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Zero-point fixture systems as a reconfiguration enabler in flexible manufacturing systems

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ABSTRACT
Today's manufacturing systems need to be able to quickly adapt to customer demands, ranging from high volumes of mass production to high volumes of mass customization. Flexible Manufacturing Systems provide a high degree of flexibility to cope with these challenges. They consist of machine tools capable of executing a wide range of machining operations while the use of pallets to reference and block the parts allows the decoupling of the setup operations from the machining centers activity. This paper presents an ontology-based framework to support the design and management of flexible manufacturing systems, aimed at integrating the various involved activities including the pallet configuration and process planning, the management policies for short-term production planning and the pallet checking to verify the correct configuration of the physical pallet.

KEYWORDS
Zero-Point pallet; Process planning; Pallet inspection; ontology-based data model

1. Introduction

The choice of the best manufacturing system architecture is deeply affected by the customer requirements in terms of demand volume, part mix heterogeneity, frequency of product modifications, level of customization, and length of the product lifecycle. Flexible Manufacturing Systems (FMSs) have demonstrated to be a proper system solution to cope with a demand characterized by at least a subset of following properties: low-mid demand volumes, mid-high variety of the part mix, short product lifecycle and mid-high customization [17]. An FMS consists of machine tools capable of executing a wide range of machining operations on workpieces that are blocked on pallets equipped with fixtures. The flexibility of an FMS may derive from the intrinsic flexibility of its elements (e.g. general purpose machining centers that can process a wide range of operations if properly tooled) and/or from enablers that allow to integrate its elements (e.g. an automatic transport system).

The use of pallets and fixtures is of key importance in an FMS because they decouple the setup operations from the machining centers activity. Indeed, the flexibility of an FMS can be fully exploited only if the pallet configuration together with the pallet management are able to quickly answer to the needs of the system every time a new part type is put into production, an already existing part type is modified or machined in a different way, or the throughput of a part type must be changed. The critical role played by fixtures and pallets is demonstrated by the attention received both at academic and industrial level. An interesting emerging trend in the fixture market is the so-called zero-point fixture system (Fig. 1.), i.e., a clamping system that can hold standard baseplates where the fixtures have been previously assembled and verified. The clamping system assures that, as the baseplates are changed, the fixtures do not need to be realigned to guarantee the correct positioning of the parts. Hence, they provide constant zero point without the need of realignment between the modular fixture and the pallet as well as a rapid and safe exchange of the fixtures.

Grounding on this technology, a modular pallet configuration can be designed, allowing an advanced management of multiple setups of the same part type or even different part types on the same pallet, together with a rapid and safe loading/unloading of the fixtures on the pallet structure.

Clearly, these fixtures are an important enabler for fast reconfiguration capability in an FMS. Indeed, since the pallet does not need a realignment upon a reconfiguration of the fixtures, it can be modified extremely fast to cope with the changes in the demand (e.g. rush orders). Moreover, the capability of assembling fixtures

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Figure 1. Modular and reconfigurable pallet.

hosting different part types on the same pallet allows an advanced optimization of the workload assignment in an FMS, even in the case of low-volumes production. Therefore, every time the production volumes change, or a new part type must be put in production, or the fixture of a part type must be modified to match a new production plan or a modification of its geometry, the pallets in the system can be rapidly reconfigured to match the new production requirements, without the need of halting the system to operate a setup.

This paper presents an ontology-based framework to support the design and management of flexible manufacturing systems where the pallets are equipped with a *zero-point fixture system*. This framework aims at integrating the various involved activities including the pallet configuration and process planning, the short-term production planning and the pallet checking to verify the correct configuration of the physical pallet. The paper will first introduce the framework and then delve into the specific activities.

2. The Ontology-based Framework

The ontology-based framework consists of an adaptation and extension of the general Virtual Factory Framework [11], while focusing on the design and management of pallet-equipped flexible production systems. Specifically, the framework aims at:

- Supporting the effective integration of the virtual representation of various factory components, such as products, operations, pallet, fixture, and manufacturing systems.
- Facilitating the management of information related to manufacturing performance, including monitoring and diagnosing errors in the workpiece setup.
- Supporting the exploitation of the mathematical models for pallet configuration to increase the efficiency of the production system.
- Facilitating the parallelization of tasks and management of distributed tools/information.

In order to achieve these goals, the following requirements must be met by a software platform that implements the concepts of the ontology-based framework:

- Development of a common language supporting the definition of machining operations, workpiece setups, modular pallets and their configurations.
- Integration of new and existing tools within the software platform to support the main involved activities.
- Development of a knowledge repository and dedicated libraries to properly address the industrial cases.

Each of the activities described in the following paragraphs will be supported by tailored software tools that can interoperate thanks to the adoption of a common data model. Such data model is formalized as an OWL ontology [19] to exploit Semantic Web potentiality in terms of formal semantic characterization, flexibility, extendibility and support for re-use and integration of different knowledge sources. In accordance with the strategy of knowledge re-use, the data model stems from previous results in the literature and represents an enhancement of the Virtual Factory Data Model (VFDM) by Terkaj et al. [15]. The VFDM aimed at formalizing the concepts of building, product, process and resource while taking into consideration geometric, physical and technological properties of the factory that are required to support its planning processes. The VFDM was based mainly on the Industry Foundation Classes (IFC) standard [4] by converting its EXPRESS schema specification into an OWL ontology (named ifcOWL) [12] and then adding specializations for the manufacturing domain. However, the VFDM did not consider the fine grained aspects of pallet configuration and, therefore, a proper extension was needed to satisfy the semantic representation of key concepts that are used by the methodologies presented in the following sections:

- the workpiece and its features, operations, and setup (see Section 3);
- the pallet and its fixture elements (see Section 3);
- the performance of a flexible production system (see Section 4);
- the visual inspection system (see Section 5);
- the monitoring data regarding the output of the pallet check activity (see Section 5).

The standard STEP-NC [9], available as an EXPRESS schema, was chosen to represent the workpiece and its operation; the EXPRESS schema was automatically converted to an OWL ontology [12] and then integrated with ifcOWL. The concept of pallet was introduced in a domain ontology on Discrete Manufacturing that extends the ifcOWL, whereas the classification of the fixture elements is based on the FixOnt ontology by Gmeiner and Shea [8], that in turn was partially derived from the FIXON ontology by Ameri and Summers [2]. A fragment of the FixOnt ontology was integrated in the scope of ifcOWL as well.

The performance of a flexible production system is characterized by specializing the pattern proposed by Terkaj et al. [16] that was already integrated in the ifcOWL. This pattern allows characterizing the evolution of the objects in the factory by defining the object history in terms of time-related properties specifying the current placement, state, visual appearance, etc., of the object itself.

Finally, a domain ontology specializing the ifcOWL was designed to formalize the visual inspection setup, paying particular attention to the case of automatic inspection supported by a laser scanning system that consists of a camera and a laser source. The formalization of the output of the pallet check activity has been addressed by further enriching the domain ontology on Discrete Manufacturing; the outcome of the pallet check is added to the history of the pallet every time that the visual inspection is performed.

3. Process planning and pallet configuration

The process planning [18] activity for part types mounted on pallets is decomposed into the four activities: *workpiece analysis*, *setup planning*, *pallet configuration* and *machinability analysis*. Hereafter, a short description of these stages is presented. More details are provided in [3].

The *workpiece analysis* is based on the STEP-NC standard [9] and its definition of machining feature, machining operation and machining workingstep (MWS), that are respectively the description of a workpiece machined region in terms of its geometrical properties, the technological information and manufacturing strategy for the machining of a feature and the associations between a feature and an operation. The goal is to identify all the MWSs that are necessary for the complete machining of the workpiece. Specifically, the planner analyses the 3D design of the workpiece in order to extract the workpiece geometrical information, i.e. the machining features, and the bounding box, accordingly to the STEP-NC standard. Each feature is associated to one or more technological operations (machining operations) which, together with the machining feature, define the machining workingsteps and the production process. A tool access direction (TAD), i.e. the tool working direction for machining a feature, is univocally associated to each workingstep. A CAM software tool is used for setting these data, which are then translated from the proprietary format of the CAM to the STEP-NC standard. The planner identifies, for each feature, the reference system, the feature type (e.g. slot, planar face, round hole) and the geometric characteristics (e.g. depth, radius, course of travel) and generates a STEP-NC machining feature. Subsequently, one or more STEP-NC machining operations are defined for each generated feature in terms of machining strategy and cutting parameters, e.g. spindle speed and feed rate. A STEP-NC machining workingstep is generated for each feature-operation association.

The *setup planning* problem consists in determining the number of orientations the workpiece must assume in the 3D space to be completely machined. Each change in the orientation (setup) of the workpiece requires an un-mounting and re-mounting of the workpieces on the fixture/pallet, which involves a certain time utilization and may compromise the machining precision and manufacturing quality.

The *pallet configuration* activity is meant to decide the number, disposition (pattern) and the mix of pieces to be clamped on the fixture system of the pallet as well as part positions and orientations. However, given the number of the machine tool axes, the accessibility of the cutting tool to workpiece MWSs depends on both setups and pattern.

The *machinability analysis* consists in the verification of the pallet machinability on a set of predefined machine tools for which the pallet configuration has not been originally designed.

Herein, the focus is on the generation of alternative pallet configurations (Fig. 2.) when the setups are given, thus responding to the industrial need of rapidly reconfiguring the pallet according to the demand as well as the fixture and machine tool availability. Specifically, we propose a methodology able to quickly provide a pallet configuration given a set of workpieces, workpieces' setups and a pallet and to asses to pallet machinability on a defined set of machine tools.

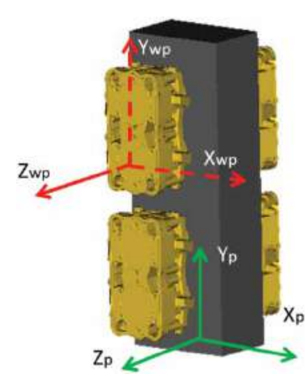

Figure 2. Example of a pallet configuration.

In the setup accessibility, we analyze possible changes in the visibility of the tool access directions (TADs) of the setup on the basis of the position of the workpiece in the fixturing face, the position of the fixturing face in the pallet (Fig. 3.), the pattern of the workpieces on the fixturing face and the patterns of the adjacent fixturing faces. Each setup is characterized by an orientation of the workpiece in the fixturing system and a set of reachable MWS (MWS whose tool access direction results to be free once the workpiece is blocked in the setup orientation/position). The computation of the accessibility is based on the kinematics study of the machine tool on which the pallet is going to be machined.

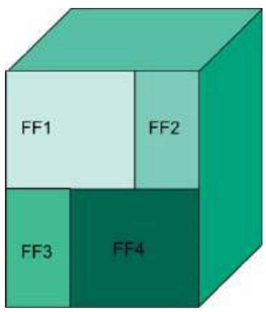

Figure 3. Example of a pallet fixturing faces (FFs).

The results provided by the setup accessibility analysis are exploited during the pallet configuration in order to grant the setup accessibility. Taking into consideration the characteristics of the pallet structures that can differ in terms of dimensions, number of fixturable areas and their decomposition in fixturing faces. The devised pallet configuration mathematical model provides optimal solutions in terms of number of finished workpieces, while the pallet results to be saturated and balanced. The adopted objective function is

$$\max \sum_{w} \frac{\sum_{s,v,p} R_{w,s,v,p} P_p^{row} P_p^{column}}{\sum_s WS_{w,s}}$$

where w represents the different part types, s the workpiece setups, v the fixturing faces, p the patterns, R is a boolean matrix equal to 1 if the sub-fixturing face v mounts pattern of workpiece w in setup s, WS is a boolean matrix equal to 1 if setup s refers to the workpiece w, P is the pattern described in terms of workpiece rows and columns. This function is then combined with other constraints to grant the accessibility and balancing while allowing the possibility to obtain alternative solutions [13].

The machinability check identifies, among the machine tools available in the shop floor, those that can be used to machine the pallet. Since no specific information of the machining operations is known (e.g. torque, required power, deriving roughness), the check is limited to the dimensions of the configured pallet in relation to the working cube of the considered machine tools. Additionally, an estimation of the machining time is computed. Since during process planning the information on the configuration of the system machine tools is unknown, machining times are evaluated under the hypothesis that the pallet is processed on a single machine such that all the mounted workpieces will be completely machined. In details, a MWS linear sequence is generated minimizing firstly tool changes, secondly rotation axes and finally movements among workpieces. Once a feasible sequence is generated, the times necessary to move between every couple of successive MWSs are estimated. Pallet machining time is the sum of estimated rapid times and MWS productive times, while throughput is evaluated on the basis of pallet machining time and the number of finished workpiece per pallet.

Further hypothesis on which the devised approach stands on are: (i) pallet shape is limited to square and cubic shape (tombstone); (ii) each pallet presents a given number of fixturing faces, i.e. the physical faces on which parts can be mounted or a rectangular sub-region of the physical faces; (iii) each fixturing face is characterized by a workpiece pattern, i.e. the number of rows and columns of workpieces; (iv) only four-axis machine tools are considered.

4. Management policies for short-term production planning

The traditional concept for pallet configuration grounds on a pallet hosting a specific kind of fixture and, hence, a specific set of parts in a given setup. Modular fixtures have pushed the capability of reusing pieces of equipment when the part types to machine change over time, but the assembling of modular fixtures onto a pallet can require a significant amount of time. Moreover, the need of checking the correct assembly of the fixture to avoid the misalignment of the part leads to additional time-consuming verifications. Due to this, modular fixture reconfiguration has never been considered from an operational point of view. The machine loading problem in an FMS is defined as the assignment of the machining operation to the available machines, taking into consideration the constraints imposed by the limited availability of tools, tool slots in the machining centers as well as their time availability in the considered time horizon. In addition, different pallet configurations can be assigned to the different time periods, thus adjusting the workload of the machines and the routing of the pallets as the demand changes.

To assess the performance of the alternative loading policies and pallets reconfigurations, a queuing model of an FMS has been adopted. A probabilistic aggregation technique has been also used to model the FMS as a single-class queuing network, thus allowing the capability of using non-deterministic processing times to approximate the behavior of different classes of pallets in the system [5]. This entails the possibility of using simple algorithm to provide an estimation of the performance of the system. One of the most used is the Mean Value Analysis [14]. Grounding on these tools, a higher-level approach is defined to look for the best sequence of reconfigurations taking into consideration the possible evolution of the production problem and the associate occurrence probability, providing a support to the robust management of the FMS [1].

5. The pallet measurement and check

Augmenting the number of changes in the pallet configuration is likely to increase the source of errors within the manufacturing system. This requires a system devoted to the check and verification of the physical pallet. The technology available today offers low price vision systems (e.g. laser scanner) that can be employed to verify if the fixtures and parts are correctly mounted on the pallet, the number of mounted workpieces and their exact position and orientation.

Among the available vision systems technologies, laser scanner was selected for pallet digitalization due to its capability to work in industrial environments characterizing the FMSs. An extended experimental campaign was conducted in order to evaluate the technology performance with reference to different surface conditions and materials. Results suggest that only completely mirror surfaces cannot be digitized, while dirty, polished and hot surfaces do not represent a problem.

The validation process of the physical pallet requires its measurement, digitalization and comparison with a reference model. However, data acquired with the scanner (physical pallet) and data extracted from CAD (reference model) are defined in different reference systems. According to the state of the art, the 3D rigid body transformation that aligns the two data sets is generally hand-made and/or only partially automated. In this work, a self-calibration procedure was implemented on the basis of the patent entitled "System and Method for three-dimensional objects reconstruction" (application number TO2010A000638 date 23/07/2010) [6]. This procedure allows a native self-alignment between the data coming from the scanner and the CAD retro-projected on the CAD reference system.

The acquisition procedure requires an artifact with well-known geometry so that a set of significant points can be identified and used. Specifically, two correspondent sets of points can be defined on the artifact: $\mathrm{Pb_i}$ $\mathrm{i} \in \{1..\mathrm{NP}\}$ remarkable points in the scanner coordinate frame; $\mathrm{Ps_i}$ $\mathrm{i} \in \{1..\mathrm{NP}\}$ remarkable points in the CAD model coordinate frame.

The relationship between the two sets of points is as follows:

$$Pb_i = \overline{R} \bullet Ps_i + \overline{T} + \overline{V_i}$$

where $\overline{R}$ is orthonormal rotation matrix, $\overline{T}$ is a translation vector and $\overline{V_i}$ is the "noise" vector. The optimal solution for $[\overline{R},\overline{T}]$ transformation allows the mapping of point set $\{\mathrm{Ps_i}\}$ onto $\{Pb_i\}$ and the scanning point back-projection onto the model coordinate system. The applied solution requires a least squares error minimization criterion given by:

$$\sum{}^2 = \sum \|Pb_i - \overline{R \bullet Ps_i} - \overline{T}\|^2$$

The verification of the real pallet configuration with respect to the designed one requires the comparison of the acquired point cloud with the stored ideal configuration, which specifies the correct positions and shapes of all the elements mounted on the pallet. Therefore, the comparison consists in the matching problem of the acquired point cloud to the reference nominal geometry [10]. To avoid false mismatches between the acquired and the ideal geometry of the configured pallet, it is necessary that the ideal representation contain only the model part that can be actually acquired by the laser scanner. Thus, a simulation of the laser scanner behavior is performed on the configured ideal representation and corresponds to the detection of all the shape elements, which are simultaneously visible by the camera and the laser. Since polygonal meshes can be derived from any CAD representation, and parts at the intermediate working steps are not available in native CAD format, polygonal meshes have been selected as reference representation of the ideal pallet configuration.

In this work, for the use case identified we adopted a rotational laser scanner composed by a rotational laser beam and a camera, whose configuration is illustrated in Fig. 4.

The mesh elements to be compared with the acquired point cloud are obtained by computing the visible elements from the laser on the part of the mesh visible from the camera point of view. This corresponds to the specification of the viewing volume, i.e. the region of the space in the modelled world that may appear on the screen from a specific point of view. The view volumes depend on the kind of projection considered parallel or perspective. In the case of a parallel projection, the view volume

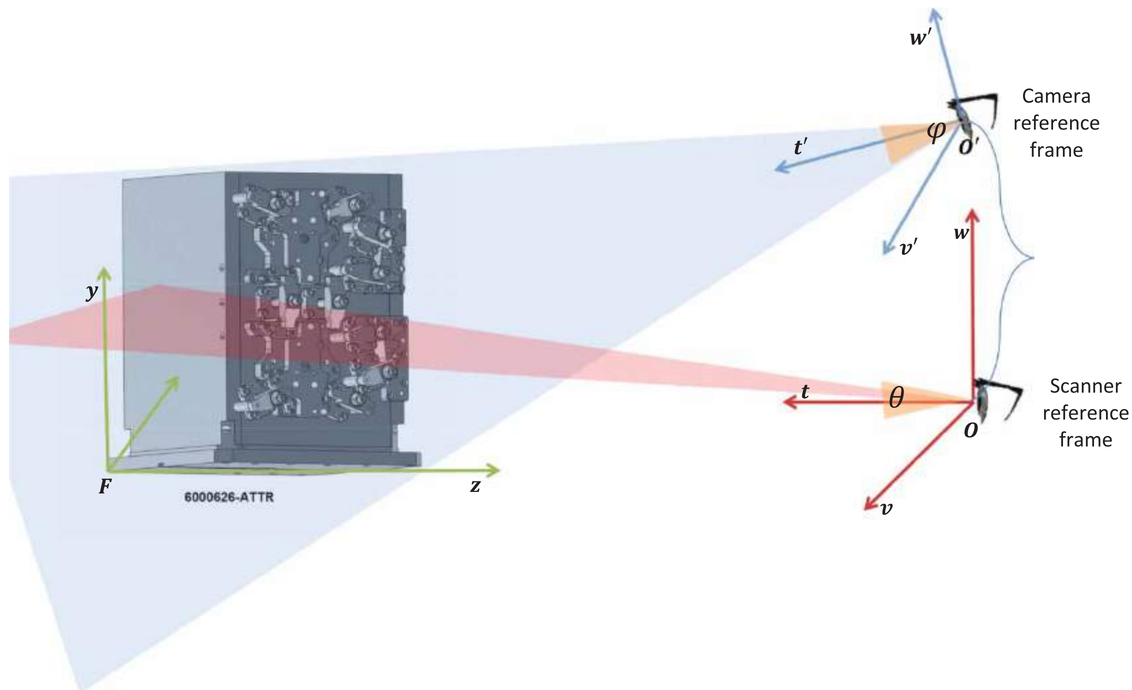

Figure 4. Simulated Pallet scan process.

is a rectangular parallelepiped, i.e. a box, while in the case of a perspective projection the view volume is a frustum. Since we are considering a rotational laser scanner with fixed position, a viewing frustum is needed. The point of view corresponds to the laser scanner camera position first, and then to laser position. In the first case, the planes of the viewing frustum are obtained considering the optical cone horizontal and vertical angles; similarly for the laser we consider the vertical and horizontal fan angles.

Once the view volumes are defined, we are able to extract the visible cells of a mesh and to get two meshes: the mesh M_C formed by the visible cells from the camera and the mesh M_{LS} formed by the visible cells from the laser. The intersection $M_C \cap M_{LS}$ includes the elements visible by the laser scanner.

Considering the efficiency requirement for the pallet check, it has been decided to exclude from the pallet inspection those elements that might produce mistakes, which from experience are those triangles almost parallel to the camera/laser ray.

Once the CAD point cloud is available, the comparison is performed. The procedure is based on the evaluation of the minimum square error as follows:

- for each point acquired, the three closest CAD points are identified;
- for each group of three points, the plane equation is evaluated;
- the distance between reference acquired points and planes is computed;
- the minimum square error based on all distances extracted is calculated.

Based on the information on the original part to which CAD points belong to, it is then possible to get the indication on the specific workpiece and/or fixture not conforming to the designed configuration.

6. Industrial application

The proposed approach has been tested in an industrial environment provided by an Italian manufacturer of tools for electrical and railway applications. The plant is equipped with two FMS systems with four parallel machines each. Due to the wide range of parts to be machined, the available pallets are frequently reconfigured to address the varying product mix.

A hydraulic press-head consisting of two components has been considered for the analysis. Both components require three setups to be machined on a single pallet. The pallet type consists of a 4-sided column fixture, but only two faces are actually used. Each face of the pallet hosts six workpieces (three of one component and three of the other), each of them placed according to a different setup (Fig. 5.). The choice of configuring a single pallet and mounting workpieces only on two of the four available faces is motivated by the need of machining a wide range of part types in small volumes at the same time, thus needing the machines to share their working time and work on small lots to avoid an increase of the inventory levels. Grounding on these considerations, the use of zero-point fixture systems has been investigated to assemble the pallet's faces differently, aiming at matching the fluctuations of the production volumes.

The pallet configuration approach presented in Section 3 has been applied to obtain pallet configurations with additional parts hosted on the available faces of the pallet. The system produced 74 alternative solutions with different part type balance and positions, including the ones used by the company (Fig. 5(b).). All the provided solutions were feasible granting the required access directions and fitting the working cubes of the machine tools used for their verification, composed by MCM Clock 600, NCCORREA Magna 3000 and THC Extreme 800.

The impact of the new pallet configurations on the FMS has been assessed in terms of machine utilization, flow time and tools' requirements, grounding on the performance evaluation and management approaches reported in Section 4. Specifically, the introduction of the pallets based on the zero-point technology was assessed to be able to reduce by 25% the total number of pallets needed in the production system, while guaranteeing the satisfaction of the same production volumes. Moreover,

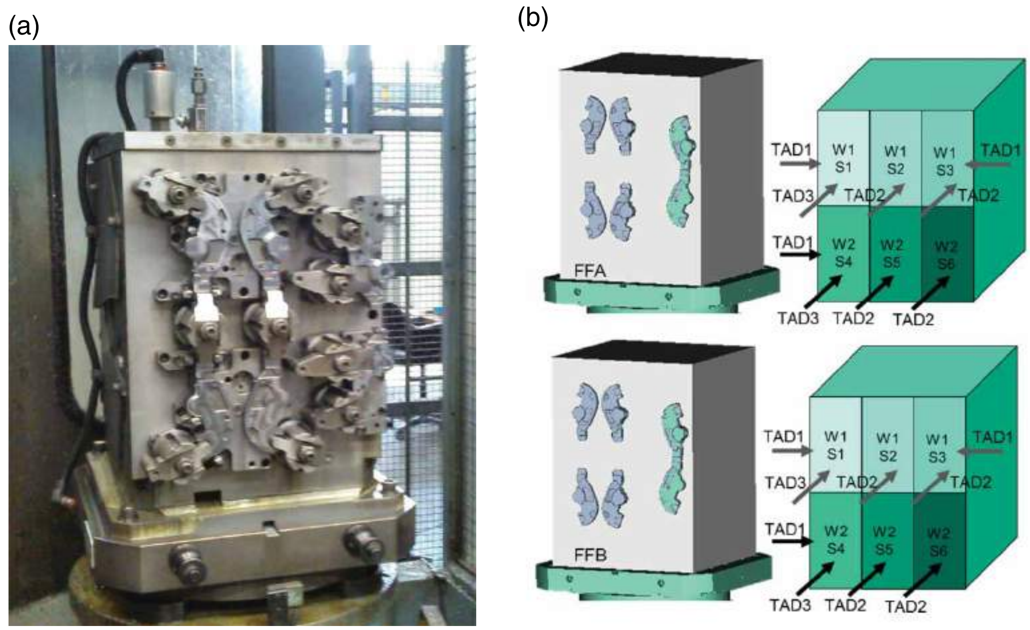

Figure 5. Pallet used for the industrial application (a) and two of the setups obtained from the pallet design system (b) where TAD_i = tool access direction for workpiece of type i, W_i = workpiece of type i, S_i. = setup.

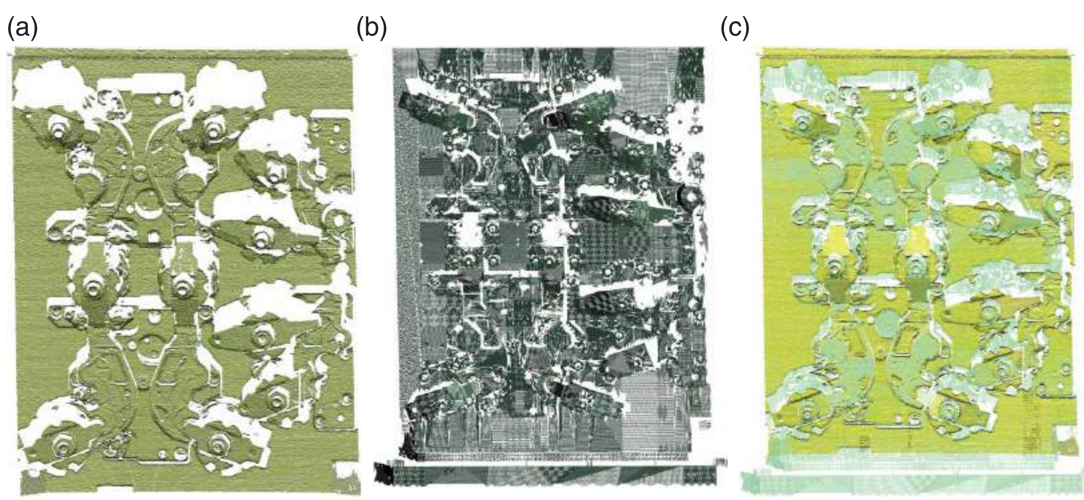

Figure 6. Acquired pallet point set (a), point set resulting from the visible point computation on the CAD configured pallet representation (b), overlapping of the above two point sets (c).

the reduced number of pallets also allowed a reduction of the idle time of the machining centers. Nevertheless, the investment in the new pieces of equipment for zero-point fixture systems is significant thus justifying the adoption of this technology only for system producing a high number of part types in very small lots.

The pallet measurement and check approach described in Section 5 has been tested on an existing pallet configuration (Fig. 5(a).) and has proved to support the identification of problems in the mounted pallet. Fig. 6 shows the point sets obtained from the laser scanner acquisition of the real pallet (Fig. 6(a).) and from the ideal pallet configuration (Fig. 6(b).) and their alignment (Fig. 6(c).). The results obtained by comparing the ideal configuration with three different acquired ones are reported in Tab. 1.

Table 1. Pallet check results.

Pallet	Error max [mm]	Error mean [mm]	Error min [mm]
No mounting error	0.2837	0.0863	0.0254
With gripping error	1.3659	0.6347	0.0272
With element error	42.9871	10.3657	0.0231

The different software tools implementing the various methodologies were able to interoperate thanks to the adopted ontology-based framework [7]. This means that also the industrial case was formalized by instantiating the classes of the data model presented in Section 2. In particular, aiming at enhancing the re-use of data, the Semantic Web approach allowed to instantiate the following linked ontology modules:

- *Workpiece library*, containing the definition of the workpieces and their features and operations;
- *Fixture library*, providing which are the fixture elements that can be assembled to obtain a configured pallet;
- *Machine library* defining the machine tools available in the production system;
- *Pallet Configuration library*, where the output of the pallet configuration activity, based on the content of the previous libraries, is stored;
- *Factory project* that imports all the other libraries and provide the virtual representation of the actual production system, together with the scheduled production plans and the results of monitoring activities.

7. Conclusions

The benefits of zero-point modular fixtures can be assessed and fully exploited only if relevant innovations are introduced during both the design and management of flexible manufacturing systems. These innovations ask for an integrated software platform that supports semi-automatic configuration and planning activities.

The approach presented in this paper wants to provide a first step in this direction. It has been tested on an industrial case to verify the applicability of the proposed solutions to assess the benefits in relation to the total number of pallets in the system and the utilization of the production resources. Such industrial case has been designed with the contribution of companies acting as machine tool builder, producer of modular fixture systems and end-user of flexible manufacturing systems.

Future activities include further exploitation of the information derived from the functional and geometric characteristics of the various elements for a deeper analysis of the identified errors in order to provide human operators with more precise information on the source of error (e.g. wrong part or not mounted part).

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