption, such as current, electric power, actuator and motor torque, speed, etc., can be timely and easily monitored in the entire plant, since they are already conveyed on the network, due to real time control and diagnostics purpose. A power consumption diagram can be derived, giving a basis for increasing the plant operation efficiency, either by a real time energy monitoring, warning for abnormal condition, or by suggesting improvements, bringing to a more efficient operation strategy. After a general discussion, this paper demonstrates its potential with a practical example based on a Gantry robot, driven in an EtherCAT based automation network.

Introduction
The **IoT** (Internet of Things) expression describes a way along the technology development process based on the internet network, where each object available in daily use can be interconnected. IoT refers to smart machines with pervasive sensing, networked to the Cloud, exchanging applications and services among them, and cover a wider, more general field; the term is distinct from M2M (Machine-To-Machine) communication which mostly focuses on the telecommunication network architecture. IoT can be considered as an extension of the traditional wireless sensor networks (WSN) that makes the object-to-object communication possible by using Radio frequency identification (RFID) or equivalent technology. It deals with connectivity in general purpose networks, warehousing infrastructure and building systems to enable the delivery of software services, data analytics and autonomous control from the Cloud. **IIoT** (Industrial Internet of Things) adds the Industrial context to the IoT, thus stressing some specific requirements, typical of Industry Control, such as Determinism, Real Time capability, Robustness and Reliability, Security and Integrity. In IIoT each object, be a physical device or an abstract entity, acquires a unique digital identity, which allows for significant changes in the industrial process control based on the idea of reducing cost and improving efficiency, by integrating progresses in software and communication technology [1–3].

The logistic chain in IoT and IIoT results in a complex task. Actually, it is difficult for users to characterize services chain performance quantitatively, since different criteria may have different roles in various jobs [4–7].

"Anytime, anywhere, any media" has been for a long time the vision pushing forward the progress in communication technologies. In this context, wireless technologies have played a key role. After studying the various IoT use cases and their architectures, it can be stated that IoT and the traditional Internet architectures are similar in many aspects. On this assumption the IoT system architecture can be divided into three layers: the perception layer, the transmission layer, the application layer [8].

The communication layer is the information source and the core layer of IoT. All kinds of information of the physical world used in IoT are perceived and collected in this layer (e.g. wireless sensors network (WSN), tags and reader-writers etc.). Network layer also called transport layer, includes access network and core network, and provides transparent data transmission capability. The information from perception layer can be sent to the upper layer using existing mobile communication network. Service layer also called application layer, includes data management sub-layer and application service sub-layer. The data management sub-layer provides at processing even complex data and uncertain information. Most of the "philosophy" implied by IoT and namely IIoT converges in the German originated project called Industry 4.0.

The paper will resume in paragraph II–IV the frame where industry applications can be viewed and improved in this context. Paragraph V and VI will illustrate this with an example based on an actual implementation of a Pick-and-Place robot. Macros based on the EtherCAT protocol are also described to suggest an Energy efficiency improvement strategy.

Application Field and Enabling Technology for IIoT and Industry 4.0

The areas where an industrial plant or process can take advantage of the IIoT are numerous and encompass the different levels in the pyramidal model of a smart factory, from the Decision making level, down to the Field level, due to a common Standard Language (mostly Ethernet-Like), resulting in added values at no or very low cost, as it is stressed in the following.

PROCESS MONITORING

Costs such as power supply, energy consumption and contractor labor can vary unpredictably, making it tough to track the company's business and the operating costs. Incorporating IoT equipped sensor technology into company's business processes can help reduce variable expenses and streamline the operations, reducing stress over business finances. By creating "smart systems" and automating responses to conditions that can increase company's expenses, it is possible to create a more predictable, cost-controlled environment.

Such technologies can also help a company to analyze the correlations between disparate data points, helping the company to discover new insights in its data that can be used to optimize company's processes in the future, namely in the field of energy efficiency.

Beyond the production line, one area where the IIoT is also useful is the customer service. By analyzing the data driven from clients and by using computer diagnostics built into a product with IoT communications technology, the customer service will no longer react to a problem of the client, but it can instead focus on monitoring the equipment and remotely fix problems before the customer is even aware that the problems exist. By heading off a problem before it is about to happen, preventive maintenance can be scheduled when it's convenient and it reduces the number of expensive repairs.

When failures do occur, IoT technology can help service organizations get systems and services up and running faster. Service technicians will be able to query devices before they go on-site to determine how a piece of equipment failed and bring the proper tools and spare parts. They will also have access to the service history of the equipment, which will help them troubleshoot the problem. The end result is lower service costs and equipment that is back online faster. Improving customer service is certainly a challenge, so the company will be able to provide a better customer care.

SECURITY AND INTEGRITY OF INFORMATION: RELATED RISK

The technical architecture of the IIoT has an impact on the security and privacy of the involved stakeholders. Privacy includes the concealment of personal information as well as the ability to control what happens with this information. The privacy can be considered as either a basic human right, or as a personal right or possession. Thereby, individuals and, by extension, companies and marketing enterprises have the right not to be watched without them even knowing about it, neither leave their data nor traces thereof in the cyberspace. To provide enough resilience to attacks, the system has to avoid single points of failure and should adjust itself to node failures. Information providers must be able to implement access control on the data provided. Measures need to be taken in order that only the information provider is able to infer, from observing, the use of the lookup system related to a specific customer; at least, inference should be very hard to conduct. Private enterprises using IIoT technology will have to include these requirements into their risk management concept and assessment [10].

DESIGN PRINCIPLES IN INDUSTRY 4.0

The term "Industry 4.0" originates from a project in the high-tech strategy of the German government, which promotes the computerization of manufacturing [9]. The first industrial revolution mobilized the mechanization of production using water and steam power. The second industrial revolution then introduced mass production with the help of electric power, followed by the digital revolution and the use of electronics and IT to further automate production.

Industry 4.0 can be characterized by a number of principles that support companies in identifying and implementing Industry 4.0 scenarios [11].

1. **Interoperability**: the ability of Cyber-Physical Systems, CPS (i.e. work piece carriers, assembly stations and products), humans and Smart Factories to connect and communicate with each other through open nets and semantic descriptions such as Internet of Things and the Internet of Services thanks to the communication standards.
2. **Virtualization**: a virtual representation of the Smart Factory which is created by linking sensor data (from monitoring physical processes) with virtual plant models and simulation models. Virtualization means that CPS are able to monitor physical processes. The sensors data is linked to virtual plant simulation models, allowing for a detailed debugging and tuning of the process during setup and initialization steps. During standard operation the virtual plant

offers a useful comparison to check for a regular running of the plants. In addition, all necessary provisions are notified, in case of failure, including next working steps or safety arrangements to be provided.

3. **Decentralization**: the ability of CPS within Smart Factories to make decisions on their own. Embedded computers enable CPS to make decisions on their own. Only in cases of failure, tasks are delegated to a higher level. The central control can be reduced to very relevant assignment.
4. **Real-Time Capability**: the capability to collect and analyze data and provide the derived insights and action immediately. The status of the plant is permanently tracked and analyzed, based on a deterministic and prompt dynamics. Among the advantages is the ability to implement redundancy strategies, by reacting to the failure of a machine and re-routing operations to another machine.
5. **Service Orientation**: offering of services (of cyber-physical systems, humans or Smart Factories) including the general services of the company among the Things involved in the IIoT (Industrial Internet of Services, IIoS). That is the services and the facilities inside the company can be shared from all participants, by exploiting the network and the web service.
6. **Modularity**: flexible adaptation of Smart Factories to changing requirements by replacing or expanding individual modules. Modular systems are able to adapt in a flexibility way to changing requirements by replacing or expanding individual modules. Based on standardized software and hardware interfaces new modules are identified automatically and can be utilized immediately.

On this basis it is quite easy to point out the similarities and a close interaction between Industry 4.0 and IIoT.

INDUSTRIAL ETHERNET. ETHERCAT

A possibility to implement the Industry 4.0 through the IIoT paradigm is based for example on the use of drives (PLC controllers, inverters …) connected by an intelligent bus system falling in the category of Industrial Ethernet (IE). Originally developed for telecommunications, the standard Ethernet is used also for industrial application such as machines and process control. This when adapted to the manufacturing field is called Industrial Ethernet, that refers to the application of the Ethernet protocols with rugged connectors and extended temperature switches in an industrial environment, for automation or process control, thus requiring more reliable behavior both in hardware and software. Components used in plant process areas must be designed to work in harsh environments of temperature extremes, humidity, and vibration that exceed the ranges for information technology equipment intended for installation in controlled environments. Plant-floor equipment must tolerate a wider range of temperature, vibration, and electrical noise than equipment installed in dedicated information-technology areas. Since closed-loop process control may rely on an Ethernet link, economic cost of interruptions may be high and availability is therefore an essential criterion. So, Industrial Ethernet networks must provide predictable performance and maintainability. In addition to physical and low-level transport protocols compatibility, a practical industrial Ethernet system must also provide interoperability of higher levels of the OSI model. An industrial network must provide security both from intrusions from outside the plant, and from inadvertent or unauthorized use within the plant.

Industrial Ethernet differs from the Standard Ethernet even from the operational viewpoint. Indeed while Standard Ethernet operates on the basis of a peer-to-peer network, where deadline in data transfer cannot be guaranteed, IE network transmission relies on switches to segment a large system into logical sub-networks, divided by address, protocol, or application. Using network switches allows the network to be broken up into many small collision domains. This reduces the risk of a faulty or misconfigured device generating excess network traffic. When field level of the network must connect to the upper office or external levels, a firewall system can be inserted to control exchange of data between the networks, to preserve the performance and reliability of the plant devices operation. The Associations promoting the existing industrial open or proprietary protocols (e.g. Modbus, Profibus, Sercos) are releasing new revisions or completely new solutions (e.g. Profinet, Sercos III, EtherCAT) fully tunneling (interfacing) in the Ethernet world, thus implementing a *de facto* interoperability [12].

Let us take as an example, which has been used in the following application paragraph, to take into consideration EtherCAT – Ethernet for Control Automation Technology – that is an Ethernet-based fieldbus system, invented by Beckhoff Automation. The protocol is standardized in IEC 61158 and is suitable for both hard and soft real-time requirements in automation technology. The goal during development of EtherCAT was to apply Ethernet for automation applications requiring short data update times (also called cycle times; ≤100 µs) with low communication jitter (for precise synchronization purposes; ≤1 µs) and reduced hardware costs. The transmission media that allows EtherCAT to operate is Ethernet protocol, based on the standard IEC 802.3. This standard supports several protocols always respecting the OSI model and, one of these, is EtherCAT. In what follows, the main features are described:

- **Functional Principle**: with EtherCAT, the Standard Ethernet packet or frame (according to IEEE 802.3) is no longer received, interpreted, and copied as process data at every node. The EtherCAT slave devices read the data addressed to them while the telegram passes through the device, processing data "on the fly". Similarly, input data are inserted while the telegram passes through. A frame is not completely received before being processed; instead processing starts as soon as possible. Sending also is conducted with a minimum delay of small bit times. Typically, the entire network can be addressed with just one frame.
- **Protocol**: the EtherCAT protocol is optimized for process data and is transported directly within the standard IEEE 802.3 Ethernet frame using Ethertype 0x88a4.
- **Performance**: short cycle times can be achieved since the host microprocessors in the slave devices are not involved in the processing of the Ethernet packets to transfer the process images. All process data communication is handled in the slave controller hardware. Combined with the functional principle this makes EtherCAT a high performance dis-

tributed I/O system: Process data exchange with 1,000 distributed digital I/O takes about 30 µs, which is typical for a transfer of 125 byte over 100 Mbit/s Ethernet. Data for and from 100 servo axis can be updated with up to 10 kHz. Typical network update rates are 1–30 kHz, but EtherCAT can be used with slower cycle times, too, if the DMA load is too high on the PC [13].

- **Topology**: EtherCAT enables a multitude of network topologies, including line, tree, ring, star, or any combination thereof. The protocol also enables a multitude of communication features such as cable redundancy, Hot Connect of segments, change of devices during operation, or even master redundancy with Hot Standby. Thus the combination of the topology variations and different network architectures enables numerous possibilities, e.g. sub-ordinated or neighboring control systems with consistent synchronization. Additional switches are not required. The physics of Ethernet allow a cable length of up to 100 m (300 ft) between two nodes. For higher distances, or the complete galvanic isolation between two slaves, fiber optic cables are used. With single-mode fiber, distances up to 20 km between two nodes can be bridged. Since a total of 65,535 nodes per network segment can be connected, the network extension is nearly unlimited.
- **Synchronization**: for synchronization a distributed clock mechanism is applied, which leads to very low jitter, significantly less than 1 µs, even if the communication cycle jitters, which is equivalent to the IEEE 1588 Precision Time Protocol standard (PTP). Therefore, EtherCAT does not require special hardware in the master device and can be implemented in software on any standard Ethernet MAC, even without dedicated communication coprocessor. To keep the clocks synchronized after initialization, the master or slave must regularly send out the broadcast to counteract any effects of speed difference between the internal clocks of each slave. Each slave should adjust the speed of their internal clock or implement an internal correction mechanism whenever they have to adjust. The system clock is specified as a 64bit counter with a base unit of 1 ns starting at January 1, 2000, 0:00.

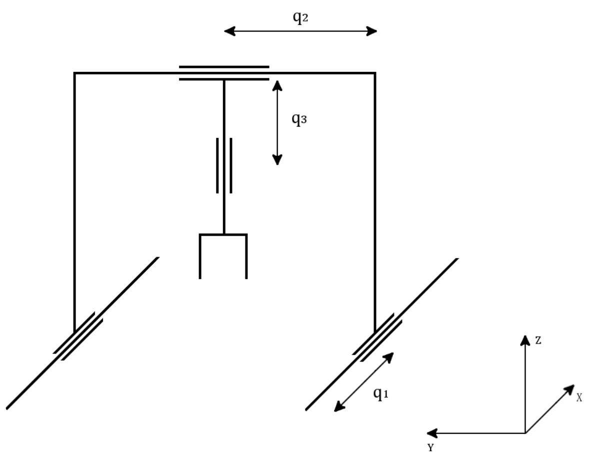

Figure 1. Schematics of the Pick-and-Place robot.

- **Diagnosis**: the fast, precise detection of disturbances is one of many diagnostic features of EtherCAT. Bit errors during transmission are detected reliably by the analysis of the CRC check sum: the 32 bit CRC polynom has a minimum Hamming distance of 4. Besides the error detection and localization protocol, transmission physics and topology of the EtherCAT system allow an individual quality monitoring of every single transmission path. The automated analysis of the according error counters enables the exact localization of critical network segments.
- **Device Profiles**: the device profiles describe the application parameters and functional behavior of the devices, including device-specific state machines. Thus the migration to EtherCAT by adjusting the firmware and the hardware is simplified significantly.

Referring to the Industry 4.0 introduced in the previous paragraph, EtherCAT fits with most of its principles. Since it is defined as a real-time field-bus, its communication system satisfies the *Real time capability* principle. The overall system, thanks to the lowest allowable time cycle, can be controlled without significant delays. The flexibility of EtherCAT moreover defines the *Modularity* and *Decentralization* principle that, with some minimum operations or settings, allows to immediately identify, in an already established plant, the possible hardware changes based on EtherCAT system. However, their operability depends on the ability of the programmer, who knows the task and the pre-programmed applications very well. At last, the *Interoperability* principle is satisfied since the devices communicate with the same standard. The remaining principles (*Virtualization* and *Service orientation*) can easily be implemented with dedicated Application Programs.

A Demonstration of Energy Evaluation through EtherCAT Variables

In this section, it will be shown how, based on the use of the EtherCAT protocol, it can be implemented an evaluation of the energy consumption related to an automated pick and place operation in an industrial plant. This procedure can extensively be applied to other section of the industrial plant and operation, where displacement and motion is involved, as long as the operation details, the parameters and time of execution of each activity are known. This can be done because all the plant variables are shared through the communication system in the EtherCAT environment and made available from any plant node.

ENERGY CONSUMPTION EVALUATION

In the following the procedure is applied to the operation of a Cartesian robot operating in a Gantry type frame to perform Pick-and-Place operation. A more detailed description of the process referred to, including physical description and trajectories calculations is reported in [14]; for the purpose of the present paper a simplified description of the operation and movements refers to the schematics of Figure 1.

When handling a product, the Pick and Place operation can be divided into three steps: i) *lift on* – is the vertical lifting; ii) *travel* – the transportation in horizontal direction; iii) *set down* – the release after a vertical drop. Using the Cartesian axes reference, the reference frame is placed along the Cartesian portal robot's so that the lift on and set down phases are accomplished along the z-axis. The travel phase is conducted along the x- and/or y-axis in function of the final point position. The dynamic model of a manipulator provides a description of the relationships between the torques of the joints and the motion of the structure. In particular, the dynamic model comes from the matrix form of Euler-Lagrange equations:

$$\tau = D(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q)$$

Where τ is the joint torque, q is the position of the reference point of the end-effector, D is the hybrid inertial matrix, C is the hybrid Coriolis matrix and G is the vector of gravity.

The actuators more commonly used to move the Cartesian robot here considered, and more in general for automation industry applications are dc or brushless motors, which in the following are modeled according to [15] with the model shown in Figure 2.

Concerning the actuator and robot dynamics the total instantaneous electrical power P_e supplied to the manipulator is given by:

$$P_e = i_a^T v_a = i_a^T R_a i_a + i_a^T K_v K_r \dot{q}_a$$

where v_a and i_a are column vectors of the supplied armature voltages and currents respectively; R_a,K_v,K_r are constant diagonal matrices of the different armature electric resistances, back EMF constants and gear ratios respectively.

According to [15] the mechanical losses can be neglected with respect to the electrical losses, thus the power consumption of the system can be reduced to the simple equation:

$$P = i^T R_1 \tau + i^T \dot{q}_a$$

Where τ is the torque vector including the inertial effects due to the rotor inertias.

The overall energy necessary to perform a given operation for an industrial robot can be then expressed as:

$$E = E_d + E_{km} + E_{gm} + E_{kl} + E_{gl}$$

Where

- E_d is the energy dissipated through the armature resistance and through the mechanical viscous friction
- E_{km} is the kinetic energy stored in the manipulator inertial field
- E_{gm} is the gravitational potential energy due to the manipulator masses
- E_{kl} is the kinetic energy delivered to the user
- E_{gl} is the variation of the workpiece potential energy

The consumption of the energy during pick and place operations however, considering a cycle time where the handled object is picked up and delivered at zero velocity, is simplified by assuming:

$$E = E_d + E_{gl}$$

The instantaneous power supplied to the manipulator is given by:

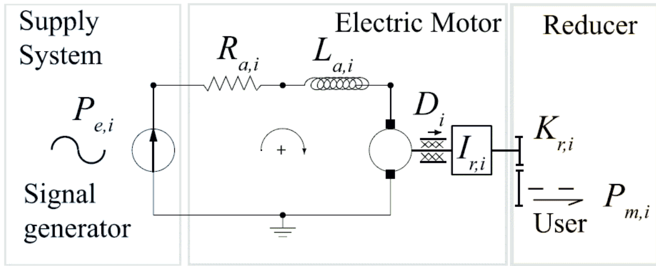

Figure 2. Electrical scheme of the robot actuators (DC or Brushless motors).

Pos.	Address	Name (Type)	State requested	State actual
M	0	EtherCAT_Master		
1	1002	L_i700_SM		
0	1001	L_i700_SM_1		

Figure 3. Master and devices address table.

Figure 4. Sub-slave structure.

$$P = \frac{\tau_{av} \cdot v_{av} \cdot 2\pi}{60 \cdot 1000} [kW]$$

where τ_{av} and v_{av} are the torque actual value and the velocity actual value [r/min]. Let T_{wc} be the operation *work cycle time* that is the overall time programmed by the controller (e.g. PLC) to complete the Pick and Place operation. In this case the energy consumption for one PLC work-cycle, E_{wc}, can be calculated as:

$$E_{wc} = \int_0^{T_{wc}} \frac{P}{3600} dt \quad [kWh]$$

USING ETHERCAT DATA TO RETRIEVE INFORMATION

The above defined calculation are here executed by proposing a function block in EtherCAT standard, thus exploiting the variables already available in the plant with a direct procedure.

The above described calculations can finally be implemented, even for different schemes and actuators, without further sensors and measurements, by exploiting the mechanical and electrical variables available on the system bus and within the PLC memory and normally used for control and diagnostics purposes. With the same assumptions even more complex models can be avoided. The EtherCAT modality to access to the bus is "Centralized" or "Master/Slave". The device Master – the network card EtherCAT – controls the bus and manages the accesses of Slave devices, according to Figure 3 addressing table.

The Master position is regulated by EtherCAT itself, while the Slave positions are controlled by the inverter, feeding and controlling the motors. Each inverter has the drive motors as sub-slaves, as shown in Figure 4.

In the following the operations are described with reference to the software made available by Lenze for applications in industrial automation design (PLC Designer and DSD Drive Solution Design programs) [16].

Figures 5 and 6 are screenshots based on EtherCAT interfaces and macros and include the main variables involved for control and diagnostics of the drives. The cycle time, defining the time employed by the robot to accomplish a Pick-and-Place cycle, is also a significant parameter influencing the energy consumption.

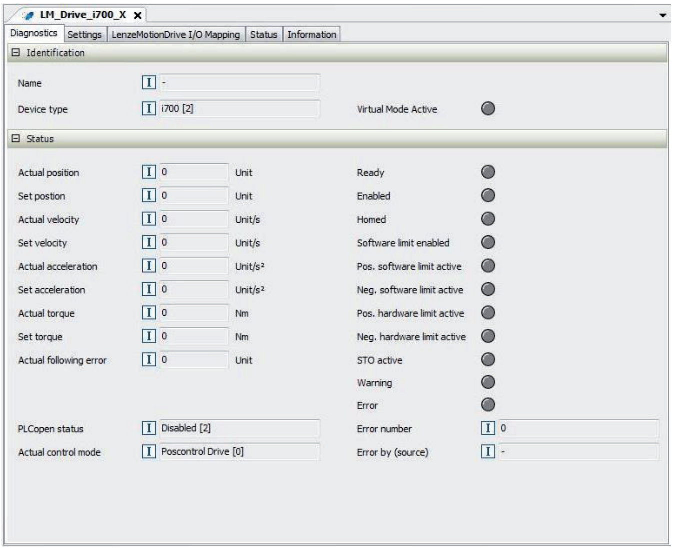

Figure 5. Variables involved.

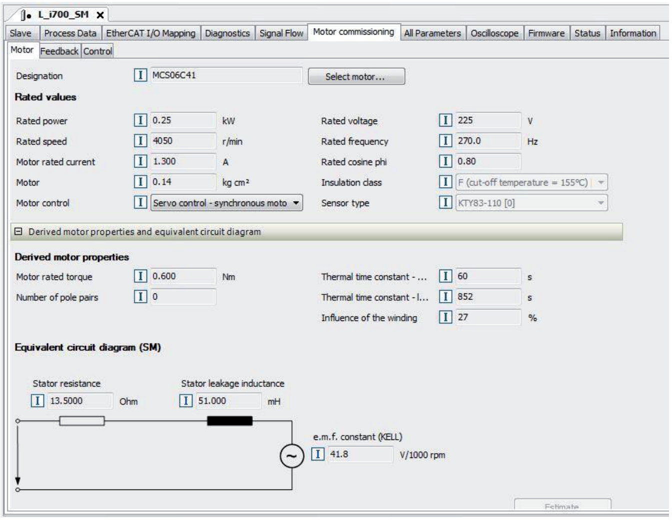

Figure 6. Further information available.

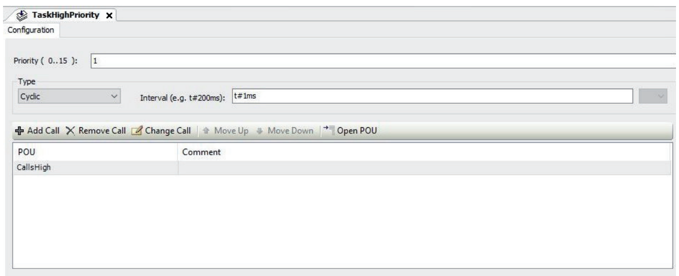

Figure 7. Setting the cycling interval.

In fact, shorter cycle times imply higher acceleration and torque, and therefore energy consumption; while longer cycle times are accomplished with smaller acceleration energy, but require a longer time when the motor has to be fed. In the mentioned software the cycle time can be chosen by setting the cyclic interval down up to 1 ms, and then increasing it (Figure 7).

To test the EtherCAT function block capabilities the Energy consumption of the motor has been calculated by using the above mentioned variables, while the *work cycle time* T_{wc} has been varied by using a *scaling method* suggested in [15]. At first a reference work cycle time T_{wcREF} has been chosen; based on this criteria, the optimal trajectory parameters have been calculated. Then a number of different simulations have been executed, by assuming a scaled αT_{wcREF} work cycle, where $\alpha<1$ implies that an accelerated process is considered, while $\alpha>1$ is for slower processes.

The trajectory parameters and the energy consumption calculated by the macros in EtherCAT are reported in Table 1 and Figure 8, thus allowing a real time monitoring, to be further processed if required.

Conclusions

This paper describes the principles that identify the new industrial era called Industry 4.0, and demonstrates the potential of EtherCAT and Industrial Ethernet protocols for its implementation. It was pointed out, with an example, how the energetic consumption for an industrial robot for pick and place task, can be derived. To this aim a dynamic model of a Cartesian robot used in the laboratory has been developed, and an application which is based on EtherCAT variables has been designed, and partially tested. The application calculates the minimum energy requested in function of motion parameters.

The scenarios opened by the IIoT are remarkable and allow to have an "intelligence" in the factory and plants, increasing exponentially the speed of decisions, thus drastically reducing the possibility of errors and allowing to make the best choices thanks to the processing of a large amount of data. The example proposed in the paper shows in particular a potential development to optimize the speed of movement of the pick and place positioner (or of a robotic arm) as a function of the available energy and / or the needs of the production. The system, based on IoT logics, could for example automatically provide for the following situations:

- availability of surplus energy that cannot be stored (e.g. for peak availability by photovoltaic): the system may decide to increase the speed and therefore the rapidity of movements, resulting in improved productivity;
- the need to increase productivity (e.g. for peak production orders to be processed or following line downtime for maintenance): the system may decide to increase the speed and therefore the velocity of movement, resulting in an improved productivity;
- the need to improve the positioning accuracy of the components (e.g. to reduce errors/defects or for improving the quality in the production of electronic boards): the system can decide a speed reduction resulting in improved positioning accuracy and reduced defectiveness;

- the need to postpone a scheduled/preventive maintenance to avoid the stop of a production line (e.g. to match the production line stopped with a generalized stop of the factory): the system can decide a speed reduction resulting in lower wear of the mechanical and increase the range of scheduled/preventive maintenance.

Further exploitation of the Industry 4.0 are under study as an extension of this work, including an experimental comparison between the evaluated and actual energy consumption. It can also be mentioned that by comparing the calculations with real consumptions, it is possible to detect failing equipment, while other diagnostic evidences can be deduced from the process variables, without added sensing equipment.

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Table 1. Scaling factor.

SCALING FACTOR	0,543	1,000	1,228	1,455	1,683	1,910	2,138
v_z [m/s]	0,230	0,125	0,102	0,086	0,074	0,065	0,058
v_x [m/s]	0,163	0,088	0,072	0,061	0,053	0,046	0,041
v_y [m/s]	0,163	0,088	0,072	0,061	0,053	0,046	0,041
a_z [m/s^2]	1,694	0,500	0,332	0,236	0,177	0,137	0,109
a_x [m/s^2]	1,198	0,354	0,235	0,167	0,125	0,097	0,077
a_y [m/s^2]	1,198	0,354	0,235	0,167	0,125	0,097	0,077
TET [s]	30,49	56,13	68,90	81,68	94,45	107,23	120,00

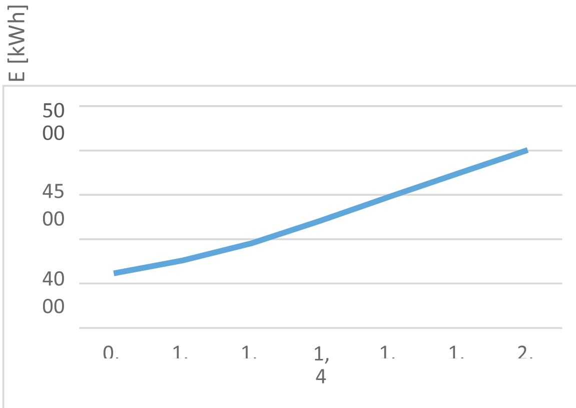

Figure 8. Energy consumption in function of the movement speed.

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