Title:
Zero-point Fixture System as a Reconfiguration Enabler in Flexible Manufacturing Systems

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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 (FMS) have demonstrated to be a proper system solution to cope with a demand characterized by at least a subset of the following properties: low-mid demand volumes, mid-high variety of the part mix, short product lifecycle, mid-high customization [10]. 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 center activity. Indeed, the flexibility of an FMS can be fully exploited only if the pallet configuration and management is able to quickly answer to the needs of the system every time a new part type must be put into production, or an already existing part type is modified or must be machined in a different way, or the throughput of a part type must be changed. The critical role played by the fixture and pallets is demonstrated by the attention received both at academic and industrial level. Indeed, an interesting emerging trend in the fixture market is the so-called *zero-point fixture system* (Fig. 1.) consisting of a two- of four-sided structure (tombstone) with one or more clamping systems. The clamping system can hold standard baseplates where the fixture component has been previously mounted. The clamping system assures that, as the baseplates are changed, the fixtures do not need to be realigned for the correct positioning of the parts. The advantages provided by the *zero-point fixture system* consist in:

- having a constant *zero point* without the need of realignment between the modular fixture and the pallet.
- easy management of a pallet characterized by multiple setups of the same part type or even different part types.
- rapid and safe loading/unloading of the fixtures on the pallet structure.

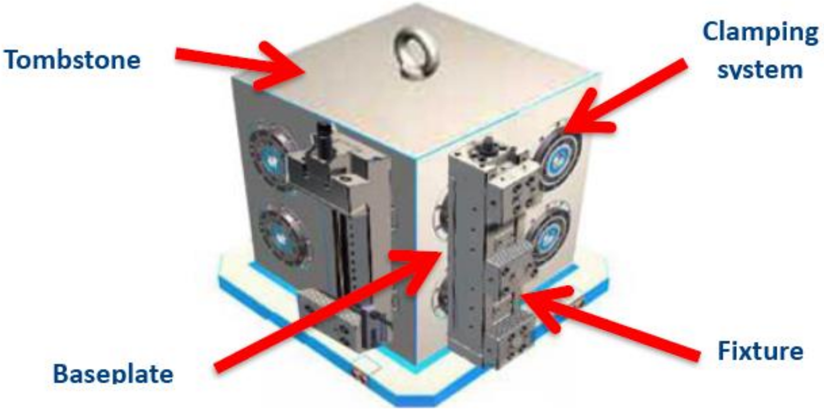

Fig. 1: Modular and reconfigurable pallet.

Clearly, these fixtures are an important enabler for a fast reconfiguration in a FMS. Indeed, the pallet does not need a realignment of upon a reconfiguration of the fixtures and it can be modified extremely quickly to cope with the changes in the demand (e.g. rush orders). Moreover, assembling fixtures capable to host different part types on the same pallet allow optimizing the loading of workpieces on a pallet even in the case of low-volume demand. 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 the geometry of the part, 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 management policies for 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.

The Ontology-based Framework:

The ontology-based framework consists of an adaptation and extension of the general Virtual Factory Framework [5] 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 the product, 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 modular pallet, its configuration, definition of operation plan and workpiece setup.
- Integration of new and already existing tools within the software platform to support the main involved activities.

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- Development of a knowledge repository/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 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. [8]. 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 [2] by converting its EXPRESS schema specification into an OWL ontology (named ifcOWL) 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 the following concepts:

- the workpiece and its features, operations, and setup
- the pallet and its fixture elements
- the laser-scanning system
- the monitoring data regarding the output of the pallet check activity
- the performance of flexible production system

The standard STEP-NC [12], available as an EXPRESS schema, was chosen to represent the workpiece and its operation; the EXPRESS schema was automatically converted to an OWL ontology 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 [4]. A fragment of the FixOnt ontology was integrated in the scope of ifcOWL as well. A domain ontology specializing the ifcOWL was designed to describe a laser scanning system and its components, i.e. the camera and the laser source. The formalization of the output of the pallet check activity is addressed by further enriching the domain ontology on Discrete Manufacturing by characterizing the history of the pallet. The performance of a flexible production system is characterized by specializing the pattern proposed by Terkaj and Urgo [9] that was already integrated in the ifcOWL.

Pallet Configuration and Process Planning:

The process planning [11] activity for part types mounted on pallets is decomposed into the workpiece analysis, setup planning, pallet configuration and pallet program generation. The workpiece analysis is based on the STEP-NC standard [12] and its definition of machining feature, machining operation and machining working step (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 association between a feature and an operation. The goal is to identify all the MWSs that are necessary for the complete machining of the workpiece.

The setup planning 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 un-mounting and re-mounting of the workpieces on the fixture/pallet, which involves 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, once selected the number of the machine tool axes, the accessibility of the cutting tool to workpiece MWSs depends both on setups and pattern.

Herein, the focus is on the generation of alternative pallet configurations when the setups are given, thus responding to the industrial need of rapidly reconfiguring the pallet according to the demand and 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 assess the pallet machinability on a defined set of machine tools. The pallet configuration is optimal in terms of number of finished workpieces, saturation and balancing of the pallet. The setup accessibility is automatically defined and granted by the provided alternative pallet configurations.

Management Policies:

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 has 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 a 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 [3]. This entails the possibility of using simple algorithms to provide an estimation of the performance of the system. One of the most used is the Mean Value Analysis [7]. Grounding on these tools, a higher-level approach can be 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].

The Pallet Check:

An increase in the number of changes in the pallet configuration is likely to increase the source of errors within the manufacturing system. For this reason, a system devoted to the check and verification of the physical pallet is needed. The technology available today offers the use of 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.

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 [6]. Since the correctness of the mounted pallet at each setup has to be identified, the approach has to deal with different types of geometrical representation. Usually, only the shape model of the final product is produced in CAD systems (e.g. in terms of NURBS and canonical surfaces) and shape models of the product at intermediate steps can be achieved by manufacturing process simulations in terms of polygonal models. Although such approximate models are not suitable for many tasks in CAD/CAM systems, polygonal meshes or point clouds can be derived from any CAD representation. Therefore, polygonal meshes have been selected as reference representation of the ideal pallet configuration. To avoid false mismatches between the acquired and the ideal geometry of the configured pallet, it is necessary that the ideal representation contains only the model part that can be actually acquired by the laser scanner. Thus, a simulation of the laser scanner behavior is performed and corresponds to the detection of all the mesh elements which are simultaneously visible by the camera and the laser. These mesh elements are obtained by computing the visible elements from the laser on the set of the mesh visible from the camera point of view. This corresponds to the specification of the viewing frustum used in 3D computer graphics, i.e. the region of the space in the modelled world that may appear on the screen from a specific point of view. The point of view of the viewing frustum corresponds to the camera position first, and then to laser position.

Once the CAD point cloud is available, the comparison of the mesh patches of meaningful zones, a priori specified by the user, and the scanned cloud is performed. The procedure is based on the evaluation for each zone of the minimum square error as follows: (i) for each point acquired, the three closest CAD points are identified; (ii) for each group of three points, the plane equation is evaluated; (iii) the distance between reference acquired points and planes is computed; (iv) the minimum square error based on all distances extracted is calculated.

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 has been tested on an industrial case to evaluate the impact of the proposed solutions. Such industrial case is designed with the contribution of companies acting as machine tool builder, producer of modular fixture systems and end-user of flexible manufacturing systems.

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