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A novel comparative design procedure for reconfigurable assembly fixtures

Ilker Erdem[a,*], Christoffer Levandowski[a], Cecilia Berlin[a], Henrik Kihlman[b], Johan Stahre[a]

[a] Department of Product and Production Systems, Chalmers University of Technology, Gothenburg, Sweden
[b] Prodtex AB, Gothenburg, Sweden

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ABSTRACT

While market requirements demand that manufacturing systems increase their responsiveness, assembly fixtures remain limited in corresponding to the same demand. Fixture designers as practitioners are left without guidance to design reconfigurable fixtures. This study proposes a comparative design procedure for reconfigurable assembly fixtures that can adapt to manufacturing system characteristics by using efficiency metrics. In this study, a theoretical analysis based on manufacturing systems is presented to establish efficiency metrics. Later, these metrics are utilized in a design procedure that offers guidance and determines the efficiency of fixtures in conceptual and detailed design stages. Finally, an experimental verification is presented.

Introduction

Manufacturing companies of today operate on a highly competitive market that is characterized by increasingly diverging customer requirements. Throughout modern manufacturing history, a succession of manufacturing paradigms have sought to solve the different challenges to meet market demands. The challenge to provide customized products was initially met by the introduction of flexibility — later to be known as Flexible Manufacturing Systems (FMS) [1]. As a result of seeking flexibility, fixtures shifted from a dedicated to a modular nature where a fixture's geometry was divided into simple sub-geometries that could be mechanically rebuilt to fit another workpiece and process [2]. However, the increased flexibility affected the performance of manufacturing systems in terms of cost and quality. In return, the operations to technologies utilized in manufacturing systems sought optimization of flexibility. This led to the birth of the concepts of agility and reconfigurability — later to be known as Agile Manufacturing Systems (AMS) and Reconfigurable Manufacturing Systems (RMS) respectively [3]. Consequently, fixtures were developed in a form where reconfigurability was met by a built-in flexibility by adjusting the internal parameters such as the length of an actuator in a kinematic structure [4]. Furthermore, the features such as adaptive (also known as active fixturing) were integrated to increase the performance of flexible fixtures by means of sensor-integrated fixture elements [5].

Today, customers are even expecting more tailored products, resulting in a large variety of product variants that need to be developed and manufactured [6]. This requires a manufacturing system that can manage the product variety, which in return leads to a need for fixtures that are able to abide by the same principle to support responsiveness [7,8] to new customer requirements, while maintaining high quality across the product range. As a part of manufacturing system development, the fixtures need to be designed to meet performance requirements and envelop the product variety. This places a responsibility on fixture designers to meet criteria and variety challenges while addressing the responsivity demand.

Stemming from the rapid development and deployment need, several systematic processes for fixture design have been developed. Initially, Trappey and Liu [9] described three major steps in fixture design as configuration, assembly and verification. Later, Rong and Bai [10] proposed a procedure in three steps: setup, fixture planning and detailed design. Bi and Zhang [11] also developed a design process where a fixture design was carried out in steps of problem description, analysis, synthesis and verification. Mervyn et al. [12] divided the fixture design process into *conceptual* and *detailed design* steps where their study offered a conceptual analysis based on cost and time. With the introduction of Computer-Aided Process Planning (CAPP), these fixture design processes were complemented with computerized automation — which was later coined as Computer-Aided Fixture Design (CAFD)

* Corresponding author.
E-mail address: ilker.erdem@chalmers.se (I. Erdem).

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Nomenclature

- W_c The weight efficiency metric of a reconfigurable fixture
- W_a The achieved weight of a reconfigurable fixture
- W_T The weight limit specified for a prospective fixture
- V_c The physical volume efficiency metric of a reconfigurable fixture
- V_a The achieved volume of a reconfigurable fixture
- V_T The volume limit specified for a prospective fixture
- Rc_c The reconfigurability efficiency metric of a reconfigurable fixture
- P_a The number of satisfied products in a product family
- P_T The number of products in the target product family
- Ru_c The reusability efficiency metric of a reconfigurable fixture
- Pr_a The number of satisfied processes
- Pr_T The number of target processes
- C_c The cost efficiency metric of a reconfigurable fixture
- C_f The capital cost of a reconfigurable fixture
- C_e The set-up cost of external equipment
- C_s The software cost of a reconfigurable fixture
- C_{wh} The cost of software development per work-hour
- T_A The allocated time for software development in hours
- C_T The cost threshold specified for a reconfigurable fixture
- T_c The time efficiency metric of a reconfigurable fixture during set-up
- T_s The time spent for a set-up operation
- T_t The time limit designated for a set-up operation
- D_c The diagnosability metric of a reconfigurable fixture
- Re_c The reliability efficiency metric of a reconfigurable fixture
- Re_i The reliability of each standard component
- Re_t The reliability threshold for a system of standard components
- M_c The modularity efficiency metric of a reconfigurable fixture
- N_s The number of standard components in a reconfigurable fixture
- N_T The total number of components in a reconfigurable fixture
- Co_c The convertibility metric of a reconfigurable fixture
- ε_o The overall efficiency of a reconfigurable fixture
- ε_i Single efficiency metric
- w_i The individual weight designated for a single efficiency metric

[13]. Even though these fixture design processes utilize various analysis techniques to apply requirements on the fixture design and find the most feasible option, the majority of the research and application efforts are limited to the use of simple geometries in modular fixtures [14].

When the span of fixture design processes is extended to reconfigurable fixtures, the researchers in literature tend to follow a certain reasoning where the design procedure for reconfigurable fixtures is mainly conducted from mechanical, control and software perspectives. For example, Yu et al. [15] and Millar and Kihlman [16] demonstrated the development of kinematic structures to create a custom reconfigurable fixturing solution. Furthermore, Zhang et al. [17] and Li et al. [18] illustrated the control system formulation through a number of actuation and process requirements such as adaptive control and smart assembly. Moreover, a formulation based on the control and process parameters can also be conducted to define the capabilities of fixture controller and software. For example, Erdem et al. [19] and Soetebier et al. [20] defined the software architecture in terms of function families, and demonstrated the integration with a graphical user interface.

Although the fixture design solutions offered by literature show versatility, the aforementioned reasoning does not offer a complete and reliable insight into reconfigurable fixture design and its long-term financial impact — in particular, fixture designers as practitioners are left without concrete guidance in how to design reconfigurable fixtures with pertinent parameters in mind. Furthermore, the lack of formal procedure and computerized support in the development of reconfigurable fixtures creates ambiguity in design trade-offs [21–23]. Therefore, there is a need to develop an adapted design procedure that encapsulates the design complexity of reconfigurable fixtures and offers fixture designers a more comprehensive verification perspective.

The objective of this paper is, therefore, to propose a comparative design and evaluation procedure for reconfigurable fixtures that unifies mechanical, control and software design perspectives. The focus of this procedure is limited to conceptual and detailed design/verification of kinematic units whereas preceding planning stages are assumed to be established. Finally, the structure of this paper is as follows: in Section "Research approach", the research approach is presented. In Section "Theoretical framework", a theoretical framework is given. Section "The proposed procedure" focuses on the synthesis and development of the proposed procedure whereas Section "Experimental study" offers the results of an empirical study to exemplify the use of the proposed procedure.

Research approach

In order to realize the design procedure, an inductive approach is formulated around two research questions. Firstly, this paper aims to determine which functions and constraints are pertinent in order to develop a reconfigurable fixture. The following research question is formulated: *What parameters can be used as means of input to design and verification aspects of reconfigurable fixtures?* Secondly, the utilization of these parameters in a systematic manner plays an important role in achieving this paper's objective. Hence, the second question is formulated: *How can these parameters be integrated and utilized systematically to design reconfigurable fixtures?* The first question is answered with a review of the available literature on reconfigurable fixture design, where the expected outcome is to establish a set of theoretically motivated design parameters. To answer the second question, design and comparative verification procedure is synthesized in conjunction with the conversion of the design parameters into design functions and constraints. Finally, a lab-based experiment is conducted to exemplify and verify the proposed design procedure.

Theoretical framework

The underlying theory of the proposed fixture design procedure will be presented in this section. Initially, the established range of fixture design theory will be presented to identify design characteristics and fundamental fixturing parameters widely accepted in literature. Later, the second section will identify the evaluation of fixturing technologies from a manufacturing paradigm perspective.