Signal Processing for self-Optimising Manufacturing Systems in Laser-Cutting and Gas-Metal-Arc-Welding.

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Summary: Self-optimising manufacturing systems have the potential to enhance robustness and performance of machines which employ processes that are characterised by the fact that the processing result cannot be measured directly during processing. "Model-Based Self-Optimisation" is a concept to overcome this problem by embedding knowledge about the process into the numerical control of manufacturing systems. It requires distributed handling of process signals on different time-scales to allow autonomous adaptation to changes in the manufacturing processes. This paper reports on works on this topic by examples from laser cutting and gas-metal-arc-welding.

Keywords: In-Process Measurement, Quality Control, Optimization, Sensor.

1. Introduction

Manufacturing systems strive for an always increasing degree of flexibility and autonomy in order to ensure the achievement of a requested product quality and limited down-time. This is accompanied by a growing variety of adjustable parameters which allow influencing more details of the complex interactions between process, machine and material. Operators therefore need sound process understanding and deep expert knowledge to set up such manufacturing systems. While this imposes an excessive demand on machine operators, it becomes impossible for them to execute control for highly dynamic processes. One solution for this dilemma is to increase the transparency of manufacturing systems through embedded intelligence.

Increasing processing speed and highly specialised processes cause manufacturing systems to operate in process domains where set-up of the processing task and stability of the process become dominant issues. Even if processes are designed to run in robust operating domains, changes in boundary conditions at runtime often result in low product quality. Such influences may arise from changes in machine status, different material properties in subsequent lots of raw material or they may result from deviating geometries due to clamping or thermal bending. Deviations from requested product quality which can be measured directly are suitable for pre-defined, fixed control-strategies if setting parameters of the machine can be adjusted independently. In those cases where a single quality-relevant measurand cannot be acquired during processing, direct control of quality is prohibited with such strategies.

2. Model-Based Self-optimisation

A new approach on manufacturing systems which are capable of optimizing themselves towards a requested product quality is the concept of "Model-Based Self-Optimisation" (MBSO) which was developed within the publicly funded research cluster "Integrative Production Technology for High Wage Countries" [1]. This is the central concept in "Technology Enablers for Embedding Cognition and Self-optimisation into Production Systems" and represents a generic approach to combine sensor data, to analyse signals and to extract information in order to be able to control complex and highly dynamic manufacturing processes on short time scales (figure 1).

Issues which have a significant influence on the processing result occur on such short time scales that technical systems are needed to control the manufacturing process itself. These systems are expected to fulfil the same task as experts, ideally enhanced with a sound physical knowledge about the process, but on a much shorter time scale. From this perspective it is essential to embed expert's intelligence and analytic thinking into evaluation capabilities and decision algorithms which run on computational systems.

Within the MBSO-concept, "Information-processing Sensor Actuator Systems" (ISA-Systems) operate at the lowest level in direct interaction with the process. Their input is a so-called "internal objective" (possibly more complex than a single setting parameter) which they try to fulfil with embedded intelligence on signal processing and actuating. The details about their control behaviour are derived from the process models and parameterised at runtime.

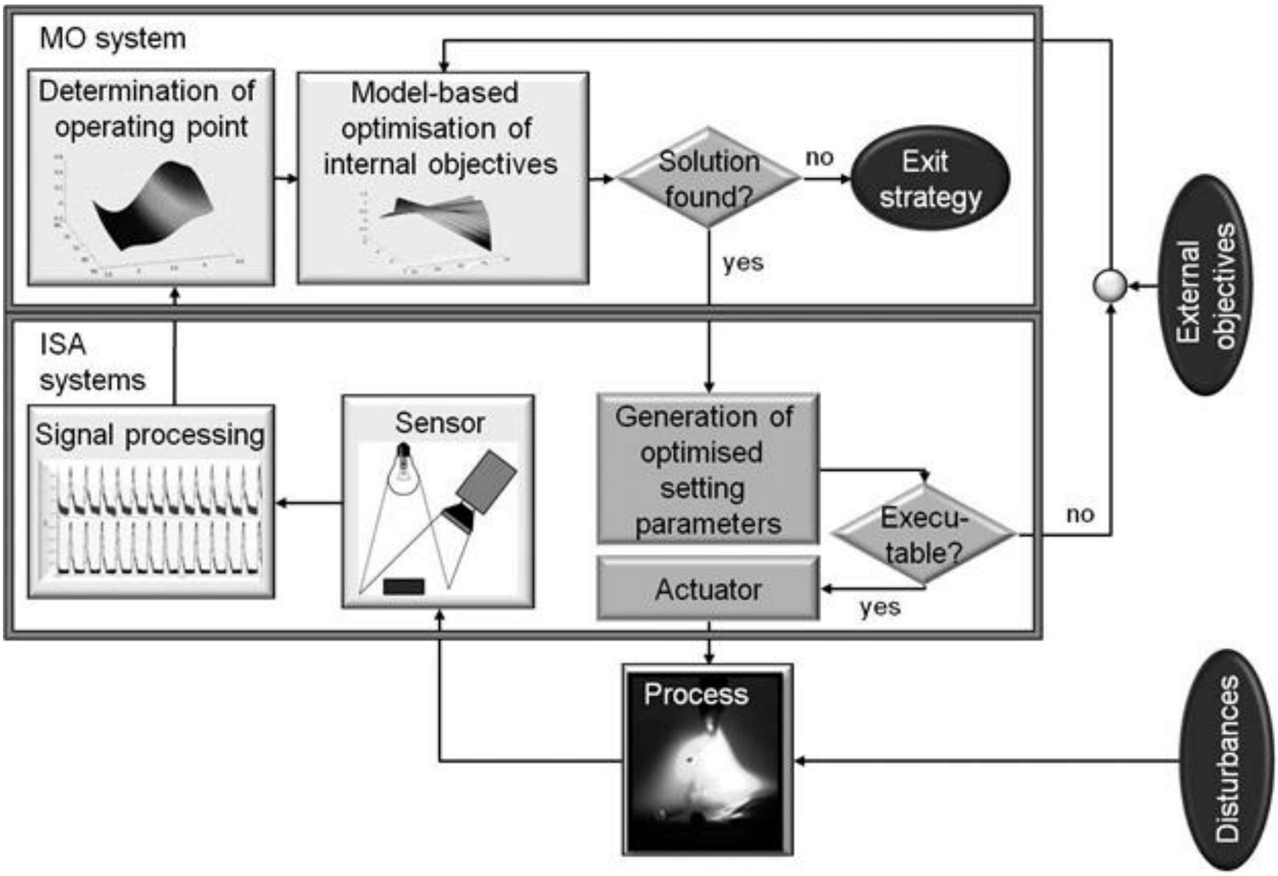

Figure 1. Concept of the Model-Based Self-Optimisation (MBSO).

The model based analysis of all sensor data allows the determination of the current operating point of the process what subsequently allows the prediction of the current product quality. If any parameters exceed the predefined tolerances, a Model-based Optimisation System (MO-System) creates new internal objectives based on the current operating point. The MO-System has to preserve the continuity of the processing and to ensure the achievement of product quality. In most environments, these steps may be executed at time scales that are much larger than control cycles and processing can take place on external computers. Still, a new solution has to be calculated within a time limit that allows taking corrective action before the product is scrapped.

The paper presents current results from research on embedded acquisition of data and extraction of features within the concept of Model-Based Self-Optimisation (MBSO). The development of manufacturing systems towards MBSO is shown for laser-cutting and gas-metal-arc welding (GMA welding). While the generic approach of the project is founded on diverse processes like 5 axis-milling, plastics injection moulding, weaving and braiding, laser-cutting and GMA-welding demonstrate the differences with regard to quality control despite their use of a thermal process for the modification of sheet-metal. The examples show the approach to arrive at an identification of surrogate measurands for determination of product quality, selection of suitable sensors, their integration and corresponding signal processing for an embedded solution.

3. Laser-Cutting

Laser based manufacturing systems for cutting of sheet metal are well established in the producing industry today. Research has advanced towards a detailed process description which incorporates boundary conditions from setting parameters for the machine down to influences from material properties [2]. One task which remains to be solved is to arrive at a description which considers the high dynamic nature of the laser cutting process and which identifies and measures quality relevant parameters.

In most cases of industrial relevance, setting parameters for the machine and the cutting task are taken from so called technology tables where the values for the setting parameters include safety margins to account for expected disturbances. While this approach leaves several optimisation potentials unexploited, competitiveness in manufacturing at the shop-floor level mainly is determined by fast set-up of a specific manufacturing task and fast processing at the requested product quality.

Processing time and product quality are mainly influenced by machine capabilities, status of the machine and material properties. The first dimension is given by design while the other ones change over time and location. Where several parameters can be measured during processing, some – including the important focal position – cannot.

Surrogate features which correlate to the not yet detectable but quality relevant parameter have the potential to solve the problem if two conditions are fulfilled a) the feature is measurable with the required precision, b) the correlation can be described over the relevant range of the involved parameters. In case that the correlation depends on the operating point itself, numerically evaluable descriptions have to be developed to hold the solution in the form of a surrogate-model (meta-model).

One example for such a correlation is the width of the kerf being cut which can be used as a surrogate feature for the roughness of the cut-face. For a given set of values for setting parameters like focal-position, feed-rate and laser-power, a value for the kerf-width can be determined such that the roughness of the cut-face stays below a requested limit. However, this correlation is not bijective. In case of a drop in feed-rate, a full new set of values for the setting parameters has to be found that ensures achieving the requested R_z. From this perspective, signal processing for self-optimisation of laser cutting has to provide all features necessary for the process models to allow optimisation and decision algorithms to set a new operating point for the manufacturing system.

Details on recent works towards embedding expert intelligence into a laser based manufacturing system that shall operate robustly and optimally with respect to a given set of criteria will be reported. In this approach, a sensor system acquires spatial signals by imaging the interaction zone during cutting. It monitors the current processing speed and the width of the cutting kerf as two major process parameters. Based on physical principles, experiments and expert knowledge – a meta-model is being developed which describes the correlation between these values and the resulting roughness of the cut-face is being predicted by simulation tools like QuCut [3] and experimental validations. Meta-modelling techniques are employed to yield a machine readable system that can be evaluated on a short time scale. With this information, the machine is enabled to adapt setting parameters according to its current status in order to achieve the requested objective autonomously.

4. Gas-Metal-Arc Welding

The flexibility of the GMA welding process makes it especially versatile in joining of thin sheet metal. Product quality herein is defined by the geometry of the manufactured weld-seam. Major influence on this product quality arises from geometric changes of the work-pieces as the gap between the joining partners changes in the vicinity of the joining position.

For the acquisition of data about changes in joining-geometry, electrical sensors are used which record transient data of the amount of energy introduced into the material and optical sensors which measure the gap-width. The automated correlation and analysis of preconditioned sensor data allows set-up of process monitoring which determines kind and level of deviations. Subsequently, modelling allows determination of the manufactured seam quality [4]. If the influence is known, adapted setting parameters can automatically be calculated by optimisation algorithms which counteract disturbances. This way, changes in process boundary conditions are equalised during processing such that constant product quality is ensured [5].

Procedures for the analysis and evaluation of sensor data acquired during processing will be reported. A joint analysis of transient electric data and corresponding high-speed imaging allows derivation of conclusions about process stability, energy transfer and mass transport. Simultaneously, the optical sensor provides information about the geometry of the gap to be welded. Prospectively, if the sensor data jointly were used with process models, information would be created that would not have been existent with any single sensor. This opens up the way for an efficient optimisation towards a high-quality weld seam by adaptation of process properties [1].

Acknowledgements

The authors would like to thank the German Research Foundation DFG for the support of the research work which has been carried out within the Cluster of Excellence 'Integrative Production Technology for High-Wage Countries'.

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