# "THE SETUP OF A MULTIHEAD WEIGHER MACHINE"

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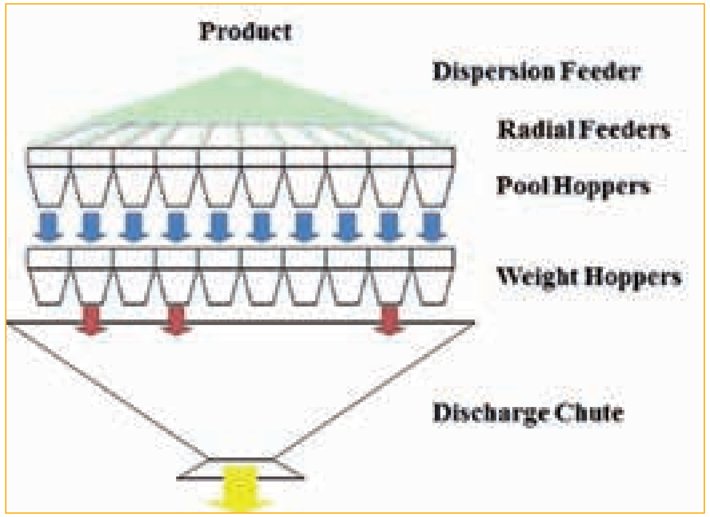
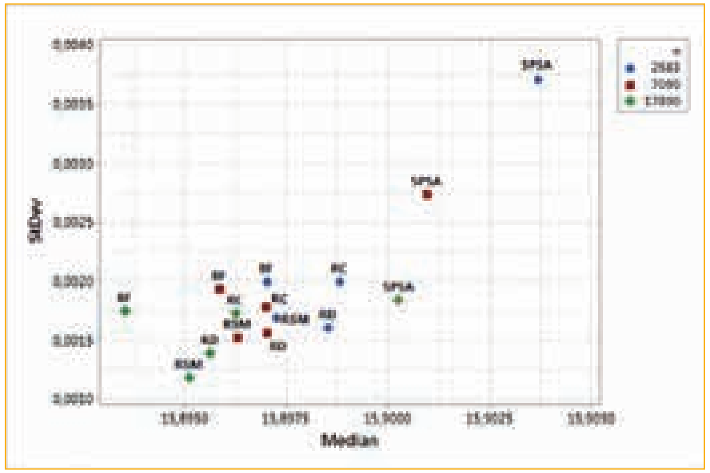
A Multihead Weigher Machine (MWM) is mainly composed of a system of feeders, a set of *H* pool hoppers, a set of *H* weight hoppers and a discharge chute to the packaging machine (Figure 1). The product is continuously fed via a central dispersion feeder and *H* radial feeders to the pool hoppers. The role of the pool hoppers is to stabilize the product before dropping it into the weight hoppers. Each weight hopper is equipped with a load cell that weighs the product and transmits the information to a computer. The computer then selects a subset of hoppers whose total weight is equal to or greater than the target weight *T*. Then, the computer opens the selected hoppers releasing the product through the discharge chute into the downstream packaging machine. For customer protection, the law requires that the weight of each package must be no less than the target weight. Consequently, a package filled with a quantity of product below the target weight is defined ``non conforming" and cannot be sold in the market.
A MWM is a complex machine which needs a setup strategy and a suitable operation software. The control software works in real time and its goal is to select the best hopper subset to open in order to achieve the package target weight, according to the product, the cycle time constraint and the objective function. This problem is equivalent to the well-known knapsack problem. Instead in my thesis we want to tackle the setup strategy which is still an open problem.
The setup problem of a MWM deals with the determination of the optimal average weight of product to be delivered to each pool hopper. This setting may change according to the type of product to be packed and the target weight of the package. An improper selection of the machine setup affects the machine efficiency in terms of ``non conforming" rate, material cost, scrap or rework cost and possible losses due to the deviation of the product performance from customer's and/or producer's target. Thus, the initial setting of the machine is a very important decision affecting the general economic performance. Currently, the setup procedures adopted in industrial practice mainly rely on the operator's skill and experience during a trial-and-error manual setup which does not guarantee the best performance. To the best of our knowledge, the setup problem has not been addressed in the scientific literature apart from some preliminary results.




1. A multihead weigher machine.

Thanks to the definition of the setup problem and its main variables together with the expression of the objective function (expected production cost per ``conforming" package ) to minimize, the problem to find out the optimal setup of a MWM has been formalized. The Solution Space of the problem has been characterized. Its deep analysis allows us to discover an interesting symmetry property to reduce its dimension and, consequently, to tackle the setup problem faster. According to the characterization of the Solution Space, five algorithms have been considered: gradient based algorithms (SPSA and RSM), a ``Brute Force" (BF) algorithm and two random sampling algorithms (RC and RD). Their performance (Figure 2) in terms of median and standard deviation of the expected cost have been compared using the same number of objective function evaluations *n*, which is used as a proxy of the computational effort. As easily predictable, the increasing of *n* causes the values of both indicators to diminish. In fact, a greater number of evaluated machine setups allows for an improvement of the algorithm performance.
We can surmise that the performance of BF and RSM algorithms become more and more comparable as *n* decreases. Moreover, the performance difference between the two random sampling algorithms (RD and RC) remains irrelevant by varying *n* and their performance are always worse than the BF and RSM ones. These conclusions have been generalized changing the MWM main parameters. Instead, the SPSA has always the worst performance regardless the number of objective function evaluations.
Lastly, the optimal solution found with the RSM algorithm is compared with two ``rule of thumbs" used in industrial practice. The expected cost of the RSM solution and its standard deviation are lower than the two industrial solutions allowing a firm to save money as much as the number of packages per minute increases.



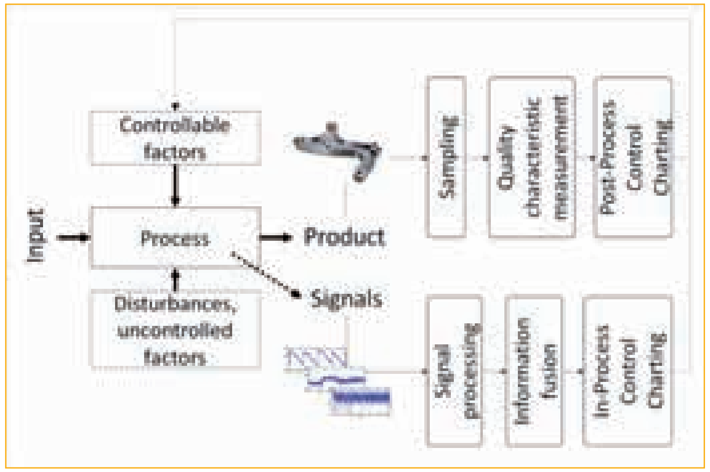

2. Scatterplot of the performance of the different optimization methods. The median of the expected cost obtained thanks to the 50 replicates, is plotted on the x-axis. Instead, on the y-axis, the value of the standard deviation of expected cost is plotted for each optimization method.

# PROFILE MONITORING OF MULTI-STREAM SENSOR DATA

**Marco Luigi Giuseppe Grasso** - Supervisor: **Prof. Bianca Maria Colosimo**

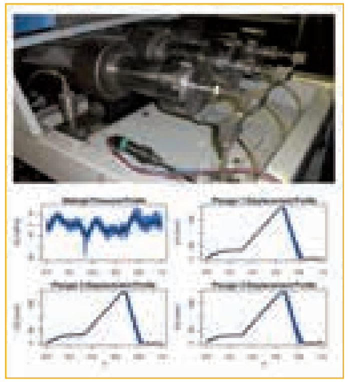
Tutor: **Prof. Paolo Pennacchi**

In the framework of industrial quality management, traditional Statistical Process Control (SPC) procedures depend on quality characteristics measured on the product of manufacturing processes. They also assume that a number of parts may be collected during In-Control (IC) operations to estimate the process parameters and to design the control charts. Nevertheless, the evolving market demands and the development of novel technologies have been leading to productive scenarios where traditional SPC methods are no more appropriate or even not applicable.
In different discrete-part manufacturing applications (e.g., in the aerospace sector), the production of high-value-added products implies extended machining times (e.g., several hours for a single part, possibly longer than the tool life). It also involves expensive tools and materials, together with high precision requirements.
The use of traditional SPC procedures, based on post-process measurements, implies a delay between the possible occurrence of a fault and the detection of its effects on the product. This yields unacceptable costs for wasting expensive materials and time-consuming re-manufacturing operations.
In addition, high customization requirements in various sectors impose small lot productions or even one-of-a-kind productions (i.e., the production of lots that consist of a single item). In that case, there is no possibility to perform a control chart design phase based on repeated processes, and hence novel quality control procedures must be considered.
A viable solution consists of sensorizing the machine tools and the production systems in order to collect data about the quality and stability of the process during the process itself. This is possible thanks to the continuous technological developments that are leading to data-rich industrial environments, where several sources of potentially useful information are easily available.
The result is a paradigm-shift from product-based SPC to in-process SPC.
A quality monitoring based on in-process data may provide a faster reaction to out-of-control shifts, thanks to condition-based control strategies aimed at quickly mitigating (or even suppressing) the effects of faults, with a consequent reduction of wasted parts. Furthermore, in-process SPC provides a potential 100% production coverage as it allows collecting data during each process run, instead of evaluating the quality characteristics on sampled products at the end of the process.
However, such a paradigm shift implies a number of novel challenges and critical issues with respect to the traditional SPC practice, because of the high sampling frequencies of sensor signals, the computational constraints, the complexity of the signal patterns, the time-varying properties of industrial processes, the streams of data from different sources, and the multiplicity of operating conditions. Those challenges and critical issues push the need to develop novel SPC approaches and to improve the existing ones.



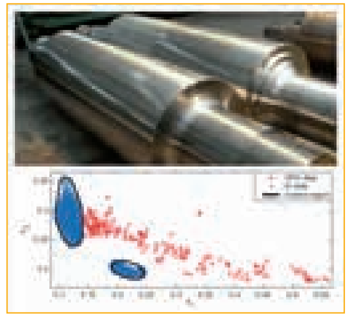

1 – A paradigm shift in SPC: from product-based to signal-based monitoring

This thesis is aimed at studying and developing novel signal-based SPC methods in order to deal with those challenges. A particular family of industrial processes in considered, i.e., the family of discrete-part manufacturing operations that exhibit a cyclical behaviour. In that case, the IC state of the process can be described by cyclically repeating patterns of acquired signals, known as "*profiles*". Therefore, this study deals with the use of profile monitoring methods for in-process sensor signals.
Different inter-related research problems are discussed and faced. In the first part of the study, the focus is on signals from a single sensor that exhibit complicated patterns or undesired misalignments. In this frame, the two following problems were faced: (i) the integration of registration information in a profile monitoring framework, to guarantee a proper management of different signal variability sources; (ii) the enhancement of profile monitoring performances in the presence of complicated signal patterns characterized by information contributions on different time-frequency scales. The analysis is then extended to signals coming from multiple sensors, which must be properly integrated and fused together in order to achieve a better and more synthetic representation of the on-going process.



2. Ultra High Pressure (UHP) pump of a waterjet plant (top panel) and multi-stream signals from water pressure and plunger displacement sensors (bottom panel)

In the last part of the study, the analysis is focused on the development of profile monitoring methods for processes that exhibit multiple IC states, which represents a challenging violation of traditional SPC assumptions. This analysis if motivated by the fact that, in different manufacturing applications, parts of the same quality can be produced by processes can not be characterized by a unique IC state. The existence of multiple IC states is due to operating modes that vary in time (e.g., different cutting parameters, different tools, different ambient conditions, etc.), and hence novel profile monitoring methods are required.
All the proposed approaches are driven by actual industrial challenges and designed for in-process utilization. They were tested by means of Monte Carlo simulations and compared with benchmark techniques. Real data from different industrial case studies, including waterjet cutting, grinding of cylindrical rolls and end-milling processes, were used to demonstrate the performances of the proposed methods in actual industrial scenarios.



3. Products of a roll grinding process (top panel) and multivariate variables in 'in-control (IC)' and 'out-of-control (OOC)' process states (bottom panel)

# A METHODOLOGY TO SUPPORT THE MODELING AND DESIGN OF MATERIAL SEPARATION SYSTEMS FOR RECYCLING

**Ali Jadidi -** Supervisor: **Prof. Marcello Colledani**

During the recent years due to the significant technological innovations, the production of electric and electronic equipment (EEE) has been marked as the fastest growing area in industrialized countries. This results in an increased amount of waste electric and electronic equipment (WEEE). In EU countries WEEE is the fastest growing waste stream having an annual growth rate of 3% to 5%.WEEE are considered critical waste streams due to their hazardous materials contents. Therefore in case of a non-proper waste treatment, they can generate negative environmental impacts.
The need for treating end-of-life products is also highlighted in other sectors such as automotive industry. It is estimated that over 15000000 vehicles retired per year in the USA and 15-25% of their total weight is landfilled. Taking into account the potential environmental impacts of the waste disposal many countries have set up new regulations and legislations in terms of end-of-life management and in order to improve the recycling process and reduce the waste disposal. Waste treatment is an important issue not only in terms of environmental concerns but also from the recovery aspect of valuable materials. In fact WEEE and end-of-life vehicles (ELV) are mixture of various materials that potentially can be seen as a resource of metals, such as copper, aluminum and gold.
Due to the complex and variable material mixture of WEEE and ELV, their material recovery is a very challenging task that has not been solved yet. For instance talking about the PCBs that are widely used in electronic products, currently only about 30-35% of metals represents in the PCBs are recovered with purity level varying between 85% to 95% depending on the element.
Indeed efficient treatment of these complex mixtures requires automated multi-stage systems composed of different size reduction and material separation stages. In this regard, Smart mechanical treatments, that are considered in this work, are ideal techniques for recovery of materials in WEEE and ELV since they involve very limited environmental impacts, energy consumption and production of by-products. Mechanical separation systems use different material properties such as conductivity, size and density for treating the input mixtures.
In spite of the extensive research works dedicated to analysis of different material separation and comminution technologies, design and performance evaluation of these systems have been rarely studied from system engineering pint of view.
In M. Colledani and T. Tolio (2013) a multi-level framework that is illustrated here is introduced for integrated modeling of the material separation systems considering the interaction among process and system levels. Indeed in mechanical separation systems there is a strong interaction between process and system levels.
In the proposed model, in the system layer the dynamics of the material flow in the recycling system is considered. This layer considers in input from the process layer transformation matrices that are required for analysis of material flow. In the process layer the physics of the process is used in order to predict the transformation matrix based on the updated estimate of the material flow dynamics calculated in the system layer. The interaction between two layers is captured through parameter exchange between two layers.
Although the proposed multi-level model is useful in capturing the process-system interaction, following relevant aspects are neglected.

- Uncertain separation matrixes

The quality of the separation processes that can be determined by the separation matrixes is not constant and can be affected by particle-particle interactions. The real experiments that are reported in this work confirm that the quality of the separation process may be degraded by increasing the material flow rate as it can increase this kind of interactions.

- Effect of the material re-processing

In material separation systems it is common to re-process the materials in order to improve the output quality or increase the amount of the recovered materials. In spite of the importance of the material re-processing, this aspect is not included in this model.
In this work a multi-level approach is taken considering these aspects and other system logistics issues such as machine breakdowns, machine processing rates, starvation and blocking propagation, and role of conveyors as finite buffers. Therefore, a comprehensive model is developed that is capable of predicting the performance and support the design of the separation systems used in recycling.
Material flow rate is considered as a system level parameter than can affect the separation quality. Indeed, on the one hand at process level the separation quality and the size-reduction efficiency is degraded with increasing flow rates. Therefore the material flow rate which is a system level parameter can affect the process level performance. On the other hand, the separation quality at process level affects the material routing in the system.
The decomposition method that breaks the system into the small sub-systems, composed of two machines and one buffer, is used in order to calculate the system performance. Moreover a methodology that is called "linearization" is introduced for quantitative analysis of the material re-processing. In this method the behavior of the reworking loop is approximated by a transfer line composed of desired number of machines. Developed methods are implemented in Matlab. The methods are validated by comparing the results with simulation models, under different system configurations. The results confirm that the precision of the proposed methods.
Another important process in recycling systems is the comminution process for shredding the input particles. Comminution processes directly affect the material routing and the efficiency of the downstream separation processes. In this work different experiments on comminution process are performed to help providing a better insight to different aspects of these processes.
The assumptions of the model and some of the key results are validated by the experimental analyses performed at the ITIA-CNR laboratory for demanfuacturing, within the cell 3 on recycling technologies and systems.
The assumption related to the effect of the flow rate on separation quality is validated thorough the corona electrostatic separation of a binary mixture composed of plastic and copper. The same process is also used for experimental validation of the linearization method.
The experiments that are performed on CES process also confirm the importance of the material re-processing in material separation systems. It also proves the criticality of choosing the right set of process parameters for material re-processing.

# DATA FUSION FOR PROCESS OPTIMIZATION AND SURFACE RECONSTRUCTION

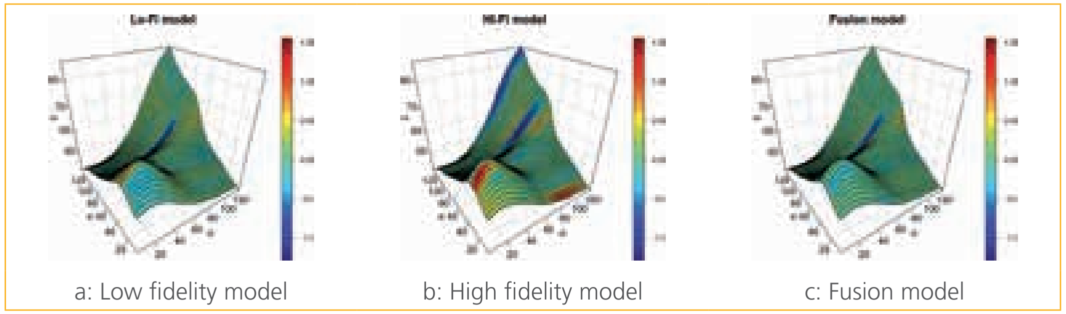
**Luca Pagani -** Supervisor: **Bianca Maria Colosimo**

Last years are characterized by the impact of global trends and manufacturing technology is faced with a number of different challenges. The topics of customized products, reduced life time, increased product complexity and global competition have become essential in production today.
The changing in modern manufacturing towards a customized productions is characterized by high-variety and high-quality products, a paradigm shift in metrology is coming on.
Information that concerning the state of the products and production processes is obtained with the aid of metrology.
Due to this paradigm shift, the complexity and accuracy of the product requirements are increasing.
At the same time, smart sensorization of equipment and processes is providing new opportunities, which have to be appropriately managed. A large amount of data can be available to aid production and inspection and appropriate methods to process the "big data"' have to be designed.
In this scenario, multisensor data fusion methods can be employed to achieve both holistic geometrical measurement information and improved reliability or reduced uncertainty of measurement data to an increasing extent.
The main purpose of this thesis is to explore new approaches for reconstructing a surface starting from different sources of information, which have to be appropriately fused. Surface is meant in a broad sense, both as the geometric pattern of a physical object to be inspected and as the surface representing a response function to be optimized.
The first part of the thesis focuses on the reconstruction of the surface geometry via data fusion. In this case, it is assumed that multiple sensors are acquiring the same surface, providing different levels of data density and/or accuracy/precision. The thesis starts exploring the performance of a two-stage method, where Gaussian Processes (also known as kriging) are appropriately used as modeling tool to combine the information provided by two sensors. Figure 1 shows the reconstructed surface, with the error map, using only one sensor (Lo-Fi and Hi-Fi models) and properly combining the available information (Fusion model).
Then, the thesis faces the problem of suggesting a data fusion method when large point clouds, i.e., "big data" (as the ones commonly provided by non-contact measurement systems) have to be managed.
In this case, the use of Gaussian Processes poses some computational challenges and this is why a different method based on multilevel B-spline is proposed.
As a second contribution, the thesis presents a novel method for data fusion, where the uncertainty of the specific measurement system acquiring data is appropriately included in the data fusion model to represent the uncertainty propagation.
Eventually, the thesis faces the problem of using surface modeling to quickly detect possible out-of-control states of the machined surface. Starting from a real case study of laser-textured surface, an approach to combine surface modeling with statistical quality control is proposed and evaluated.
The second part of the thesis focuses on using data fusion for process optimization.
In this second application, data provided by computer simulations and real experiments are fused to reconstruct the response function of a process.
In this case, the aim is to find the best setting of the process parameters to maximize the process performance. It is shown how data fusion can be effectively used in this context to reduce the experimental efforts.










1. Prediction of the surface with error map

# UNCERTAINTY EVALUATION AND PERFORMANCE VERIFICATION OF A 3D GEOMETRIC FOCUS-VARIATION MEASUREMENT

**Wahyudin Permana Syam -** Supervisor: **Prof. Givanni Moroni**

Quality is an important aspect of a product. High quality product ensures the functionality of assembled products and the interchangeability among products from different manufacturers. To verify product quality, tolerance verification (geometrical measurement) by means of coordinate measuring systems has to be carried out. Advancement of manufacturing technology enables a significant reduce of critical dimensions, together with an increase of geometric complexity. This creates challenges in coordinate metrology: tolerances become tighter. Optical-based metrology instruments are a potential option to verify these tolerances. But of course also in this case traceability is a fundamental aspect to ensure reliable measurement results.

This thesis addresses the problem of traceability of a focus-variation microscope as 3D coordinate measuring system. First, the traceability of the instrument will be discussed considering its performance. Proposals for reference artifacts and procedures to conduct performance verification according to the ISO10360-8 and ISO10360-3 standards are presented. These proposals consider both 3-axis and 4-axis configurations of the instrument.

Second, an approach is presented for task-specific uncertainty evaluation by simulation, coherent with the ISO15530-4 standard. The proposed simulation approach is based on spatial statistic model considering the correlation among captured points. To support the simulation and consider all significant error sources, characterization studies to investigate the influencing factors of measurement by focus-variation microscopy are presented, too. Finally, industrial case studies are carried out to validate the simulator developed. The validation conforms to the ISO15530-4 standard.

As a by product of this study, algorithms to associate ideal substitute geometries to sampling points will be discussed. An improvement of non-linear least square fitting is presented, based on the optimization of the initial solution through chaos method.