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Integrated training in using different Coordinate Measuring Systems to support Digital Manufacturing

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Abstract

Highly qualified labour force is a key resource for growth. In modern manufacturing, the competent use of advanced measuring equipment for inspection and digitization of parts is an essential competence that is needed for both advanced product/process engineering and quality control. Coordinate Metrology (including 3D digital measuring technologies) is by far the most important tool for these specialized activities. As widely reported, the individuals operating the measuring systems - with their decisions - are frequently one of the most relevant error sources in Coordinate Metrology operations, especially when dealing with new measuring technologies supporting Digital Manufacturing (e.g. Computed Tomography, Fringe-projection, Reverse Engineering). The paper reports the intermediate results of an initiative aiming at innovating training in Coordinate Metrology, focused on supporting the needs of SMEs in the supply chain of the automotive industry. The main target group are industry employees operating in SMEs that are newcomers on 3D measuring technologies. An integrated concept for training in Coordinate Metrology has been developed using a blended learning approach, based on a 10-steps structure and incorporating the learning outcomes required to operate different measuring systems in a consistent way.

Keywords: Training in industry; Coordinate Metrology; Blended Learning.

1. Introduction

Manufacturing is today embedded in the digital transformation, intensively using computer integrated systems, simulation, information-sharing models, data exchange and automation. Alongside specific technological progresses (e.g. Additive Manufacturing technologies), in general sense Digital Manufacturing (DM) is continuously developing in the Industry 4.0 scenario including both new manufacturing technologies and the adoption of elements such as Cyber-Physical Systems, Internet of Things and Internet of Services. Within this evolving context, many aspects and

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activities in the industrial operations still need the direct contribution of human resources, as long as they are able to intercept the "blind spots" [1] in the manufacturing chain, where machines capabilities are not yet sufficient. Thus, the DM operator is in charge of quickly taking the right decisions on production operations and control through intelligently processed information, acquired by digital sensors and systems. For these reasons, the DM operator needs a wide range of competencies to face and manage the increasing complexity of manufacturing environments, with new procedures, operations and organizational structures. On the other side, the company culture must feed an innovation-driven environment starting from the human resources. The results of a recent survey [2] among industrial workers show that the user's knowledge and skills update, the attention to effective training programs and a collaborative organization with self-training teams are key factors for the DM success. Thus, to drive these transformational opportunities, it is fundamental to update the workforce with competencies aligned to Industry 4.0 specific requirements.

According to predictions of World Economic Forum [3], it is expected a drastic change of the required skills in respect to the ones seen as important today. Future workforce requirements will cover cognitive abilities (52%), systems skills (42%), and complex problem solving skills (40%), in addition to the basics for information and communication technologies (ICT). Following the increasing of automation and digitalization of work processes, companies will depend on employees with ICT specializations who can analyze big data, make coding, develop applications and manage complex database networks. To perform effectively within Industry 4.0 work environments, it is clear that employees should have continuous learning [4], updating their competencies not simply in their own professions but in a wider interdisciplinary perspective. The ability of adaptation to constant technological advancements is indeed vital for both employees and organizations. While companies need to invest on their future workforce abilities to be able to profit from technological advancements, current workers should enlarge and develop their skills for staying in the job market.

2. The need of advanced measurements

In the Industry 4.0 and DM context, advanced measuring equipment for inspection and digitization of parts are an important resource that is needed both for advanced product/process engineering and for quality control activities. It is worth noticing that almost 1% of EU GDP (i.e. Gross Domestic Product - Total value of goods and services produced by a country in a year) [5] is spent each year in measurements by a diversity of organizations in society, industry and official organizations. Coordinate Metrology (CM) is by far the most important tool for these specialized activities [6]. Many measuring systems are used in industry, with system architectures, sensor types and configurations depending from the application. The most important Coordinate Measuring Systems (CMSs) are Cartesian Coordinate Measuring Machines (CMMs), Articulated Arm CMMs, Fringe-projection Systems, Laser Trackers and Industrial X-Ray Computed Tomography Systems. These CMSs provide the information that link the many different steps in product's design and manufacture, from product idea to ready for use product, strongly supporting the concept of information-driven manufacturing.

CMSs are effective means for product geometry investigations for R&D purposes. Advanced and in-depth part analysis allows optimizing product specifications and determining which aspects are the root causes of product failures or non-conformity to the specifications. CMSs are also used to perform Reverse Engineering, acquiring the product geometry (i.e. cloud of points) to be used as starting point for the creation of the real part digital model. Coordinate measurements are often performed to assess product conformity to geometrical specifications in customer-supplier relations, to define acceptance or rejection of manufactured parts. CMSs can also be the main source of information to control the manufacturing process, monitoring critical features on the part while the part is being produced or immediately after, to feedback the process.

The many opportunities and applications of CMSs are however put beside the need of highly competent personnel to operate, program and manage these advanced measuring systems. The operator with his or her decisions and actions may indeed represent a relevant error source [7]. An operator must be aware of the effects of actions taken, since skipping some important activities often does not interrupt the measurement flow and the operator may obtain a result anyway, without awareness of its validity. Since measurement data are used to take decisions (e.g. about product conformity), an incorrect measurement procedure can lead to wrong decisions, productivity losses, low-quality products and loss of reputation.

For example, since Articulated Arm CMMs are manually operated, the measurement result is strongly affected by the operator ability to acquire an appropriate number of points on the correct part surfaces and with proper distribution. Moreover, Articulated Arm CMM use can be physically demanding in case of large and complex geometries: the operator assumes difficult postures avoiding to interfere with the setup, affecting both accuracy and productivity.
Simple measuring systems are not the only affected by the operator's activities. As example of CMSs having high complexity, in the application of industrial X-ray Computed Tomography for dimensional metrology, the user defines the measurement setup and many scanning parameters [8], mostly depending on the understanding of complex physical phenomena. Because of the complexity of the analysis, an improper parameters setting has a strong influence on the digital model acquisition and processing, and therefore on the measurement results.

3. Actual training offer and new needs

Training in Coordinate Metrology is a subject that is relevant to a number of sectors of industry; therefore different providers including most equipment manufacturers, specialized training centers and consultancy services offer training opportunities. There is wide variety in terms of course content, infrastructure, course duration and teaching methods. A number of initiatives contributed to the development of a common understating of this specialized training. One of the earliest worldwide was initiated in Italy in the 90's, with focus on the qualification and certification of personnel operating CMMs, and resulted in the first documented "body of knowledge" published in 1997 [9]. Depending on the candidate's sought level of qualification and education, the document specifies requirements in terms of topics, required number of training hours, required months of practical experience and examination procedures. Nowadays, most of the educational proposals are still focused on Cartesian CMMs, since their wide diffusion in automotive and aerospace quality control activities. A standardization of the training in CMM is offered by AUKOM courses [10], with basis on a national project run in Germany (1998-2001). The AUKOM training is proposed in different languages and it is centered mostly on Cartesian CMMs, with additional courses on Geometrical Product Specifications (GPS) concepts, quality management and Industrial Computed Tomography. A harmonized training on CMMs over Europe is also provided by the CMTrain association, founded on the basis of the EU project "European Training for Coordinate Metrology" (2002-2005) and using a blended learning approach. Training in portable CMSs (i.e. Articulated Arm CMMs and Laser Trackers) is for example provided by the Coordinate Metrology Society (CMS) [11] in the USA.

In the industrial practice, the operator is typically provided with instructions for the use of a specific CMS in the workplace by the equipment manufacturer or related organization. This training should be intended as a final application to the specific equipment of general metrological competencies, however it is often the only education the user obtains, in some cases limited to essential instructions to operate the equipment. This implies a potential lack of fundamental knowledge about Coordinate Metrology, GPS and recommended procedures among others. The result is an increasing of the operator-related error sources, who is unaware of the influence of his or her decisions and actions. In addition, the lack of comprehension about application fields and advanced functionalities of the equipment leads to an incomplete exploitation of the CMS's potential, limiting its use and its related economic benefits.

One of the causes of limited access to comprehensive training offer is linked to frontal teaching style, which is one of the most common teaching methods. Curriculum content is taught, exemplified and demonstrated by way of lectures in a classroom. This teacher-led style of teaching presupposes that course participants are all able to absorb, learn, understand and grasp all learning content at the same time, which is hardly possible with industrial operators having often different backgrounds and education type and level. If such a learning approach is taken, only limited attention can be paid to the needs of individual course participants [7]. Furthermore, this is not the optimal approach in terms of efficiency, since learners must travel to the place of learning, reducing productivity and overall sustainability, especially for small-medium enterprises (SMEs) that cannot afford to send to a training course of several days the only or few persons they have enrolled for quality control tasks. Thus, referring to industrial user as main target group, high quality and easy access learning opportunities for lifelong education on CMSs are an emerging need in Digital Manufacturing.

The feedback collected from over 900 participants out of industry and universities at CMTrain [12] courses show that the following aspects are important:

- Flexibility in time, speed and space for learning.
- Need of hands-on practical work on real measuring equipment.

- Interactivity in learning material using multimedia elements, including comprehension questions in the learning material with immediate feedback, to enable effective autonomous learning and self-assessment.
- Possibility to choose an efficient (taking pre-knowledge into account) and effective (learn only the topics of interest) learning path, tailored on each participant requirements.
- New measuring technologies related content, with specific attention to SMEs operators' requirements.
- Adaption of the content digital distribution to the preference of learners (tablet, computer, printed version).
- Possibility to share knowledge after the courses by using social media, keeping the learning community connected.

4. New training concept for Coordinate Metrology

To answer the request of innovative, updated and structured learning in the field of Coordinate Metrology, with a perspective of its role in the Digital Manufacturing evolution, a manufacturer-independent training system is under development within the Erasmus+ KA2 project "European Training for Coordinate Metrology 4.0". The aim is to design, implement and validate a set of tools and learning content to innovate education in Coordinate Metrology, which is a subject that is relevant to a number of sectors of industry throughout the EU. The automotive industry is the main reference context, with attention to the specific measurement technologies related to the Digital Manufacturing. Those include most important CMSs, i.e. Cartesian Coordinate Measurement Machines (CMM), Fringe-projection Systems, Industrial X-Ray Computed Tomography (CT), as well as methods for Point Cloud Metrology and Reverse Engineering. Interoperability of systems is also included as key enabling technology for Digital Manufacturing. To support the measurement activity, the learning content also covers the interface between part design and part verification. With information out of the technical drawing and other information sources, the requirements for planning and performing the measurement tasks are gained. Thus, the learning material incorporates content for the identification of measurement requirements e.g. the GPS system concepts, geometrical tolerances, advanced specifications, and CAD models. To complete the CMS operator's skills, the learning content covers the guidelines for measurement infrastructure management, as well as CMSs' performance verification and maintenance procedures.

4.1. Definition of levels of competencies

The main target group are participants from industry. A two-level structure of the learning material has been chosen to take the pre-knowledge of the individual learners into account, with the possibilities to define customized learning paths. The two levels differentiate between Basic (Lev. 1) and Advanced (Lev. 2).

Lev.1 operator is provided with fundamental aspects of CM and of basics of GPS system for the purpose of measurement. Lev.1 operator knows basics of operating principles and main industrial applications of CMSs and he is able to autonomously perform coordinate measurements according to good measurement practice and respecting recommended procedures. Lev.1 operator is able to perform basic measurement programming and simple post-measuring tasks, respecting indications received by Lev.2 personnel and being aware of general responsibility activities inside the metrology environment.

Lev.2 operator is generally more expert in all the fields covered by Lev.1. Has a deeper understanding of GPS system concepts and of Coordinate Metrology foundations (i.e. traceability and uncertainty), both for the purpose of measurement and for the verification of CMSs' performances. Lev.2 operator is prepared on CMS specific features (e.g. operating principle, configurations, applications, related error sources). Lev.2 operator is able to fully identify the measurement requirements according to the technical drawing indications and to the aim of the measurement (e.g. product conformity assessment, manufacturing process control, R&D), selecting the most suitable CMS for the specific measurement task. Thus, he is involved in the inspection planning and in the definition of the whole measurement process, with attention to advanced programming and measuring strategy definition. Lev.2 operator is able to perform data evaluation, to apply advanced statistic methods, to perform simple uncertainty calculations and to create advanced results reports. Finally, Lev.2 operator is in charge of responsibility tasks such as: management of the metrology room, management of measuring standards, and supervision of Lev.1 operators.

4.2. Definition of levels of competencies

To cater for the needs of a heterogeneous group of learners and to facilitate the accessibility to the learning material, it is important to offer a variety of different learning forms and to work towards a learner-centered approach rather than teacher-centered modalities. Blended learning [7] is an optimal integrated learning concept that combines different learning forms, such as currently available networked learning via the internet together with traditional forms of learning and learning media. Blended learning refers to a combination of different learning methods that allows traditional face-to-face teaching to be linked in a didactically appropriate way to alternative forms of learning (e.g. e-learning) followed by hands-on workshops where learners and teacher meet and interact in person using the CMS. Feedbacks over the last ten years indicate clearly that multiple learning styles and media are needed for lifelong learning because user needs vary with age, technical background and level of education. To enhance access for all, the learning material will be distributed adapting to the individual learning style. An e-learning platform enables learner-tutor communications and self-assessment questionnaires. The learning material is available for the learners through different devices (e.g. tablets, web-based learning platforms or printouts) and allows the adaptation to individual preferences (i.e. previous experience, available time, preferred studying method). The e-learning style fits the limited availability of industrial workers to join face-to-face lessons, allowing each learner to study with own rhythm. The blended learning activity also includes a limited-time participation of learners to hands-on workshops using CMSs, to apply knowledge acquired via the e-learning platform to selected case studies and using real measuring equipment under the guidance of a tutor. The learning material will be available in different languages (English, French, German, Italian, and Portuguese) to meet the industrial operators' needs at national level. International standards and official documents links are updated and refereed to national entities where available.

4.3. Modular structure of the learning content

The structuring of the learning content is inspired to the European Credit system for Vocational Education and Training (ECVET) [13], a system having the aim of structuring qualifications through the organization and recognition of competencies acquired in different training experiences. Successful ECVET implementation requires that training systems and related qualifications would be described in terms of Learning Outcomes (LOs), which are statements of what a learner knows, understands and is able to do upon completion of a learning process. The LOs are then consistently brought together in Learning Units (LUs), which are collected to create specific learning paths and related qualifications.

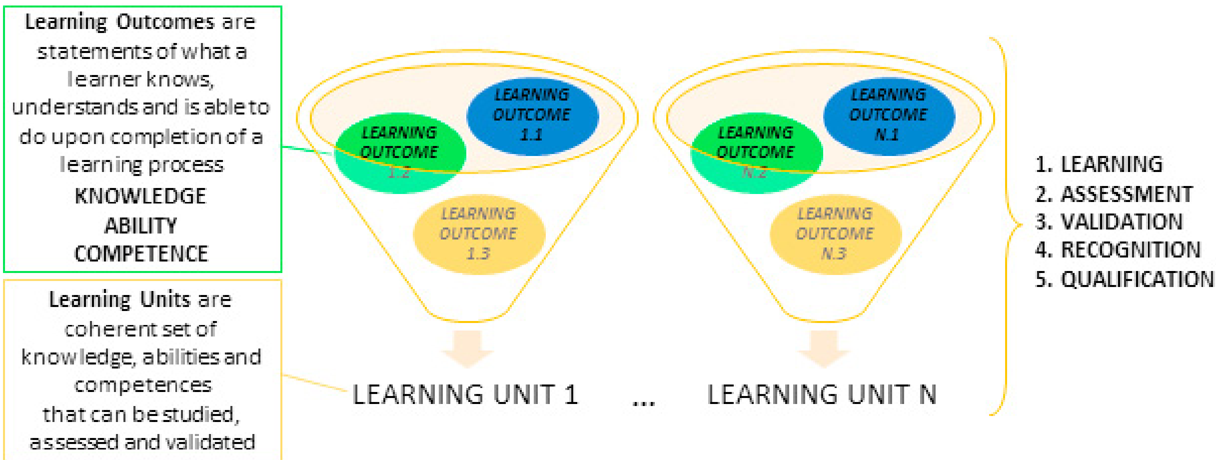

Fig. 1. Main elements of the ECVET System [13].

Due to the variety and complexity of measuring technologies (i.e. different architectures, sensors, amount of data, applications, etc.) the listing of LOs and their grouping in units is challenging. Based on a detailed analysis of public documentation, existing training offers, feedback from industrial customers and training experience at the institutions of authors [7], more than 200 LOs have been identified as relevant for using the most common CMSs, core of the training offer:

1. Cartesian Coordinate Measuring Machines (CMM)
2. Articulated arm CMM
3. Laser Trackers
4. Fringe-projection Systems
5. Industrial X-ray Computed Tomography (CT)

The modularity of the ECVET system enables to explicitly organize in a modular way the competencies required, taking advantage of the commonalities in the use of different CMSs (e.g. GPS system concepts), and at the same time highlighting what needs specific attention on a given measuring device. A large portion of competencies related to CM are of general relevance and necessary whatever is the measuring technology in use. Whereas, some other learning outcomes are specific and therefore different in relation to the selected CMS.

Through this organization, different training paths are available considering the combination of transversal/cross LOs and device specific ones, and two categories have been identified as follows:

A. FUNDAMENTALS LOs: transversal/cross LOs, identical for all the CMS-related learning paths. Once acquired and assessed, they remain valid for a learner having interest in another specific CMS.
B. TECHNOLOGY SPECIFIC LOs: Related to specific aspects of the single CMS. They are faced, assessed and validated only in a particular CMS-related learning path.

Thus, the learner has the possibility to learn following different independent learning paths, facing only the CMS that is relevant for his actual work or requirement, aiming at a learning experience customized on the individual needs. Moreover, thanks to this modularity, the addition of new LOs or new learning paths (i.e. additional CMSs) will be easily possible in the future, with a continuous effective update of the learning system.

4.4. Modular structure of the learning content

Since the main target group are industrial operators, the identified scheme for the learning content structure is consistent with the recommended workflow of activities to perform verification of GPS using a CMS, linking the need (measurement aim) to the outcome (measurement result). The structure is compatible with the ISO GPS matrix model: starting from the comprehension of the technical drawing indications, the CMS operator performs a sequence of activities related to the respective columns E to G of the GPS-matrix (i.e. measurement; measurement equipment; calibration) [7,14]. This approach contributes to a proper structuring of the learning system. The content is distributed over ten sections developing along with the metrologist's workflow, summarized in the following 10-steps:

1. Identification of measurement requirements
2. Inspection planning
3. Equipment selection
4. Workpiece preparation
5. Measuring system preparation
6. Measurement process execution
7. Evaluation process
8. Measurement uncertainty
9. Documentation
10. Infrastructure and environment

Each of these sections is available for both levels and contains a number of chapters that deliver the content to the learner. Each section contains fundamentals and/or technology specific LOs, so each CMS-related learning path can be consistently structured by the 10-steps.

As an example, Table 1 summarizes the 10-steps learning structure related to the Fringe-projection Systems content. Fringe-projection is an interesting measurement technique for quality control in industry, being used as stand-alone device or more and more frequently with automation and advanced set-up (e.g. automated cells, robots) for in-line operation, enabling for automated manufacturing and measuring processes and quality assurance of freeform parts (e.g. car bodies) thanks to its unique capability to produce measurement data with high efficiency and adequate accuracy in many applications.

Table 1 : Summary of Fringe-projection System content related LOs, structured by the 10-steps workflow

	Section title	Learning aims
1	Identification of measurement requirements	To identify the measurement requirements by the technical drawing, CAD model and other information sources. To recall the GPS system elements with focus on the tolerances to be verified, including datums and datum systems, modifiers and filters indicators for form tolerances.
2	Inspection planning	To design an inspection plan for Fringe-projection Systems based on the measurement requirements and on the measurement aim (e.g. product conformity, product R&D or reverse engineering). To recall the possibilities of automations and advanced set-up to optimize the measurement activity. To recall and apply the decision rules for conformity and extrapolate the target (required) measurement uncertainty.
3	Equipment selection	To explain the working principle of a Fringe-projection System. To recall the main components of a Fringe-projection System (i.e. projector, camera, kinematic system). To recall the industrial applications of Fringe-projection Systems and the limitations in their use. To interpret the performance indicators for Fringe-projection Systems and state typical reference artefacts.
4	Workpiece preparation	To be able to clamp and locate the workpiece to optimize points acquisition, to ease further registration procedures. To be able to choose suitable reference points and to be able to apply the reference points for fringe-projection measurements. To be able to explain the need of coating and to recall the coating procedure of workpieces.
5	Measuring system preparation	To recall and explain the different options and steps for the configuration of a Fringe-projection System. To explain the qualification procedure of a Fringe-projection System. To recall the initialization procedures for automated cells and advanced set-up.
6	Measurement process execution	To explain how the acquisition procedure of a Fringe-projection System works. To understand how the registration procedure of multiple acquisition works. To describe automations related to the Fringe-projection System acquisition procedure.
7	Evaluation process	To be able to process point clouds to enable their use for the purpose of measurement. To describe the point cloud data processing operations (i.e. outliers' removal, data enhancement, data processing, filtering, features extraction and dimensional and geometrical analysis).
8	Measurement uncertainty	To interpret fringe-projection measuring results being aware of measurement uncertainty. To recall main error sources related to coordinate metrology (i.e. operator, procedure, device, workpiece, environment). To be able to reduce the device related error sources for Fringe-projection Systems.
9	Documentation	To report the fringe-projection measurement including results, explicative pictures, information about the measurement process and device configuration. To recall different types of documentation related to the specific measurement aim.
10	Infrastructure and environment	To recall the good practices for managing the measuring environment where Fringe-projection Systems are in use. To safeguard reference standards to assure their integrity and stability. To assure fringe-projection performance by periodic maintenance and verification.

As example, the seventh step is related to the data evaluation process, and it is one important element of attention in particular for Fringe-projection Systems. The related chapters cover the fundamentals of point cloud metrology. 3D measurement data generated by modern CMSs are large and dense sets of points representing the surfaces of parts (i.e. point clouds). Point clouds are the basis for the digitisation of parts into computer models, as needed for advanced product/process engineering and quality control. The learning content develops along with data general representations and computational perspectives to address dimensional and geometrical characteristics evaluation.

Consistently with the relevant ISO GPS standards, this section explains how to obtain measurement results from a digital representation of the real workpiece. It covers the geometrical characteristics definition, the operations to create GPS system features (e.g. association and construction to establish datum systems) and the final evaluation for quantifying geometrical and dimensional deviations. Although some pre-processing operations are not standardized yet, the main currently used measurement software processing techniques are introduced and illustrated (i.e. filtering, outlier removal, registration). Furthermore, Reverse Engineering (RE) processes are also illustrated to address industrial needs. The RE-related learning modules offer the learner opportunities to gain new knowledge to perform geometrical shape modelling, processing and analysis, thus enabling new competencies on geometrical methods and tools for design, product R&D and quality control.

5. Integrated framework of reference for the qualification of personnel in Coordinate Metrology

Beside the training purposes, the definition of the expected LOs is relevant for the development of a framework of reference listing the required competencies of an industrial operator using a CMS. Based on the implementation of the ECVET architecture, a European system for the identification and recognition of skills and qualifications in Coordinate Metrology is under development [15]. The ECVET structure enables the qualification framework to be consistent with the available training proposals, but to be independent from the specific one. Each LO describes what a person knows and is able to do, and therefore it is neutral to how, in which context and over what duration individuals have developed their competence [13]. Since this framework could be applied to all the training proposals and covers a specific and relevant area of competencies of great importance for the digitization of the manufacturing industry, the following benefits are expected:

- To increase the employability of learners and the confidence on qualifications related to Coordinate Metrology;
- To make training programmes comparable in terms of learning outcomes, not in terms of curriculum only;
- To allow easier identification of training needs in SMEs as well as larger industrial organizations;
- To allow the recognition of learners' specific skills and knowledge acquired in different companies and countries.

6. Conclusions

Coordinate Metrology is a subject that is relevant to a number of sectors of industry throughout the EU, the most important being the automotive industry. Currently there is a lack of coherent EU-wide provision of manufacturer-independent education and training on new measurement technologies suitable for the needs of SMEs. The on-going activities aim at offering new high quality opportunities for lifelong education and competencies recognition on relevant measuring technologies, including: CMMs, Industrial X-Ray CT, Fringe-projection Systems, and Reverse Engineering. A new learning system is under development to meet the requirements of industrial operators in terms of accessibility, content organization, actual experience, required level of competence and national language. A modular architecture enables a customized learning experience and an easy update of the learning material in the future, to maintain high level of contents and to attend continuous technological innovations.

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