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An enabling digital foundation towards smart machining

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Abstract

Today's major challenges for manufacturing companies in the aerospace and automotive industries are clear: global cooperation with multiple supply chain partners, production optimization, management and tracking of information so as to meet new requirements in terms of traceability, security and sustainability. The need for a data exchange standard that allows disparate entities and their associated devices in a manufacturing system to share data seamlessly is clearly obvious. And the first expected impact is the 'next generation' smart controller that could really enable an intelligent machining process based on real-time monitoring and diagnosis, self-learning decision and adaptive optimization. The four-year project titled FoFdation envisions a 'Digital and Smart Factory' architecture and implementation. This has the potential to achieve significant benefits in earlier visibility of manufacturing issues, faster production ramp-up time, faster time to volume production and subsequently shorter time to market, reduced manufacturing costs and improved product quality, as well as sustainability objectives like low energy consumption and waste reduction. The present paper describes the on-going work with specific focus on the definition and implementation of the FoFdation Smart Machine Controller (SMC) in an adaptable architecture that satisfies both commercial and open source CNC controllers. It highlights the project's end use validation framework as well as sets a strong Manufacturing Information System foundation on which process optimization and control as well as sustainable practices can be based. It presents the general vision of the target solution for the SMC developed in the FoFdation project. It is based on efforts past and present both by academia and industry in various capacities and proposes tentative implementations based on the STEP-NC standard to define the machine controller of the future.

1. Introduction

Realizing the objectives set out by the FoFdation FP7 [1] project requires that several concurrent pieces are integrated with each other. At the center of these pieces is the machine tool controller that represents the low-level task execution and this is defined by the Smart Machine Controller (SMC). This central piece is an enabler in that it allows the development and expansion of the ideas that FoFdation aims to resolve. Supporting this SMC central piece is the Manufacturing Information System framework (MIS). This framework aims to provide the broad scope and requirements for an integrated Information System which are to be validated by defining practical exploitations through the Use Cases (UC) driven by the needs of the Automotive and Aeronautic industries. Facilitating the exchange of information within this framework is the Digital Manufacturing Information Foundation and Pipeline (MIP). Such a foundation ensures that uniform and standardized information and data models are available to the development and integration of various composite IT applications. Within the SMC, supported by both the combined foundation of the MIS and the MIP, focus is then shifted to the amelioration of production. This is first (A) done through the Smart Machine Optimizer (SMO) tasked with producing, by simulation, reliable and predictable machining times for process planning and management; producing, by simulation, predictable surface quality for a given operation under a given set of

conditions; allowing in-process quality control while guaranteeing an efficient sustainable production environment. Secondly (B) amelioration is also obtained by Manufacturing Execution System (MES). Consequently, it is tasked with the supervision of productivity and sustainability indicators as defined by various manufacturing industries. An extension of these indicators is expected through the work undertaken by this Consortium. All of these concurrent pieces are encapsulated by the Smart Enterprise Content Management system (SECM) within which all of the content produced by the developments and integration in FoFdation are managed on a very high level.

2. FoFdation SMC

Focusing on the central low-level task execution of the SMC, the original vision in FoFdation for the SMC is to implement an advanced machine controller based on an open-architecture and standards such as a PC driven by Linux RTOS and Enhanced Machine Controller (EMC2), including the XML standard enabling data access, and data visualization application. Additionally, an extended STEP standard will be seamlessly integrated to bring CAD-CAM data down to the shopfloor level, thus enabling intelligent and self-learning manufacturing process as defined by 'Smart Machining' [2]. A smart machine is defined here as a machine equipped with an advanced controller that knows the capabilities of the machine to be driven [3]. Such a machine is able to define the most efficient method, e.g. based on closed-loop machining and generic algorithms, to produce 'first part correct' every time. Such a machine will do this all while monitoring itself and utilizing data that closes the gap between the designer, manufacturing engineer, and the shop floor while allowing high level production management and supervision. With the FoFdation HMI (FHMI) as the brain of the smart machine, a knowledge-based system will collect information from individual thrust areas and make decisions based on predefined business and production logic. It also addresses the need for an encompassing system that is responsible for the coordination of manufacturing activities, monitoring technologies, construction inputs, thus enabling an optimal machining solution for desired quality and maximum productivity. To accomplish the above SMC characteristics, the generalized architecture in Fig. 1 was developed providing micro and macro communication interfaces through real-time and non-real-time Profibus, Powerlink and Ethernet protocols. FoFdation is expected to define a unified and open IT architecture at the shopfloor level in order to enable both progressive and breakthrough innovations for industry. The progressive innovation must be based on defined components that are compatible with legacy systems, thus supporting the

industry's transformation by introducing more IT-assisted technologies into conventional and existing manufacturing chains for better optimization of the manufacturing process.

Within the economic recovery context, the SMC architecture must be compatible with legacy brand name NC controllers. This condition is necessary to support the transformation of prevalent brand name controllers mostly based on ISO G&M code into STEP-NC compliant controllers, thus allowing companies to increase their production performance without heavily investing in new expensive machines and time-consuming training [4].
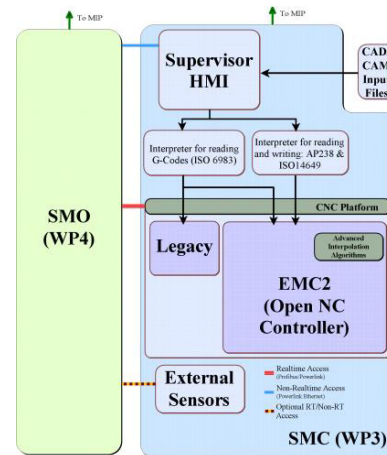

Fig. 1. Generalized FoFdation SMC (FSMC) Architecture

Breakthrough innovations for the legacy mandate will be based on a STEP-NC SMC interface for part programming tightly integrated with the SMO optimization module and running on a dedicated Windows PC. The controller will be able to generate cutter trajectory and optimize the cutting strategy in real-time. This is possible with an embedded STEP-NC Windows-based SMC interface on the FHMI including its own tool-path generator, e.g. for surface milling. The STEP-NC interpreted programming makes it possible to use the STEP-NC standard with the existing machine tools and NC controllers, which still understand G-code programming [5]. Therefore the innovation of the SMC is not just a product in the conventional sense but it is an architectural framework that can be implemented on several platforms, existing brand name controllers included. To accomplish the general objectives and long term goals of the project, implementations and innovations developed need to be usable in the short term by industry to show immediate benefits and encourage commitment and investments from machine tool industry leaders. Envisioning the long term evolution of the industry, FoFdation proposes a framework to support the evolution of the numerous

CNC controllers while encouraging Open cohesive breakthrough innovations in its SMC.

3. SMC Foundation

3.1. MIS Architecture

Supporting the central SMC is the MIS framework. The integrated manufacturing information architecture is described to facilitate the implementation of a MIS framework as a solution to share and exchange manufacturing data. The architecture defines the general requirements and functionality of the system to be developed. It also outlines validation methods for the system by defining end uses through the UCs driven by the needs of the Automotive and Aeronautic industries while at the same time establishing global Use Cases and data models between several engineering manufacturing activities that could be applicable to any complex structured industrial environment [6]. Analysis of today's manufacturing process and a study of industrial IT software revealed how they are implemented within different industrial realities and highlights the relative level of interoperability and incompatibilities that exists between the different IT components such as Manufacturing Execution System (MES) [7], Enterprise Resource Planning (ERP), Product Lifecycle Management (PLM) systems. This effort provided a strong foundation for architectural and UC definitions and addresses the impediments of current systems while satisfying the general industrial outlook.

The UCs from Automotive and Aeronautic sectors, defined at different levels (enterprise, factory, and machine tool level), gives the requirements and the objectives for the proposed FoFdation system. One such target for the new MIS Framework is reconfigurability and the capacity to integrate within industrial standards [8]. The Automotive UC objective is to realize a unique MIS framework for product planning and sequencing, which can be used in several plants with different configurations. To this end, Fig. 2 shows the scope of the necessary phases for a product designed to be on the market and linked with main activities performed to manage the execution steps. The MIS flow (Fig. 3) aims to monitor, manage and optimize production data flow from set-up to product shipping and optimizing machining workload with minimized energy consumption for each step shown in Fig. 2. The Aeronautic UC (Fig. 4) objective is to improve production profitability by streamlining the manufacturing process with subcontractors. Therefore the aeronautic company will implement an integrated MIP to describe all manufacturing process resources. Using inputs from every partner in the chain with intimate knowledge of their activities, optimizations are made to the chain and to production based on the self

learning/tuning performances obtained from the MIP data. At the completion of the job, the digital 'as-delivered' part is instantly delivered to the company. It can be virtually check, modified and controlled prior to its acceptance. Using this MIS framework as a base and the validating UCs, this architecture takes into account how the system will function: the interface, functionality and technology. It does not neglect the many different tools used today at all factory levels.
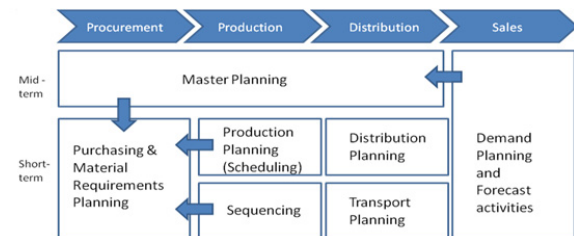

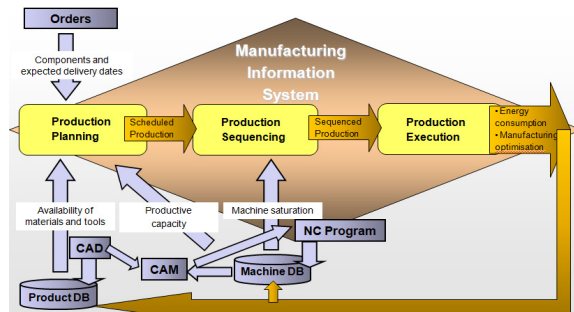Fig. 2. Relationships between different manufacturing activities

Fig. 3. Flow of the Manufacturing Information System

3.2. Digital MIP Foundation

Facilitating information exchange in the described MIS framework is the Digital Manufacturing Information Foundation and Pipeline (MIP). Its main objective, a cornerstone in FoFdation, is to realize the foundation for composite application development and integration to reduce costs and time-to-market as well as the basis for 'manufacturing-business process orchestration'. The data models for the Product, the Production System (machine tool) and the Sustainable Production Process are established in Fig. 5. This constitutes the MIP to enable IT applications within the global enterprise PLM and ERP to access and deal with data from design and engineering to manufacturing and management. Developing this scheme, followed analysis of existing information models, weakness identification and the extension or development of new data models for products beyond shape, machine tools and processes. Thus allowing the implementation of smart controllers with flexible enterprise integration. Seen as a promising approach for the definition of uniform IT models, efforts were

undertaken within the STEP (ISO-10303) activities.

All resources from STEP are used and the resulting model must allow the representation of product data from its conception, through its realization and ultimate recycling. Although work has been done to develop STEP models for manufacturing and machining processes, it is at present limited to modeling the product structure information such as geometry, dimensions and tolerances. Areas of this model that are severely lacking will be filled by new or extended models such that complete product information (Part Manufacturing Information) is available at the shop floor. See [9,10] for the definition of different data models based on existing standards.
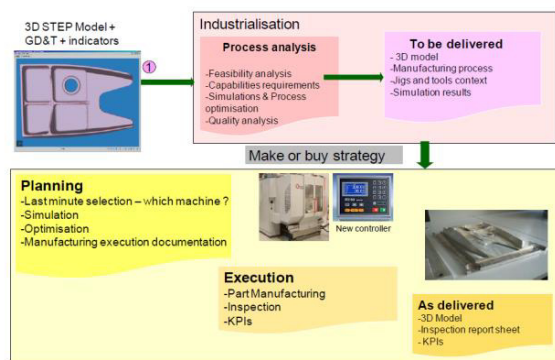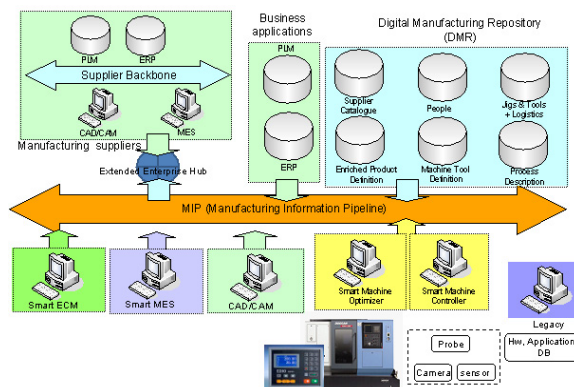

Fig. 4. Aerospace Use Case

Fig. 5. Description of the Manufacturing Information Pipeline

4. Optimized Sustainable Production

4.1. Manufacturing Optimizer

Given the strong need for production amelioration and discrete high added value products particularly within the diverse manufacturing industry, relying on milling operations and machine-tools, the Smart Manufacturing Optimizer has the following focus: reliably predicting machining times, by simulation, for process planning and management, producing predictable surface quality, by simulation, for a given operation under a given set of conditions, allowing in-process quality control while guaranteeing an efficient sustainable production environment. Industrial solutions will be produced for current CNC machines and controllers while at the same time enabling the realization of the next generation machine controllers, again a cornerstone objective of FoFdation.

The SMO is approached from two sides: 1) creating perfect simulation models of an imperfect machine; 2) developing an intelligent framework enabling shop floor actions using knowledge of these models to increase machining process capabilities and sustainability. *The perfect model of an imperfect machine and process*: For reliable adaptive manufacturing, the SMO develops a good description of the machine tool and machining processes by defining its 'signature'. Tools and methods are defined to obtain and verify a machine tool's signature [11,12]. These are then developed and applied physically to the machining processes. Conversely, the integration of the machine signatures into simulation and verification tools to simulate the real machine tool and machining process becomes viable. Signature transformation to simulation space is a high focus point for the SMO to which experimentation and validation methods are already defined within the project activities. Accomplishing these preconditions will allow for both simulation estimation of machining time and surface quality to be closer to the reality that is seen on the finished part. Ensuring that progressive changes are made to the current trend in simulation which provide idealistic time predictions based on simplistic models and perfect surfaces not based on reality (Fig. 6).

Accurate correlations between measured and simulated feed rates can be established and from there more optimized feed rates can be proposed. This in turn aids time estimation and provides a good base from which to drive surface quality simulations. Such a simulator, which depends highly on the development of real kinematic and dynamic model (signature) of the milling process, will provide realistic estimation of machining time and representation of surface quality.
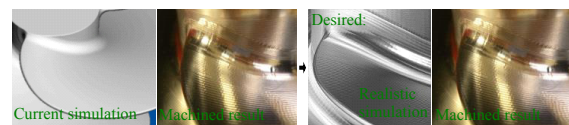

Fig. 6. Realistic feed rate simulator results

The intelligent adaptive & sustainable approach: Even given a perfect model of the imperfect machining process as discussed above, the machining process reality seldom executes as simulated. To address this issue, two distinct alternatives are proposed for the SMO developments. This proposal extends the tools and methods used to define the signature of the machine tool

and machining processes from the above discussion. Thus enabling the capture of the signature in real-time as well as in-situ condition monitoring during the manufacturing process. The final goal of this is to attain reliable adaptive control of the manufacturing process. Based on the Consortium background, a prototype is expected that will verify and test the adaptive intelligent framework using Delcam's CAM and NC software platforms with supporting ARTIS Monitoring technologies [13]. The integrated marriage of these two software (CAD/CAM) and hardware (Monitoring) platforms ensure that once isolated knowledge from either is easily and effectively transferrable. Thus preventing production disturbances and producing an increase in quality that is predictable and timely within the SMC.

4.2. Sustainability in Manufacturing

Production amelioration with the implementation of sustainability metrics is obtained by the development of a new MES. Sustainability in manufacturing, considered from the triple bottom line definition [14], reveals multiple application possibilities. The goal of the MES is for supervising productivity as well as the defined sustainability indicators. Operating alongside ERP systems, MES is more capable to fulfill sustainability demands due to its close relationship to the process environment. FoFdation's concept extends the MES toward sustainability monitoring and control. Combining FoFdation cornerstones such as the SMC and the SMO with a smart MES approach ensures the application of other optimization strategies alongside monitoring-only strategies. By using the Automotive UC to define the scope (Fig. 7), production-related KPIs were identified on the machine level within manufacturing. With a defined scope of identified KPIs an application of monitoring activities can be designed. Activities in this area can be used in both the aerospace and automotive sector, where energy is identified as one of the biggest operating costs by the introduction of monitoring devices such as PROFIenergy [15]. As some disadvantages can be identified on current systems, e.g. limitation to PROFIBUS controlled devices and negligence of important auxiliary devices, new monitoring strategies and architectures defined in FoFdation are necessary. Architecture to fulfill the requirements of the given UC is proposed in Fig. 8 [16]. It shows actual resource consumption in which production data acquisition is enriched using internal and external sensors with specific simulation elements. This concept, internally validated with experimentation, is based on the need for multiple measurement sources on the machine tool to provide information specified in the ISO 14955-1. In the case of relevant energy consumers, unknown or complex energetic consumer

behavior, and potential implementation of feedback or optimization loops, the use of external sensors is essential. Given the SMC and SMO architectures coupled with real-time data acquisition, the energetic behavior of the auxiliaries can be influenced by adaptive control through converters according to given process parameters.
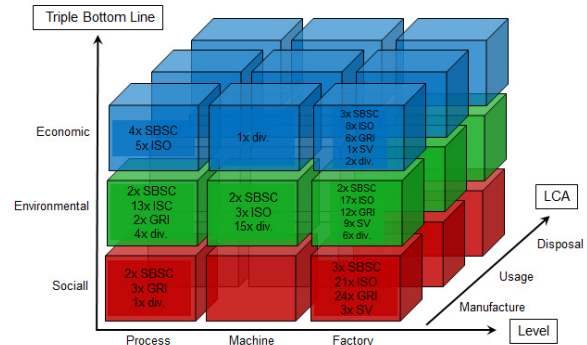

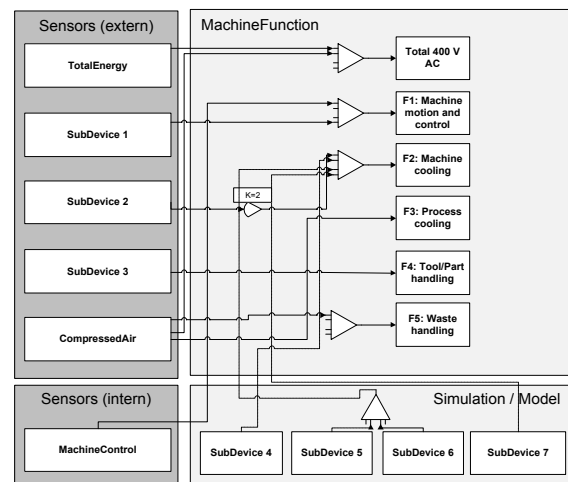Fig. 7. KPI classification according to individual needs

Fig. 8. Monitoring combining sensors with simulation (ETHZ)

Using Profibus-based Artis hardware, energy consumption can be optimized, where for example, the machine's idle state can be monitored and corrective actions taken to reduce or eliminate power to non-essential auxiliaries. Conversely, aggregated information from ERP and other sources can be exploited by the MES to improve global optimization strategies even in non-real-time. Better use of available data from internal sensors, in some cases real-time data acquisition provides another reliable data source. Looking for example at a tool breakage monitoring application based on internal sensor monitoring of the control unit, detailed knowledge of the physical interrelations and energetic behaviour, in combination with given PLC logic, can be used to apply consumption models with reliable information output. The developed monitoring software, running on the machine tool's PCU, creates a

total of 7 data packages specified by the ISO 14955-1 [16] and the given UC requirements, and are transmitted to the prototype MES system provided by Tekniker. This combination of information sources reveals a production data acquisition system that is comprehensive with a low cost-per-information ratio.

5. Integrated FoFdation System

Encapsulating all the developments and integration in FoFdation, starting with the SMC at its core, produces a global to local creation of content for an enterprise. To manage these contents on a very high level necessitates the functionality of the SECM system. Given that Enterprise Content Management (ECM) are inevitable in modern enterprises, more autonomous systems are dominating nearly all aspects of the organization from management to production, from marketing to supplier management. Since required autonomy can only be assured through effective automated content management systems it is prudent for FoFdation to use integrated information systems such as Enterprise Resource Management (ERM) together with active knowledge management models such as ECM as well as respective supporting systems in order to be intelligent enough in operation.

According to [17] there are two types of data that the enterprises need to properly manage, i.e., business data (e.g., accounting and personnel data) and product data (e.g., CAD and CAM data). FoFdation's proposal intends to address these two types and use the concept suggested by the authors: a web-based knowledge management that facilitates seamless sharing of product data among various application programs including business-oriented and engineering-oriented systems in virtual enterprises. The encapsulation of developments and integration around the FoFdation SMC provides exploitable industry-defined Use Cases that enables: a strong framework for uniform and standardized information sharing; optimization by simulation and in-situ quality and process monitoring with a strong emphasis on sustainability by energy and waste reductions [18].

6. Conclusion

FoFdation can be summarized in a phrase: higher productivity and quality with lower impact to the environment. Under the impact of fast paced information technology and competitive pressures that face developed countries, FoFdation facilitates these while providing a framework to tackle future challenges around interoperability and standardization. The new factors - globalization, service orientation, knowledge intensity, and responding to environmental concerns - highlight the importance of undertaking research in the area of manufacturing on a global level. The game is not over in developed countries. It continues at a global scale but the standards for interoperability and the rules for equity are still dramatically missing. FoFdation and its further extended projects can be seen as a stepping stone towards a "brave new world" of manufacturing.

Acknowledgements

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