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Measurement-uncertainty as an innovative management tool in modern engineering systems

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Abstract **– In this work, a methodological approach based on the evaluation of the measurement uncertainty is used, in order to face the issues connected to the validation of measurements of distributed measuring systems, taking into account the requirements set by a scenario of high connectivity and big data. The methodology provided involves and follows from the rigorous methods applied in metrology discipline. It focuses on the measurement uncertainty evaluation, to be used as an innovative tool for better knowing the underlying systems/subsystems - from time to time analysed, towards problem-solving, setting or directing some improvement actions and thus, towards the possibility of being more confident in reaching the targets that have been set.**

I. INTRODUCTION

Among the aspects representing the modern systems and technologies, the possibility of interconnecting billions of objects - heterogeneous in kind and nature, cloud computing technologies, instruments and apparatuses, may be considered some of the most promising and effective technological trends [1].

According to this scenario, new organization models for industrial assets are set, like Industry 4.0 [2], and most of the activities are planned [3], [4]. The cornerstones of the the current industrial scenario on the one hand offer remarkable opportunities and need adequate competences and coordination, on the other hand.

In this framework, measurement uncertainty allows focusing the attention on a methodological organised management of the variability [5], which is an unavoidable aspect to deal with, due to:

- high connectivity and big data [6], [7],
- multidisciplinary skills, organised models and applications,
- enlarging scenarios from the interconnection horizon between companies point of view [8], [9]
- new quantities to be measured, mostly connected to physiological and human perceptions.

Managing the variability of data is a strong support to the validation of information which is one of the most important requirement that have to be fulfilled. The possibility of having available many disparate data appears promising from an information and knowledge capability standpoint. On the other hand, some difficulties have to be overcome, e.g. those linked to the data analysis and interpretation [10], [11]. Due to the lack of a standardized and univocal method of data integration, it is likely that the information extracted from these data, are affected by an uncontrolled variability.

Furthermore, modern industrial realities are called to develop and apply methods and models in order to stay competitive and prevent obsolescence of their assets. This is achievable by exploiting the advantages coming from the synchronization of the efforts requested to the various fields, areas, disciplines and related technologies involved, with the final aim of holding control of the quality of the overall informative flow. In facts, multidisciplinary is one of the most innovative aspect, since people are not completely ready in communication, knowledge sharing and integration, reciprocal translation of concepts, harmonisation of operational and decisional flows. Moreover, synergy is not trivial to build: operating tools exist but they are tailored to specific contexts. Often, an integration of complementary methods may be useful for exponentially enhance the results and the improvements.

Although a scheduled approach appears to be promising, such as that proposed by the international reference standards, e.g. [12], [13], the methods and tools provided seem to be not exhaustive and not-completely decisive, in the upcoming new era that we are called to manage.

This paper aims at demonstrating how a structured methodology, aiming at evaluating and reducing the measurement uncertainty, may be considered an innovative management tool in modern engineering systems, by reinterpreting approaches and solutions of improvement, well-established in the engineering systems. The application allows showing how the scenario is reinterpreted.

In Section II the proposed methodology is presented, applied and discussed with reference to an industrial test case, referred to the interpretation of product and process quality systems [5], [14]. The concepts and approaches typical of measurements are used with the aim of justifying and physically explaining the problems and the motivations for the obtained improvements. Conclusions end the paper.

II. METHODOLOGY AND TEST CASE

A methodology is shown, pivoting on the measurement uncertainty evaluation. The measurement uncertainty evaluation and its reduction are used as a tool supporting actions for the improvement of decision's reliability. Therefore, the measurement uncertainty, as defined in [15], is intended as an efficacious engineering tool. The approach considers the product and process conformity check [16]. The theoretical and experimental methodology, aims at:

1. identifying the main uncertainty causes, taking into account real issues (STEP 1);
2. in field evaluating the uncertainty of measurement, merging all the most remarkable contributions (STEP 2);
3. defining improvement actions, able to reduce the uncertainty and to recursively increase the reliability of decisions and provided solutions (STEP 3).

Finally, by iterating the afore-mentioned steps in a recursive manner over time, the methodology used is expected to provide an indication about the assessment of the performances to which it is referred, in line with the continuous improvement principle of many industrial management systems.

The spiral of fig. 1 highlights the recursive approach of the method provided, showing the steps and sub-steps, which are defined below:

STEP 1: Uncertainty causes identification
- 1.1 Characterization of the scenario
- 1.2 Requirements and constraints
- 1.3 Analysis's boundaries
- 1.4 Materials
  - 1.4 a Literature survey
  - 1.4 b Test environment

STEP 2: Measurement uncertainty evaluation
- 2.1 Uncertainty budget and test plan
- 2.2 Indicators for measurement uncertainty

STEP 3: Reducing the measurement uncertainty
- 3.1 Measurement uncertainty results
- 3.2 Remarks

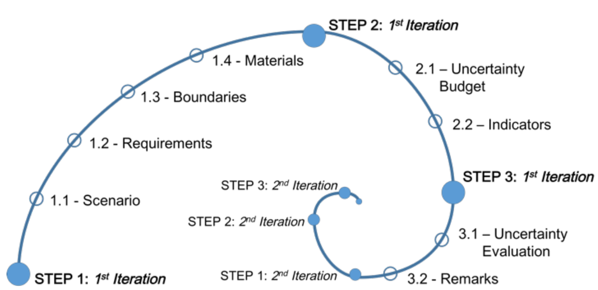


Fig. 1. Graphic illustration of the methodology

A. STEP 1: Uncertainty causes identification

The first step of the methodology aims at detecting the main uncertainty causes in the examined scenario, by means of four main sub-steps, as follows.

A.1. Characterization of the scenario

Goal of this sub-phase is supporting the identification of consistent boundaries of the industrial/social scenario, in order to set up a suitable focus for the analysis and to suggest possible actions for improvement and for technical-economic growth.

With reference to a selected test case, the analysis is focused upon some available operating methodologies used to organize efficiently the different steps of the production and management processes. In many industrial sectors [14] some examples refer to the six-sigma model especially if measurement topics are concerned, due to: (1) the measure step in the Define, Measure, Analyse, Improve and Control (DMAIC) process, and (2) the actions referred to instrumentation and measurement procedures, thus affecting all the other steps. Successful applications of the six-sigma method can be found in the literature and in the industrial normal practice. However, the lack of interpretation of the specific physical reality considered can cause significant problems instead of improvements [14].

The metrological support, intended as (1) the rigorous quantifying of the improving effects and (2) the physical explanation of the causes of problems and improvements, may lead, in synergy with the six-sigma methodology, to some positive effects in all the investigated spheres (production, technology and organization).

A.2 Requirements and constraints

The most significant and meaningful aspects influencing the real situation should be clearly identified at this stage, meaning that the main uncertainty causes influencing the measurement results should be identified, at least in a qualitative manner. A list of priorities of the most influencing uncertainty causes should be also set up, in order to define suitable directions of action.

If the selected test case is taken into account, the optimization of all the involved aspects of the production process appear to be a general requirement to be fulfilled, in relation to the need to reduce the cost of production.

According to the experimental data in the six-sigma model, the following priorities are set:

- Quantitative evaluation of the obtained improvements due to the realized interventions;
- Quantitative and experimental indicators in order to check the amount of improvement.
- Identification of the most important causes of variability in order to identify the field towards which planning corrective actions should primarily be directed.

As for the metrology priorities, the following are summarized:

- Complete definition of the measurand [15];
- Definition of a model of the phenomenon;
- Definition of a function relating the measurand to the different physical quantities of interest.

Integrating the metrological and six-sigma methods requires that some operations and typical methodological approaches of both are correlated and even 'translated' between each other, in order to allow an effective synthesis to provide improvement in the results.

A.3 Analysis's boundaries

The object of the analysis should be clearly pointed out, since it allows stating some fixed boundaries, and therefore keeping limited the uncertainty causes, on which basing the next steps.

Taking into account both six sigma and metrology disciplines the following indicators are mainly considered. Typical indicators [17] used as far as for the six sigma model are:

- the gauge repeatability and reproducibility,
- the Cp and Cpk values,
- the Pp and Ppk values.

When facing the measurement requirements, as for the aspects concerning the unambiguousness and completeness of the measurand, the following elements can be pointed out:

- identification of the measurand,
- identification of the measurement procedure,
- identification of the 'true quantity value'.

In summary, a finer identification of the boundaries for the analysis consists of the integration of analytical considerations (bottom-up approach) to synthetic information (top-down approach).

A.4 Materials

In this section, the experimental environment, in order to get the needed data for the measurement uncertainty evaluation to be performed in STEP 2, is chosen.

A.4a Literature survey

The first question one should pose is: "do similar solutions, close to the needs previously highlighted, already exist?" If yes, do they meet the above-fixed requirements? This information usually derives from experience, or from references, manuals, texts and knowledge.

With reference to the merging of the methodologies considered, some studies have already been carried out by a parallel interpretation of the situation in a public health organization according to the GUM [15] and to the six-sigma model [14]. However, in the industrial framework further improvements in this direction are not easy to achieve, since in the state-of- practice each one of such integrated approaches are very advanced.

A.4b Test environment

At this point of the discussion, the experimental environment for the tests, the equipment, the instruments are selected and set-up. In fact, a reference to carry out the analysis is needed: it is often an experimental one (laboratory environment), or it is created in field (e.g. industry), or it could be a combination of them. The creation of the reference is an unavoidable phase, since it allows carrying out the comparison between the analysis results themselves, with the fixed target, previously defined.

The test case used to demonstrate the advantages of the so far described approach refers to the issues connected to the realization of high performance turbochargers are taken into account. The increasing performance required for turbochargers imposes the fulfilment of more stringent requirements in terms of the mechanical design and tolerances, and consequently also in terms of the performances of the measuring system for productive process control. The reduction of the leakage of fluid under pressure together with the increase in the required power to the new models are the main goals fixed, which are translated into the following:

- A more stringent tolerance on the minimum clearance between the turbine wheel and the turbine house (tolerance B, given as an interval along the axial direction Fig. 2)
- The design of a turbine with a longer axial extension, whose outer profile ends with angles α between turbine wheel profile and rotation axis, which are larger with respect to the normal axis, as depicted in Fig. 2, (ø indicates the turbine profile diameter).

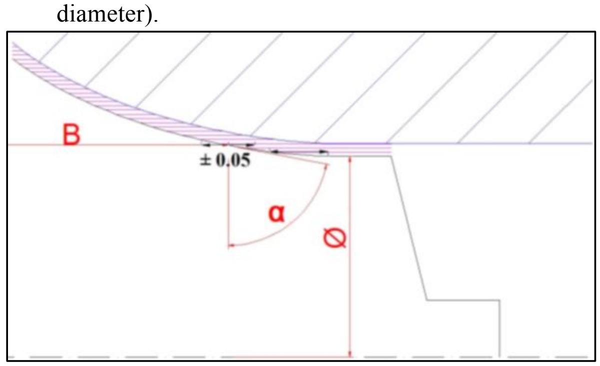


Fig. 2. Tolerance indication B and angle α [14]

This development strains the existing measurement methods, even if based on sophisticated optical gauges [18], which reproduce the mechanical verification through a calibrated gauge able to measure the position B along the rotation axis, where the axial profile of the turbine achieves a diameter $ø_{gauge}$ of given value, with reference to the plane A (Fig. 3).

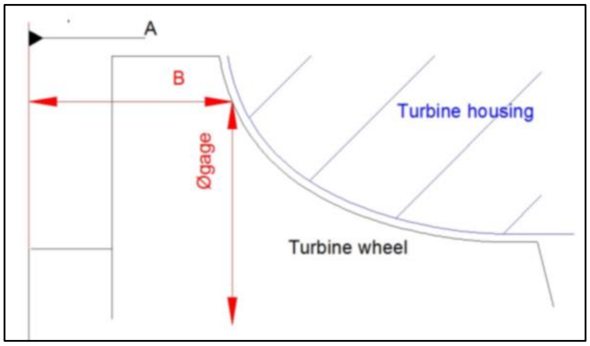


Fig. 3. Measurement design for tolerance checking on the turbine wheel [14]

The adjustment of the measurement procedure to the new requirements carried out according to the six-sigma approach, led the company to provide 100% control of production, with reference to both dimension B and run-out, since the process resulted not capable.

B. STEP 2: Measurement uncertainty evaluation

With reference to the aspects detected in the previous phase (STEP 1), in STEP 2 the measurement uncertainty is evaluated, so that the most remarkable contribution to the measurement uncertainty are suitably taken into account.

B.1 Uncertainty budget and test plan

The first sub-step enables us to focus on the main ones, which appear the most significant in terms of magnitude of the impact on the situation analysed. In a parallel way, depending on the main uncertainty contributions that have been selected, a proper design of experiments should be set, enabling the acquisition of measurements, as an input of the second sub-step.

Carefully analysing the method of measurement, the following uncertainty causes are envisaged:

- a lack of significance of the tolerance B: as the angle α increases, the tolerance gradually loses physical meaning and tends to align with the axis of rotation, while the clearance has a radial direction.
- a strong influence of the slope of the turbine profile at the point where the measurement is performed, on the control of the profile itself, performed through a single point identified by a predetermined diameter.

Therefore, it is assumed that the obtained limited capacity values do not reflect the real capacity of the production process but that they arise precisely because the measuring system is inadequate for meeting the requirements.

Thus, an improved solution for control of the profile has to be proposed and the stability of the improvements should be gained, in order to be compliant with the DMAIC procedure.

B.2 Indicators for measurement uncertainty

Measurement uncertainty should be evaluated quantitatively, thus in this sub-step it is necessary to choose proper indicators to give evidence to measurement uncertainty. To this aim, canonical terms may be considered [15]. In other cases, the operating reality asks for a specific definition of the variability of measurements. In this latter case we speak of “variability” rather than “uncertainty”, because the canonical definitions cannot apply.

Measurement theory could give a new and efficient support to the goal of justifying completely the results from a physical point of view. The guarantee that along the axis of rotation of the turbocharger (the x-axis), there is no interference between the profile of the turbine wheel and the volute of the turbine housing requires that, for each abscissa x, the clearance g(x) is positive but lower than the dimensional tolerance. Therefore, the true value of g(x), which is defined as the difference between the radius $r_v(x)$ of the volute and the radius $r_g(x)$ of the impeller, is dependent on the true values of $r_v(x)$ and $r_g(x)$, and this must be ensured along the entire circumference. The principle of operation of the optical calliper [22] allows us to obtain directly the radius or diameter of the impeller body, r=r(x). Nevertheless, if we wish to use the optical instrument to obtain the abscissa for which the turbine realizes a given diameter (as required by the set tolerance, Fig. 3) the instrument is required to provide a differential indication, of the type

$$dx = dr\ tan\alpha \qquad (1)$$

where α is the angle of the profile with respect to the normal to the x-axis. It is clearly noted that the variability corresponding to dr is amplified with increasing angle θ and that this results in a reduction in the capability indices calculated with respect to a set tolerance. The analysis of the process capability (within- and overall capabilities) is studied in terms of the process capability Cp and Cpk indices and to the process performance Pp and Ppk indices. Tests are carried out at different values of the angle α in order to detect its effect on the provided solution, which is compared to the current measurement procedure.

At the end of STEP 2 the measurement uncertainty evaluation procedures are available as well as the methodological approach adopted, included the simplifications of traditional methods. The simplification is intended as a contextualization of the canonical techniques, which are “translated” into the most appropriate terms for the context in exam, otherwise resulting a mere application of formulae

C. STEP 3: Reducing the measurement uncertainty

As a third step of the methodology the information provided by the measurement uncertainty is interpreted in order to support the definition of improvement action plans. In general, the underlying assumption is linked to the correlation there is between the knowledge of the measured phenomena and the accuracy of the measurements that have been performed on them.

C.1 Measurement uncertainty results

The resulting measurement uncertainty is used in order to address the most reliable and confident improvement actions. The calculation of the measurement uncertainty, besides allowing in reaching some pre-set targets or giving directions to reach them, may provide further indications that were not available preliminarily.

An improved solution for control of the profile is proposed, which envisages calculation of the surface's shape error, incorporating into a single new measure the existing tolerances on B and on the run-out (Fig. 4). The physical meaning is changing with profile diameter ϕ_1 and ϕ_3, respectively.

If the radius measurement uncertainty is considered, the relationships can be obtained as in Eq.2 and Eq.3, where σ_r^2 is the whole variance of the radius measurement by the laser gauge, σ_{las}^2 is the variance of the radius measurement by the laser gauge for a fixed x and σ_{x-las}^2 is the variance of the axial positioning of the laser.

$$\sigma_r^2 = \sigma_{las}^2 + \left(\frac{dr}{dx}\right)^2 \sigma_{x-las}^2 \qquad (2)$$

$$\frac{dr}{dx} = \frac{1}{tan\alpha} \qquad (3)$$

Eq. 2 and Eq. 3 highlight the fact that, in direct r(x) measurements, high values of θ act in the direction of reducing the whole uncertainty, since θ reduces the effect of the uncertainty σ_{x-las}^2 of the axial position of the laser. Moreover, a dimensional measurement in a perpendicular direction with respect to the profile detected that, when the profile is characterized by a large angle α, the value obtained agrees substantially with the parameter actually needed.

To minimize the effects related to possible angular misalignments, choosing as a reference for the optical calliper the grinding axis of the wheel, takes advantage of the high reproducibility of the grinding process used for the realization of the turbine wheel profile itself. For this reason, the effects related to possible angular misalignments are neglected, in particular between the optical axis of the calliper and the positioning axis of the shaft of the turbocharger.

The measurement process and the new definition of tolerance are now consistent with the physical reality.

The improvements obtained are evaluated by means of the indices for statistical process control. With reference to the former specification of the tolerance B, in Fig. 5 (a) the process capability evaluation data for a turbine profile with a small angle α are given, with a lower tolerance specification limit (LSL) of 20.1 mm and an upper tolerance specification limit (USL) of 20.2 mm. Data processing allows us also to predict, based on these performance values, the out-of-specification value, which resulted unsatisfactory.

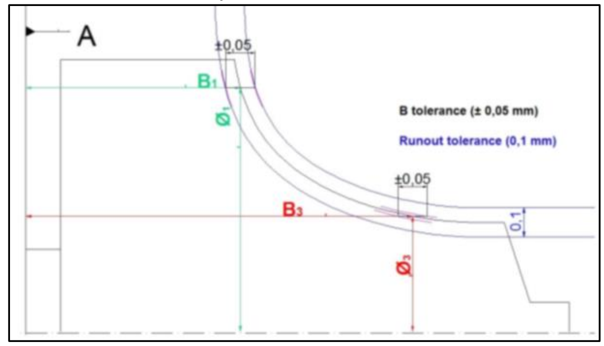
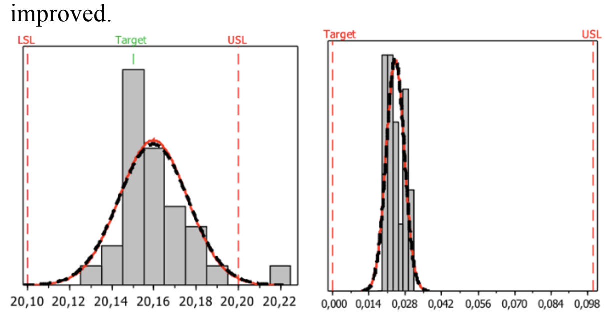


Fig. 4. Comparison of tolerance on dimension B depending on position, B1, B3, along the turbine wheel profile with respect to run-out tolerance [14]

With reference to the latter specification of tolerance and the general profile form, the data of the process capability evaluation for a turbine profile with a low angle α are shown, with an LSL of 0 mm and a USL of 0.1 mm, are shown in Fig. 5 (b). The performance indices are greatly improved.



(a) (b)

Fig. 5. SPC of turbocharger – Ppk before the intervention for a model with a low (a) and high (b) α angle [14]

Similar satisfactory results are obtained with reference to the potential capability (within-capability) data and the overall capability data in terms of Cp and Cpk and in terms of Pp and Ppk, for a turbine profile with a large angle α [14].

The actions realised demonstrated that the measurement uncertainty reduction can be seen as a contribution to the knowledge of the system, also in respect to other competence areas.

C.2 Remarks

The integration of metrological considerations within six-sigma procedures returned an improvement of the real physical meaning of the situation thus allowing the streamlining of a procedure for control of turbochargers in the automotive sector. In particular, a new control method (Fig. 4) consisting in measuring in the perpendicular direction at each point of the turbocharger has been set. The reference axis for the measurement system has been chosen according to the grinding process of the turbine wheels. Both actions derive from a careful analysis of the measurement uncertainty. The related following advantages have been achieved:

- a reduction in the necessary controls;
- a reduction in the dedicated manpower;
- a reduction in the observed scrapes, which are often false alarms;
- a reduction in the time taken for the operation.

In this sub-step, the direction of further actions to reach new improvement targets are defined. Having the possibility of highlighting new directions of action means fixing new targets and thus repeating the steps again. Moreover, for example, if measurement uncertainty cannot be negligible, further actions are needed in order to reduce it, and this is achieved by iterating the procedure.

III. CONCLUSIONS

In this work, a methodology based on the evaluation of measurement uncertainty has been proposed, as a tool for supporting management in the complex scenario characterised by a large amount of data provided by different instruments and devices. With reference to the online control procedure of the critical geometrical dimensions of a high-performance turbocharger for automotive applications, the methodology is applied, the uncertainty budget and the modelling of the measurement process are carried out. Coherent actions for increasing and consolidating the improvements, in synergy with the canonical methodologies largely adopted in product/process quality systems management are finally set up. Because of the aspects considered in this work, the following aspects have been achieved:

- Concepts translation in order to interpret them from a physical perspective;
- Studying the past actions for tolerances designing
- Tolerances re-designing;
- Exploiting the force of the technological processes to define measurement references.

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