Development and first applications of gentelligent components over their lifecycle

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The separation of a physical component and its corresponding information contradicts the successful implementation of new applications over the lifecycle of the component. However, this obstacle can be overcome by means of gentelligent components with enhanced capabilities in terms of component-inherent information storage or decentralized communication capabilities. Focused on a number of applications for the design, manufacturing, and maintenance of gentelligent components, the following paper demonstrates the advances and advantages of gentelligent components and systems over their lifecycle. The scope of the paper includes novel technology for information storage, information generation and monitoring as well innovative methods for the design and maintenance of gentelligent components.

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1. Introduction

The recent shift from mass goods to individualized products has drastically increased the required product specific data storage and data management effort. Lately, product-relevant information needs to be exchanged not only between the different in-house departments of a given manufacturer but also between customers and suppliers. Furthermore, the individualized production process itself results in a significant amount of product-related information within the framework of constantly changing production parameters [1,2]. Hence, the amount and variety of information to be exchanged have increased considerably and – more importantly – are expected to continue their rise in the future [3], as the market demands improved traceability of individualized products, starting from their primary material source over the production to their distribution and implementation. Additionally, enterprises with distributed manufacturing resources aim for high visibility and traceability of their products during the manufacturing process in order to support their real-time collaborative manufacturing decisions [4]. For this purpose, production enterprises have started exploiting the potential of the available information technology, such as Radio Frequency Identification (RFID). In the case of cost-intensive or security-relevant components, individualized identification methods, e.g., Data-Matrix-Codes or RFID-Tags, have become a standard in industrial production [5]. By applying the identification mark directly onto the component, a fast identification and tracking of related product information is provided [6]. However, access to product-specific data is often possible only for the product manufacturers, since only they can access the central information servers where such data are stored. Later on, such data must be generated with much effort.

The Collaborative Research Centre (CRC) 653 “Gentelligent Components in their Lifecycle” provides a novel approach to storing component-relevant lifecycle information inherently into the component. Gentelligent is a portmanteau word that combines the attributes of genetics and intelligence abilities in one adjective. Gentelligent components are able to feel, communicate and store information from their environment and, thus, act as autonomous intelligent individuals [7]. Based on this technology, real life information becomes available and can be used over the entire lifecycle of the component, providing advantages for many applications in production, application, individualization of components or a design improvement for the next generation.

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This results in a closed information loop whereby all relevant data – e.g., production data, load information from the usage and maintenance as well as damage information – are transmitted over the course of the lifecycle of the component as one data format, stored inherently in the component. Fig. 1 demonstrates this information cycle by means of an exemplary car component. Over its lifecycle, the gentelligent component continuously acquires and transmits a growing information base, starting from its design, over the production, usage and maintenance stages and back to the next evolutionary design stage where it transfers its lifecycle experience to a subsequent component generation (Fig. 1).

This closed information loop over the lifecycle of the component as well as the inheritance of the lifecycle information provides several advantages and enables novel optimization methods for many applications. Furthermore, intelligent components enable tracking of product-specific information (e.g., production order) [8]. As a result, they can be used for adaptive process planning and control during the production phase [9].

This paper is focused on the application of gentelligent components in the production, usage and maintenance stages as well as on the advantages they offer for the evolutionary design of next-generation components. The following chapters introduce, among others, novel aspects of acquisition, storage, management and usage of lifecycle information of gentelligent components. Below, the basic technology of gentelligent components is presented.

### 2. Information acquisition and storage by gentelligent components

The capability for storing data is crucial to any information-driven technology. Component-inherent information storage, i.e., writing and reading data by exploiting the physical properties of a component itself, provides several unique benefits here. Using inherent recording methods, individual and confusion-proof data storage can be realized, linking single components to their corresponding data sets. Furthermore, inherent data records can be used to avoid mistaken part identification caused by the increasing diversity of components manufactured within the same process. Similarly, incidents during manufacturing can be attributed to the exact component which has caused them – a fact that can extremely important in case of later liability disputes.

Nonetheless, probably the most important advantage of inherent storage over external repositories is that all relevant information remains present over the entire lifecycle of the component. Following, the current lifecycle data format and inherent data storage technology are presented.

#### 2.1. Information structure – gentelligent markup language

In order to transmit relevant component information over the whole lifecycle of the component, a unified, self-contained data format is developed. A modular approach instead of a monolithic

![Fig. 1. Applications of gentelligent component over their lifecycle.](image1)

![Fig. 2. Sample GIML file: production log (excerpt).](image2)
one is chosen. Such a design allows for maximum flexibility in terms of processing time and memory capacity in a large variety of gentelligent components. On the semantic layer, the hierarchical Gentelligent Markup Language (GiML) provides a high scalability with respect to the different use cases. As a basis for the textual representation of gentelligent information, GiML uses the Extensible Markup Language (XML) [10], which can be both easily human-readable and, at the same time, machine-processed with a large inventory of pre-existing software frameworks. Specifically, GiML is realized by implementing an XML schema [11] defining the permitted structure and data types of a particular XML file that conforms to the GiML specification [12]. Fig. 2 depicts a sample GiML file.

If necessary, e.g., due to capacity requirements, this textual GiML file can optionally be compressed to a binary representation in accordance with the Efficient XML Interchange (EXI) compression algorithm [13]. EXI exploits the strict syntactical structure of XML documents given by the associated schema, in this case – the GiML specification. EXI compression ratios of GiML files range up to 20:1 for typical files such as process sheets. Additionally, in cases where enhanced security is desired, it is possible to encrypt and sign the (binary or textual) GiML file using the RSA (Rivest, Shamir and Adleman) public-key cryptosystem [14]. Encryption does not allow public access to the information; only authorized parties that possess the corresponding private key may access it, whereas cryptographic signatures allow anyone to verify the authenticity and origin of a given file.

In addition, the modular XML-based design provides full backward and forward compatibility by adapting the structure schema to new use cases and their data model requirements. The process log presented in Fig. 2 requires a storage capacity of about 300 bytes when stored in compressed GiML format. Such electronic product data can be stored inherently in a gentelligent component over its entire lifecycle. Suitable storage technologies for lifecycle storage of product information are presented in the following chapters.

2.2. Component-inherent high-frequency communication

In recent years, Radio Frequency Identification (RFID) applications and the Internet of Things have gained a lot of attention in science and industry. RFID systems consist of a reader and a transponder, commonly referred to as tag. The field of applications is growing rapidly, and it includes supply chain management, inventory control, security management, and logistics [5]. However, commonly used RFID transponder antennas, typically dipole-like antennas, suffer from performance degradation under the influence of a metallic environment, especially when placed directly on a metallic surface. For the use of transponders under harsh operating conditions, e.g., in a manufacturing environment, it is desirable to integrate them into the metallic component. As a result, the range of application is mainly limited by the transponder dimensions.

In order to overcome the limitations of common RFID tags, a novel high-frequency communication transponder is developed. The transponder can be placed inherently into a drill hole within the metallic component, which is then used as an antenna. Fig. 3 below shows the design and the integration of the developed transponder.

The transponder consists of a waveguide to micro-strip line transition that is required to connect the analog and digital components for the communication, data storage, read out of sensors, and data processing. The waveguide to micro-strip line transition is realized as an antipodal finline [15]. The transponder is 26 mm long and has a diameter of 8 mm; the 26 mm length enables a carrier frequency of 24 GHz. Due to the high carrier frequency, a conventionally power supplied RFID transponder is not applicable. Hence, a hybrid transponder concept is developed where the transponder utilizes data communication at microwave frequency and is powered by light. For the power supply of the digital components, a photodiode array is used and placed transversally into the circular waveguide (see Fig. 3). Any incidental light is guided from the aperture of the drill hole to the photodiode array by polymer optical fibers [16]. As a result of the axial alignment of the waveguide to micro-strip line transition, only a minimal area of the photodiode is used for the microwave data communication. Consequently, the remaining area is used to convert the incidental light into electrical power. For this purpose, the low power digital and the analog components are integrated behind the photodiode array in order to minimize the influence on data communication and optical power transfer. The high-frequency transponder developed for the integration into metallic components enables a communication speed of up to 80 kb/s for the communication link between reader to transponder and 100 kb/s in the other direction. In order to transmit lifecycle information inherently into the component, it is equipped with an 8 kb storage. Subsequently, it can provide the lifecycle information of the component by means of the GiML-format described in Section 2.1. An EEPROM is used as a storage technology; thus, dynamic information can be exchanged and saved on the physical component in terms of process planning or quality control. Furthermore, the transponder is used as a configurable platform for the connection of low power sensors, e.g., component integrated temperature sensors [17]. Thereby, load information
can be received over the entire lifecycle of the component, e.g., during production and usage, and can be transmitted to a service application so that a condition-based maintenance of the component can be performed. Such applications of component inherent sensors and communication technology are demonstrated in the subsequent Section 3.

2.3. Component-inherent information storage

If a robust storage technology for static product information is required, a component-inherent storage technology can be used. The surface of the component is the preferred place for inherent information storage. As a result, many identification techniques, such as Data-Matrix-Codes or RFID-Tags [5], are located on the surface layer of a component. However, such techniques require additional effort in order to be applied to or removed from this surface layer. In order to avoid additional work steps and to maximize the storage capacity, a finishing face milling operation is used for writing information directly in the surface layer. To guarantee flexible use and industrial application, this approach avoids any additional manufacturing resources and neither interferes nor extends the established process chain [18]. Therefore, a tool concept is developed that allows for a parallel face milling and writing of defined micro-patterns while applying productive process parameters. The micro-patterns, which are formed by micro-dimples and which represent single data bits, embody binary coded data (Fig. 4a). To realize multiple depths of cut during a single cutting edge engagement, a high-dynamic Fast-Tool-Servo (FTS) for milling operations is developed [19]. For an active positioning in axial direction, a piezo-ring actuator is placed between a tool holder and a frame (Fig. 4c). The tool holder is mounted with two hinges designed as steel spring membranes. The hinges themselves are attached to the frame. By using this type of bearing, only axial translation of the tool is enabled. For integration into conventional milling machines, a standard spindle connection for milling spindles (DIN 69893 HSK-A 63) is considered.

The controlled cutting of micro-patterns requires oscillation frequencies to be lower than the eigenfrequency of the system, since phase shifts occur above this frequency range. Therefore, the moving mass must be as small as possible. For this purpose, the tool holder is made of titanium. The moving mass, including an end mill with screw-in threads (Fig. 4c) and cutting inserts, is reduced to 320 g. The first eigenfrequency is identified at \( \omega_0 = 4.5 \text{ kHz} \). At a frequency of \( f_z = 4 \text{ kHz} \), a structuring depth of about \( \Delta z_p = 12.5 \mu m \) is realized. By connecting its control to the machine tool control, the cavities are cut depending on the position of the cutting edge on the workpiece surface (Fig. 4a). While designing micro-patterns for data storage, revolutions without excitation must be considered to keep single cavities from overlapping. For this process parameter combination (Fig. 4b), a data density larger than 500 bit/cm\(^2\) is achieved.

By preprocessing the excitation signal, the data is digitally coded and encrypted to prevent attempts of plagiarism and to ensure the authenticity of the components. Furthermore, forward error correction can be applied to increase the tolerance regarding mechanical and chemical damage of the surface. Using directed illumination, an optical read-out method is used in order to reconstruct the depth of the machined micro-patterns. A modified Hidden Markov Model (HMM) approach, followed by Viterbi-like decoding, tracks the edge of the cutting edge engagement, obtaining the depth and, thus, the binary digits [20]. The influence of the different coding methods and materials is analyzed in order to prove robustness of this method [21]. Besides component identification and protection against plagiarism, the presented FTS allows the machining of tailored surface topographies regarding optical and haptic appearance. This represents a promising approach to machining components for the consumer market.

3. Applications of gentelligent components over their lifecycle

The increasing variety of products, especially in the single or low batch production, has lead to an increase in the complexity of the tasks of process and production planning and control [22]. The following chapters discuss promising approaches, gentelligent components provide for managing such complexities over the lifecycle of the product. Dedicated applications for gentelligent
machine tools and their potential of enabling a product-driven production planning and control as well as an online quality monitoring system and status based maintenance strategies are presented in the following sections.

3.1. Gentelligent machine tool

Within a gentelligent production, the gentelligent components are manufactured by a gentelligent machine tool. This new kind of tool is able to sense and measure the forces between the tool and the workpiece during the machining process. Based on the provided force signals, the machining process can be monitored online and optimized for the next component generation. Sensory machine components which are directly involved in the force flux of the machining process are integrated within the gentelligent machine tool. A sensory clamping system that fixes the workpiece and a sensory z-axis-slide that carries the spindle are used for the observation of milling forces (see Fig. 5).

The determination of the process forces is achieved by measuring the mechanical strain in the integrated components. The sensory z-axis-slide and clamping system of the machine tool are completely re-designed under the aspect of integration of strain sensitive sensors without affecting the stiffness of the components. FEM simulations are performed in order to find optimal sensor positions in the component structures; such positions correspond to locations that exhibit the highest sensitivity to mechanical strain. Generally, machine components are designed for a high overall stiffness so that the required machining accuracy and process stability can be achieved; as a result, only minimal strains occur in their structures under machining forces. In preliminary experiments, amplified strain-signals from conventional strain gauges show a very low signal-to-noise ratio. A method to increase the signal amplitudes, without increasing the signal noise, provides a local adjustment of the force flux in the components. Subsequently, the adjusted force flux leads to an increase in the local mechanical strain. This is achieved by application of small notches in the structure of the z-axis-slide [23] as well as holes in some parts of the clamping system [24]. In this case, the strain sensitivity is increased by three to four times, whereby the influence on the overall stiffness of the components is negligible. To capture the mechanical strain, as seen on the z-axis-slide, two different types of micro-strain gauges are integrated into the notch grounds. The first type includes laser structured strain gauges (L-DMS), which can be sputtered on any surface shape and which can be subsequently structured using a laser beam [25]. The second type consists of micro strain gauges which can be applied to flat surfaces only and which are based on flexible polymer substrate (μ-DMS) [26]. The strain gauges are connected with electronic signal processing devices in order to compute and communicate the sensor signals to the unit control via CAN-Bus. The investigated components are integrated into a milling center DMG HSC 55 linear (see Fig. 5). After calibration of the sensory z-axis-slide with a force sensor, the forces applied to the tool in x- and y-directions could be captured with a resolution of 10–13 N by means of a sampling rate of 500 Hz. In the z direction, however, the forces are captured with a lower resolution, possibly due to the higher slide stiffness in this direction. Afterwards, the calibrated z-axis-slide is used for the further calibration of the sensory clamping system. Two approaches are investigated: Calibration by colliding, which is executed by driving the spindle smoothly against the workpiece, and calibration in process, which is accomplished by processing dynamic signals during the machining. The colliding calibration allows to measure the tool stiffness, which is used to detect the static tool deflection during the milling. A validation in a manufacturing environment shows that both sensory components can be merged into an active “feeling” system that provides continuous and accurate force signals during a milling process. However, future research should focus on advancing the development of such “feeling” workpieces; ideally, these will be able to detect the thermal effects of the machining process and

**Fig. 5.** (a) Developed sensory machine components with integrated strain gauges in notches, (b) influence of the notches on the slide stiffness, (c) influence of the notches on the sensitivity.
to provide information about their own deformation, based on component inherent sensors (see Section 2.2).

3.2. Online quality monitoring during production

The gentelligent machine tool provides process signals from the manufacturing process and thus enables monitoring of the machine, process and workpiece quality. The provided signals are integrated within a model-based system for quality monitoring. Using this system, the workpiece quality can be reconstructed by means of process models which transfer the measured process signals to the corresponding process conditions. Using a deflection model of the endmill, the tool deflection for peripheral milling can be reconstructed from process forces [27,28]. The reconstructed tool deflection is transferred into the resulting shape deviation of the workpiece surface and is evaluated regarding the required shape tolerances of the workpiece. Fig. 6 below gives an example for the reconstruction and evaluation of the shape deviations of the workpiece from the measured cutting forces. It shows the captured force signals as well as the related position at the machined workpiece (see Fig. 6a). It also illustrates the reconstructed tool deflection over rotation where the tool contact line is indicated (see Fig. 6b). The shape deviation of the resulting workpiece surface is reconstructed by transforming the tool deflection by the contact line. In Fig. 6(c) the reconstructed shape deviation is compared to the measured workpiece shape from an exemplary milling process.

The exemplary results demonstrate that this method can be used to accurately reconstruct the shape deviation and the surface topography of the machined workpiece. The surface quality is reconstructed on the basis of a process model that considers the influence of the cutter runout. It is used to identify the runout parameter of the endmill, based on process forces, and to compute its influence on the surface roughness of the workpiece [29]. In order to monitor the current workpiece quality, the shape deviation and surface roughness is determined and evaluated against the required shape and surface tolerances. The developed method enables an accurate online assessment of workpiece quality information by taking the inherent force sensors of the machine tool into consideration. Thus, a novel method of a quality based process monitoring is enabled.

After the machining process, the acquired process and workpiece information is transferred to the component inherent data storage by means of the gentelligent lifecycle data format (GIML). The evaluation and feedback of current process conditions and quality information from the machining process to the process control enables a reactive and learning process planning and control (Fig. 7c). The generated quality information can be used to generate a database for the knowledge-based automated process planning [30]. As a result, the reactivity and quality of production planning and control can be improved. Furthermore, the quality monitoring system can be advanced in order to enable a process-integrated quality control loop, aiming at an automatic adaption of the machining processes.

3.3. Manufacturing planning and control based on gentelligent components

Various disturbances in the manufacturing processes and organization occur stochastically and have a negative influence on the overall production efficiency. For that reason, process plans have to be revised and jobs have to be rescheduled and coordinated with maintenance measures or rework operations of single workpieces within a batch. In many cases of single part or small batch production, alternative process plans, process plans for on-demand operations and workflows for rework orders have to be generated and handled. This massively increases the complexity of the manufacturing organization and imposes high requirements on the manufacturing planning and control in terms of flexibility, adaptability and responsiveness [31].

Gentelligent components and machine tools, on the other hand, provide an opportunity for manufacturing planning and control on an individual basis for each workpiece of a batch. Inherent data storages allow decentralized information flow between single workpieces and information systems or machine tools. Gentelligent components in machine tools combined with new monitoring systems offer information about workpiece and machine tool state (see Section 2), a feature that has not yet been available in production. This information can be used to identify the best production sequence for every individual workpiece of a batch, depending on the current state of production.

Fig. 6. Reconstruction of the shape deviation at the workpiece from cutting forces.
Therefore, an adaptive approach to integrated manufacturing planning and control, based on gentelligent technologies, is developed. In order to find suitable manufacturing processes for the production of a specific component, possible manufacturing technologies and sequences are identified within a process planning module (Fig. 7a). Based on a specific manufacturing task as well as on information derived from the product feature model (according to ISO 10303-224), all feasible process sequences are generated by a rule-based system. This is implemented in an ontology the represents the company-specific manufacturing knowledge (see [32] for further details). The selected process plan is transferred into a lifecycle data format, referred to as GIML-file (see Section 2.1), and is stored inherently by using the novel component inherent transponder (see Section 2.2).

After every process step, the manufacturing control module analyses any deviations from the reference specifications concerning manufacturing quality, time and costs, by examining the current state of the gentelligent components. All possible subsequent manufacturing sequences are evaluated and the most appropriate working step is selected (Fig. 7b). In order to address production objectives like short processing time and low production costs, the multi-criteria evaluation method Analytic Hierarchy Process is applied [33]. This enables a flexible and responsive reaction in case of occurring disturbances (e.g., using alternative resources in case of a bottleneck) and ensures flexibility in both manufacturing technology and organization. To evaluate the capability of the approach in terms of its responsiveness, a discrete event simulation model of an exemplary shop floor is developed [9]. A simulation study is carried out with three scenarios: a reference scenario without disturbances and a scenario with deterministic disturbances, both with conventional hierarchical planning. Then, a third scenario using the adaptive approach to integrated manufacturing planning and control is investigated. This decreases lead time by up to 22% in comparison to a production affected by disturbances (Fig. 8).

At the end of production, the process monitoring module generates a product-specific production protocol (Fig. 7c). There, process signals from the machine tool are interpreted to acquire state and quality information from the machining process (see Section 3.2). Future research should still focus on the feedback of manufacturing information into process planning by utilizing data mining methods. Furthermore, procedures for the experience-based creation of rules for a condition-based manufacturing control are under development. In the following chapters, enabling technologies for the adaptive approach to integrated process planning and control are presented, using milling processes as an example.

### 3.4. Intelligent maintenance planning of gentelligent components

Over the course of their lifecycle, gentelligent components provide inherent sensor and condition information and, thus, enable novel strategies for more precise maintenance planning. The high frequency transponder, described in Section 2.2, gathers information from the internal strain and temperature sensors of the component. Made of novel and highly sensitive magnetic magnesium alloy [34], the sensor can detect the component stresses over its entire lifecycle and, thus, provide the information needed for intelligent maintenance planning. The stress measurement is performed by utilizing the Villari-effect of the sensory material. Thereby, the traction, or compression, stress of a sensory component can be obtained by an eddy current signal [35].

![Fig. 7. Manufacturing planning and control with gentelligent components.](image)

![Fig. 8. Results of the discrete event simulation study.](image)
The detected component stresses are needed to organize and plan maintenance events. The developed method “Component status-driven maintenance” enables the identification and analysis of the current component status [36]. Based on this information, the method predicts potential damaging of the component and provides information about the remaining service life. Finally, it identifies appropriate maintenance measures.

The systematics of the status-driven component maintenance is based on a control cycle, as shown in Fig. 9. The control cycle consists of a knowledge base, a comparison module, a diagnosis module, a forecast module, and a reaction module [37]. The monitoring of the component starts with the comparison module, which uses the detected stresses to determine the current condition of the monitored component. After the condition is determined, it is stored in the knowledge base where essential information, such as the experienced load points or the stresses of a component, is kept [36]. The comparison module is followed by the diagnosis module. Here, the interactions of the component with its surroundings are analyzed, with a focus on the interactions with other gentelligent components of the application. In this case, the main causes of errors and their impact on the entire assembly or machine are of particular interest.

If the causes of the critical errors are known, the prediction of the future component conditions and the remaining service-life takes place in the forecast module. The basic steps of this module are presented in Fig. 10.

In the first step, the condition of the component is identified by means of the conversion of the measured stress into a time-related collective stress. This evaluation of the stress is carried out according to the Rainflow method. With the aid of linear damage accumulation, the collective stress allows the calculation of a time-related damage pattern.

Fig. 11 shows collective stresses of 50 s. These resulted from measurements that are taken during the testing of different wheel carriers of a race car (GI-Component 1...3). Following this, the damage pattern is calculated in accordance with the received stresses. Finally, the damage patterns show that component 1 has the highest damage due to the highest stresses in the first 50 s.

The second part of the forecast module consists of the knowledge base. It includes damage patterns of comparison
components that are monitored over their whole lifecycle as well as the classification of the damage patterns of the monitored component itself as well as identical components that are stored in the database as empirical knowledge. Once the classification features of the components are identified in the database, those components whose damage pattern is closest to that of the monitored component are selected from the existing records in step four. After the comparison components are selected, the evaluation of their data follows in the fifth step. For the comparison components, the complete lifecycle up to the time of their replacement is known. Their complete damage pattern is therefore also known. This provides information about the stresses experienced by the comparison components and the total damage sustained. These are evaluated statistically so that the future stress on the monitored component and the remaining service life can be determined in step six [35].

The results of the diagnosis module and the forecast module are concluded in the reaction module. Here, the selection of a suitable maintenance measure, based on the methodology of case-based reasoning (CBR), takes place. With CBR as a problem-solver, the current case is solved, using solutions of similar past problems [38] as a guideline. The current case describes the current condition of the monitored component. For the description, the findings of the comparison, diagnosis, and the forecast module are used. Solutions in this case represent appropriate maintenance measures. In the same case, the same maintenance measure is applied directly to the current component. In similar cases, the maintenance measure is adjusted according to the similarity of the attribute matches. After that, the current case and the adjusted maintenance measure are stored in the knowledge base.

Finally, the maintenance and load history is stored inherently in the component, using the Gentelligent Markup Language (GIML) data format, as described in Section 2.1. This information can be transmitted to subsequent generations by means of an evolutionary design, which is described in the following chapter.

4. Design and development of gentelligent components

Product lifecycle information from the usage or manufacturing phase of the gentelligent components could be used for the design of the next generation components. For this purpose, the algorithmic feedback of lifecycle information in the design process has to be enabled. This procedure provides an evolutionary adaption of gentelligent components to their real environmental requirements.

Investigations of load cycles, cluster analysis and optimization strategies are necessary for the presented design method. Based on these approaches, a concept of a process model is developed for a car component, in particular, for the wheel carrier [39,40]. The main challenge is to transform the inherent lifecycle information of the components into useful design information. In the first step, a transformation model is developed in order to reconstruct the component loads from the local stresses. Using the component inherent sensors, the strains \( \varepsilon \) are measured during the exploitation phase of the component. These data are transformed to forces \( F \) at the application points of the wheel carrier. By analyzing a simulation of different load cases, an equation for the transformation of the load-depended strains is evaluated using linear regression. The equation for the application point at the bottom of the wheel carrier is given below (Eq. (1)):

\[
\begin{pmatrix}
\varepsilon_{1X} \\
\varepsilon_{1Y} \\
\varepsilon_{2X} \\
\varepsilon_{2Y}
\end{pmatrix}
= 
\begin{pmatrix}
F_x \\
F_y
\end{pmatrix}
\begin{pmatrix}
-0.1692986 & -0.1806184 & -0.0684381 \\
-0.4256452 & -0.4040402 & 0.2738836 \\
0.0539143 & 0.1451508 & 0.0128671
\end{pmatrix}
\]

(1)

Subsequently, the forces are classified by a cluster analysis. In this case, the \( k \)-medoids-methods are used to reduce the data volume and to identify the significant load cases. This information is applied to an optimization strategy for the parametric design of the wheel carrier [41]. Based on the observed loads from the lifecycle, a multi-criteria design optimization is developed; this optimization is used to take the light weight design and the equalized stress distribution in the component into consideration. Subsequently, a generative parameter model is chosen for the design optimization. A model for the optimization strategy is implemented based on elements of the application points, connection elements and an axle-bearing. For the determination of the optimal design
parameters, a genetic algorithm is applied. The concept of the optimization strategy is depicted in Fig. 12.

The evolutionary design process is evaluated for the wheel carrier. For this purpose, different race tracks are simulated by a multi-body simulation of the race car. Consequently, the forces at the application points of the wheel carrier are detected. Moreover, strains measured from real driving sessions are transformed into forces and integrated into the data pool. Fig. 13 depicts the impact of different load cases on the design of the wheel carrier.

The consideration of different load cases observed within the lifecycle for an evolutionary design method generates optimal solutions for each load case. By observing component loads over their entire lifecycle, several relevant load cases can be acquired. As a result, an optimal design, according to real lifecycle situations, can be generated by the developed design method. Future research will focus on advancing the method of evolutionary mechanisms on entire assemblies.

5. Conclusion

Product related information and physical products are often separated over the product lifecycle. Hence, any lifecycle relevant product information has to be acquired with significant effort. In order to reduce this information management effort and to enable new approaches to a lifecycle oriented design, manufacturing and maintenance, this paper provides novel applications based on gentelligent components with inherent information storage and sensors. Using the lifecycle information of gentelligent components offers the following advantages:

- To provide an efficient information management over the product lifecycle, adequate information models and component-inherent storage technologies are necessary. For this purpose, a gentelligent data format based on the XML-scheme is developed. The developed GIML data protocol is highly adaptable and, compressed by a factor of 20, it can be utilized for a variety of information tasks over the course of the lifecycle of a product. The GIML protocol is backward and forward compatible for the exchange of lifecycle information and can be used for product design, manufacturing planning and process documentation as well as for the usage and service documentation.
- The key enabler of gentelligent components is represented by their inherent data storage and communication technology. A high frequency communication module which enables the multidirectional transfer of product information and storage of lifecycle and which has an internal memory of 8 kB is developed.
This transponder provides a microcontroller which supports sensor applications like strain and temperature measurement, which can be integrated inherently in the component.

- Another inherent storage technology provides binary information, which stores binary information directly on the surface layer of the machined component by an axial actuation of the cutting edges during the machining process. As a result, an information density of 0.5 kB/cm² can be achieved. Such data can be read optically from the components surface even if corrosion occurs or surface layers are applied.

- Gentelligent components can even be applied to a production system: connecting such components to each other results in a corresponding gentelligent system. Additionally, a gentelligent sensory machine tool that enables an internal process monitoring is developed. This component inherent multi-axis strain sensor technology provides accurate readings of the process loads and cutting forces during the machining process.

- A method for the online monitoring of the manufacturing quality delivers detailed state information of the process and workpiece condition. Using the cutting forces measured by the gentelligent machine tool, the tool deflection is reconstructed during the manufacturing process. Consequently, shape deviations at the machined surface can be estimated and the workpiece quality can be validated online.

- An intelligent component-driven production is realized by decentralized and inherent intelligence and storages provided by gentelligent components. Based on the individual gentelligent workpiece and an adaptive process planning algorithm, manufacturing interruptions can be reduced. As a result, lead time in a complex and diverse job shop production can be reduced significantly by ~22%.

- During the utilization phase of the component, information provided by the gentelligent component – e.g., component load information – is used to organize and plan maintenance measures. The newly developed method “Component status-driven maintenance” enables the identification and analysis of the current component status by means of component-inherent sensor technologies. Based on a similar load patterns from a load database, damage propagation can be estimated, the current condition of the component can be determined and, thus, future service and maintenance measures can be scheduled more precisely.

- For the design evolution of gentelligent components, the loads experienced over the lifecycle are applied to the design optimization. Load information provided by a gentelligent wheel carrier of a racing car, for example, is used to improve the design of next generation components. The improved design of use-case specific components demonstrates the potential benefits of a design evolution based on lifecycle information and gentelligent sensor and storage technology.

This paper gives a short overview of the possible applications of gentelligent components and illustrates the potentials of the provided storage and sensor technology for a number of lifecycle applications, such as planning, manufacturing, maintenance and design. Further research in the CRC 653 will focus on the development of a lifecycle demonstrator and on the reduction of information interfaces for continuous information flow over the lifecycle of the product.

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