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Automated design evolution for parametric design applied on computer-aided welding fixture designs

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Abstract

Design engineers are required to deliver design solutions by a fixed deadline. Increasing demand for shortening lead time limits the exploratory and creative freedom of the designer. This paper proposes an automated design system that can substitute part of the repetitive and standardized tasks in the design process, increasing efficiency and shifting the design engineer's efforts to creative work. Computer Aided Welding Fixture Design is an engineering domain increasingly being pressed for shortening lead time. Welding Fixture Designs are multi-part structures that secure an assembly product during a welding process. The compact and complex assembly product to be fixed and welded presents a configuration and geometric challenge for the fixture regarding sequence, collisions, tolerances, welding path, human interaction, etc. This paper presents the welding fixture design problem in its general form. To describe the freedom of automation, the paper introduces the term decision space as the subset of a design space feasible by automation. Depending on the desired outcome, the decision space can be exploited through various strategies and automation approaches. This paper presents one of these approaches by implementing an evolutionary algorithm to the parametric fixture design problem of the use case. The results show reduced engineering efforts and the potential for expanding the exploratory spectrum of design proposals during conceptualization.

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1. Introduction

In manufacturing, the design process is considered to be the methodological approach in which design engineers generate and realize solutions for a problem based on requirements and specifications. Creativity is a critical element of the design process [1]. However, in some industrial applications, like welding fixture design, creativity is a mere fraction of the design process, overshadowed by routine design tasks [2, 3]. To meet the need for shorter design time and to restore some creative freedom, many design fields increasingly rely on automation [4]. Design automation as a tool for design engineers is becoming more feasible because of the increased computational power and information processing.

Design engineering involves many phases and perspectives where automation can be instrumental in almost all elements of the design process [5]. The segmentation of the design process into manageable elements is relevant for the ability to employ design automation by identifying the segment's inputs, outputs, and evaluation criteria. Figure 1 shows how a design segment can be constructed with inputs and outputs. The process outputs can be evaluated according to formulated design requirements. With that, the steps within the segment could be explicitly defined. However, in industrial processes, interventions often interrupt or break the design process flow. When applicable, the automation system has to be built keeping in mind the knowledge and perspective of all experts involved in the process [6, 7].

This paper addresses design process automation in the application of welding fixture designs, showing automated design evolution for a use case based on welding fixtures for industrial metal assemblies. Often, fixture design is considered a subprocess of the welded product design, whose configuration is partly derived through the welding quality [8] and the product tolerance definition [9]. However, smaller or high-detail products can cause challenges in the fixture design due to geometrical and configurable constraints, which in turn can impact the welding quality and process. In that respect, it is critical to ad-

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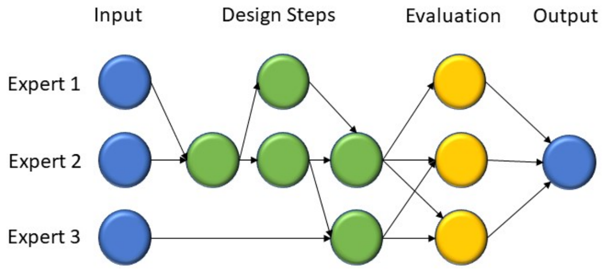

Fig. 1. A representation of a segment of a design process described through input, process, evaluation of the process, and output.

dress the fixture design as an independent automation step of the product development sequence.

This paper suggests a set of terms that can be used to characterize the design requirements within the derived sub-space. In this, the design requirements are used to express the design space and, through parameterization, also formulate the decision space: the tangible sub-space of the design space that is explorable by an automation system. A further elaboration of the decision space and the dependent terms can be found in Section 3.

The welding fixture is described in the use case through a simulation. The simulation is used in an evolutionary algorithm to evolve a design proposal by modifying the fixture geometry to meet the design requirements. This framework (Figure 3) presents the potential of optimizing industrial parametric design problems, such as welding fixtures. It further addresses the associations between identifying a feasible design proposal and selecting an automation tool. Rather than formalizing the strategic selection process, the paper provides a basis for future research on this selection.

2. Fixture Design

Computer Aided Fixture Design (CAFD) engineering has been continuously gaining more attention [10, 11]. This paper addresses welding fixtures as examples of multi-component and intricate designs that impose configuration and computational challenges. In general, fixtures are assembly structures designed to position and fixate a product in some or all degrees of freedom, usually for processing the product through machining or welding. The welding fixtures, for example, as seen in Figure 4, have to be designed by taking into consideration the overall welding process, which entails the interaction of the fixture with the components to be welded, the components' operating unit, fixture operating unit, and welding operating unit. A typical scenario of a welding process would include a human operator preparing and setting up the welding fixture and the components. Then, an automated manipulator robot is tasked with welding the components together. An alternative scenario could be an autonomous welding process using cooperative manipulators [12].

Welding Fixtures can be described through a set of requirements as seen in Table 1). The requirements are extracted from literature [10, 11] and provide the basis for formulating the design problem. The requirements can be parameterized explicitly by variables that can take a given value or value range on a per-use-case basis. Through this parameterization, the design problem and, with that, the depicted design space are defined. The welding fixture design presented in this paper is constructed by standardized fixture toolbox assemblies that are parameterized. These standardized assemblies are responsible for locating, clamping, and supporting the components during the welding process. The assemblies are produced as sheet metal or milling parts; other methods like 3D printing are also possible [13].

Table 1. Welding fixtures design requirement categories

Fixtures [10]	**Welding Fixtures [11]**
Physical	Multi-body product conditions
Tolerance	Conductivity (thermal and electrical)
Constraints	Welding & Process conditions
Collision prevention	Workstation conditions (protection, control, etc.)
Usability	
Affordability	

Following the design process segmentation shown in Figure 1, the Welding Fixture design process can be defined by experts involved in the realization of a design solution. The experts can be clustered according to their responsibilities as shown in Table 2. Those responsibilities directly relate to the design requirements, as each expert is responsible for verifying a design from their own perspective. In practice, multiple duties can be assigned to the same expert. The role of a specific expert varies with their involvement and contribution to each design segment. The level of participation is included in the table regarding the realization of the design evolution system of the use case.

3. Design & Decision Space

A design space defines a multidimensional combination and interaction of parameters and input variables that is envisaged to lead to an outcome that assures quality and adheres to all constraints and limitations imposed on the design process. In practice, a design space depends on the subjective expert's perception of the problem, referred to as design freedom. The intersection of all experts' design freedom forms the resulting design space, as shown in Figure 2. Expert knowledge cannot always be documented or reasoned; thus, the design space (and its bounds) remain a theoretical interpretation of the design problem.

In the context of this paper, a *decision space* refers to the subset of the design space where the design problem and its requirements are formulated and parameterized, thus potentially allowing automation. As shown in Figure 2, the decision space aligns with the requirements through the notion of decision freedom, a term introduced in this paper to describe the subset of the requirement targeted by automation and is expected to produce design proposals.

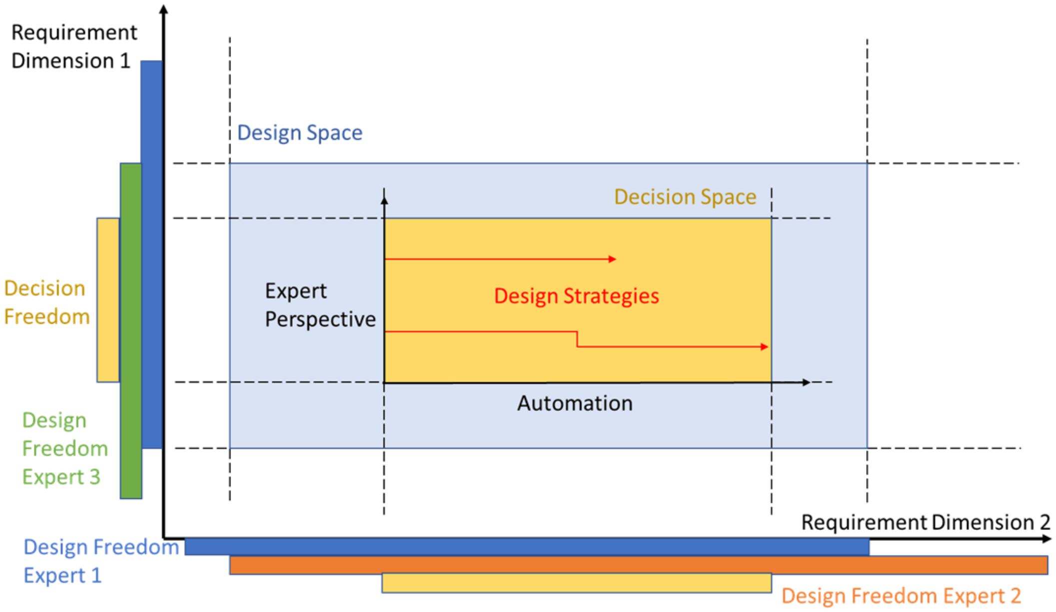

Fig. 2. A representation of the essence of a design space and a decision space of n-dimensional requirements simplified in a 2D map.

Consequently, how the decision space is explored primarily depends on the automation choice (i.e., algorithm framework) and the approach used. The latter is referred to as design strategy. Figure 2 represents design strategies as directions in the decision space, governed by the experts involved.

Decision freedom is the interpreted range of a requirement that excludes tacit expert intuition. Depending on the range, if any, the requirement can provide a feasible design space in which the design can be explored parametrically for possible solutions. If the value of a requirement is fixed, then that requirement is not part of the explorable decision space but a constraint to it.

Expert perspective is the association between expert input and how it is used to produce a design strategy. This is determined by the human interaction embedded in automation. The imposed design strategy can be perceived as a single direction toward exploration by accounting for all possibilities and uncertainties. Through the choices of the expert, automation can explore the decision space. In terms of optimization, this would refer to initializing the fixture design parameters. If the automation allows the initial strategy to be modified, the exploration experiences a discrete jump in the decision space, as shown in Figure 2. This modification can alter the course of the evolution and the resulting design proposal.

Decision uncertainty in any system is a product of the lack of knowledge or aleatory uncertainty in processes and observations. For the evaluation of the design requirements, some processes can be deterministic, while others are considered stochastic. The requirement can be explicitly evaluated for deterministic evaluations, whereas an approximation of the expected requirement evaluation is computed for uncertain processes.

The terms mentioned above are used in the framework of an algorithm that can navigate through a decision space, as described further in Section 5. Defining the terms according to a use case narrows down the design problem into an explorable region, accessible by automation, that could entail feasible design proposals.

4. Use Case: Design Requirements

The proposed approach is demonstrated in an industrial use case for welding fixture design. The use case addresses any welding fixture (with variable dimensions and complexity) as long as it can be composed of assemblies from a standardized toolbox. The assemblies in the standardized toolbox (see examples in Figure 4) are defined by a set of parameters (i.e., influencing geometry and material properties) that the automation system can modify. The process covers the early development stages of the fixture, where the aim is to develop a feasible design proposal. Detailing and modifications in the design proposal are expected in later design stages performed by the experts. For the purpose of this publication, a sample product is used for demonstration.

For realization, various experts (Table 2) are involved with the design evolvement. Expert involvement, if present, contributes to decision freedom. The experts not involved in this design segment and whose input is already fixed during earlier processes are classified as constraints. The remaining experts are classified under detailing, referring to contributions in later design stages. This configuration of the use case is associated with the sequential design development of the product [14, 9]. From Table 2, it can be seen that some knowledge about the fixture is already established and provided as a constraint to the system. Product tolerance is set by optimizing the contact

Table 2. List of possible welding fixture responsibilities and expertise.

Expert Responsibilities	**Use Case Contribution**
Core Fixture Designer	Decision Freedom - Deterministic
Collision Fixture Designer	Decision Freedom - Deterministic
Robot Welding-Path	Decision Freedom - Stochastic
Ergonomics Designer	Decision Freedom - Stochastic
Product Designer (Tolerances)	Constraint
Welding Process Analyst	Constraint
Fixture Stress Analyst	Constraint
Fixture Assembly Expert	Detailing
Welding Spatter Protection	Detailing
Poka-Yoke Designer	Detailing
Electric & Pneumatic Cabling	Detailing

location of the locators and clamps with the product. Welding quality is ensured by defining the optimal contact of the weld guns with the weld joints. Fixture loading stresses are enforced by constraining the parameters of the fixture toolbox assemblies within predefined limits. Some other aspects of the fixture design, such as spatter protection, poka-yoke of fixture operation, fixture assemblability, and cabling, are considered beyond the scope of the conceptual design stage.

The remaining requirements aim to derive a fixture design proposal whose geometry does not self-collide or interfere with moving bodies (i.e., the weld guns, the operator, and the components during packing and unpacking). Good design proposals can be considered those whose requirements are met; however, due to limitations of the fixture toolbox and time limits, an automation system is not necessarily converging. Therefore, the non-converged design proposals are evaluated in their ability to minimize collision and interference. This can be done under the assumption that the expert could improve the design proposal with additional modifications, potentially some that are beyond the definition of the decision space and the automation.

The design proposals are considered feasible when i) the design requirements are fulfilled and ii) the design proposal is comparable to the quality expected by an experienced expert. As a higher-level objective, the automation system, including setup and post-processing of the design, should reduce expert efforts compared to a completely manual design.

5. Use Case: Design Evolution

The welding fixture design problem formulated in the use case is solved by an evolutionary and explorative method, as described later in the section. This section presents a framework (Figure 3) as an example of an approach to explore the decision space. The framework includes the design problem formulation from the design space until the design evolution in a closed-loop system. The aim is to represent the decision space based on an evolutionary algorithm implementation.

The decision space is explored using simulated annealing, a stochastic global meta-heuristic optimization algorithm [15]. Its implementation utilizes simulation models and approximation functions, requiring little to no knowledge of the system dynamics. The welding fixture objective cost (here comes Equation 1) is defined as a single objective function seen as the sum of weighted requirements per fixture assembly functionality b (i.e., positioning, clamping, and supporting). The objective cost function focuses on static and dynamic fixture collisions. Internal collisions between the static geometry of the fixture are modeled deterministically, whereas dynamic interferences with moving bodies are stochastically approximated [16]. These are collectively represented by the function $f_{b,k}(p_b)$, where p are the geometric parameters of the fixture, and k is an index corresponding to an expert responsibility as seen in Table 2 (i.e., core fixture, collisions, welding-path, ergonomics). Each stage is evaluated on its collisions assigned by the indicator function I_k.

$$\min_p\left(\sum_b W_b^T \sum_k I_k f_{b,k}(p_b)\right) \quad \text{s.t. } g(p_b) \leq c \tag{1}$$

The weights (W) are selected experimentally to prioritize collisions that are more critical for the feasibility of the design proposal. Additionally, the welding fixture design constraints described by $g(p_b)$ are defined as previously shown in Table 2. The reference contact points of the fixture with the welded components are derived through tolerance and welding quality analysis and are used as constraints during geometry exploration. Loading stresses on the fixture geometry are computed per fixture assembly, and their geometric parameter values are limited within the acceptable stress range. Additional constraints are applied to the welding contact direction of the weld guns, adhering to the welding quality standards.

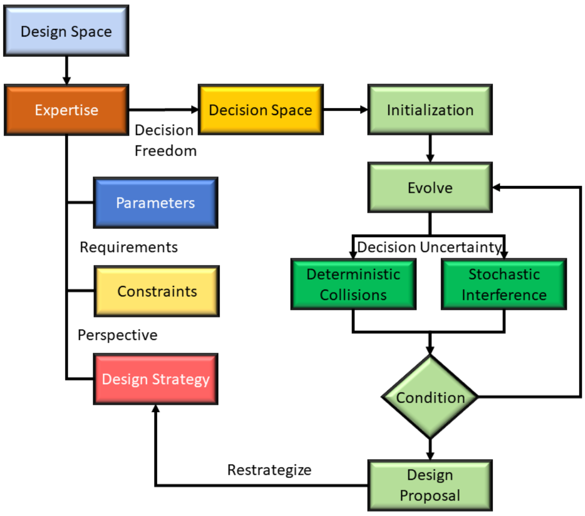

Fig. 3. The framework for the design automation system.

The geometry and positioning of the fixture design are modified through parameters p_b modeled via probability distributions. These are local parameters of height, length, and off-center displacement of the fixture toolbox assemblies and their global position and rotation (transformation) as part of the fixture design. The distributions are chosen based on the optimized physical parameter, e.g., Von-Mises distribution for the angle of rotation and beta distribution for linear distance. The algorithm is terminated when the objective function is minimized (i.e., requirements are met) or a predefined number of evolution

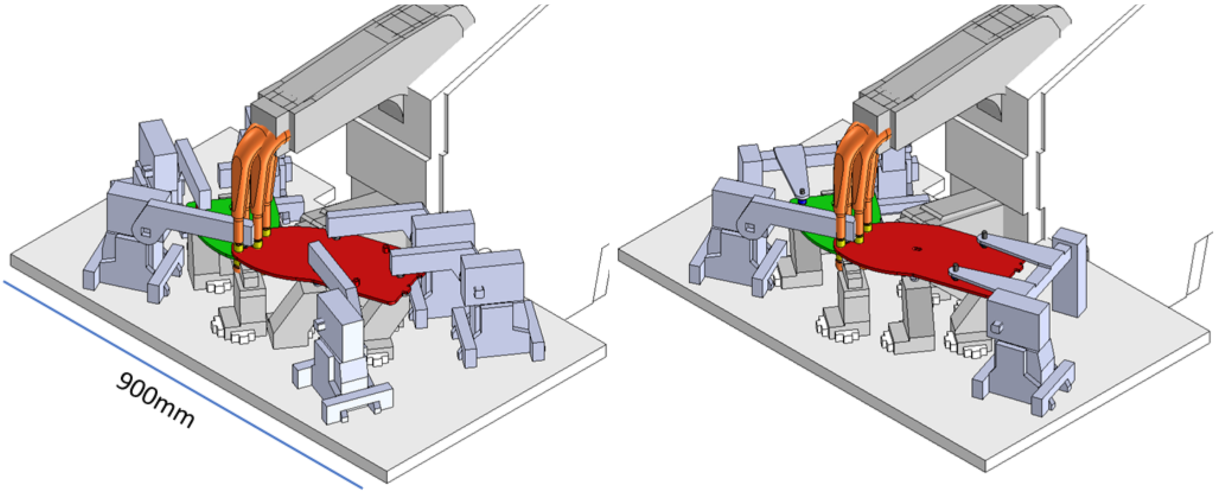

Fig. 4. Examples of two fixture designs developed from the same fixed product.

steps have been performed. The algorithm hyper-parameters (i.e., termination steps, distribution coefficients, etc.) revolving around the algorithm's configuration are selected based on standard practices and experimentation. As the decision space is explored by sampling, and due to the stochastic nature of the objective cost function, it is common for the convergence to be slow, requiring millions of samples. Thus, the aim is to produce viable design proposals instead of exact design solutions, which could drastically reduce the samples required.

Evolved designs are evaluated by an approximation model for welding fixture static collisions (deterministic objective) and dynamic interference (stochastic objective) as shown in Figure 3. The implementation of simulated annealing is shown at an abstract level as an iterative algorithm approach executed until convergence conditions are satisfied. The framework shows how the requirements and constraints define the decision space, with the design strategy contributing to its exploration. The design strategy entails all choices of algorithm hyper-parameters and design parameter initialization, which can drastically affect how the design proposals are sampled over the decision space. This is why a design strategy is represented as a single direction (Figure 2) by which the decision space can be explored. if required, the designer can interrupt the automation and alter the proposed strategy by modifying the design parameters or the algorithm hyper-parameters. This change would cause a shift in the direction of the design strategy and affect the design proposals that are explored.

6. Use Case: Design Impact

The use case implementation of design automation is focused on the reduction of efforts yielded by the experts in completing the design process segment at hand. This includes the efforts of setup, automation execution, and post-processing(if necessary) of the design proposal to meet the requirements. The comparison is empirically assessed through a series of design development sessions, including a manual and an automated fixture design for the same components. Overall, fixture design automation required less than 30% in designer efforts than the manual process to reach a feasible design proposal. For welding fixtures with 10-15 toolbox assemblies ($2-5$ parameters per assembly), viable design proposals could be generated within a few hours. This considers non-optimized connectivity to a Computer-Aided-Design software that consumed about 80% of the computational time. For larger welding fixtures, the average time to reach a feasible design proposal increased exponentially.

The distinction between designer efforts and overall efforts contributed to the design process is addressed in Figure 5. The figure provides a lead-time interpretation of design automation to the process efforts in addition to the designer efforts [17]. This representation is common in industrial applications, such as part manufacturing, where processes can operate autonomously and overnight, extending the available production time within a day.

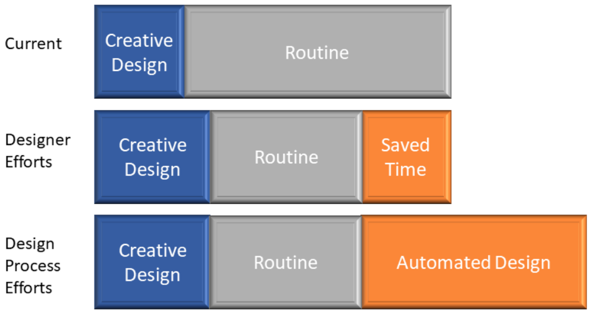

Fig. 5. A representation of efforts required for a design process with and without design automation. Based on [17].

For better utilization of the automation system and to handle extensive computations, the automated system is considered to run overnight after deploying an initial design strategy by the experts. Multiple parallel sessions and strategies are deployed to expand the decision space exploration and sampling rate, producing a broader collection of design proposals. The design proposals that meet the requirements or achieve the lowest minimization cost are assessed by the design expert, who chooses which design proposal to be developed into a solution. Two examples of created designs can be seen in Figure 4, where the experts were able to verify the design proposals as feasible design solutions equivalent to those produced manually.

The reduction of design automation efforts is based on two observations: i) the system requires minimal initialization effort from the design expert, and (ii) the system can autonomously run without expert supervision once a design strategy is established. This allows a stable operation of the design automation outside of working hours and without direct control. The core benefit is the possibility of executing long and expensive simulations without penalty on lead time and with less designer effort.

7. Conclusions

In this paper, a design automation methodology has been presented for welding fixture designs. A set of terms related to design requirements with the succeeding decision space have been introduced, representing possible design proposals achievable by automation. The link between the two is based on the involvement of design experts during the design stage of interest and how their knowledge is utilized or applied. The proposed design automation includes expert interaction during the initialization of the design problem and as a controlling unit of the design evolvement. The control is achieved by design strategies chosen by the expert as the approach of exploration and utilization of the automation system. The exact formulation and capabilities of the design strategy for best expertise utilization and algorithmic integration are still a work in progress.

The presented use case is based on the early conceptualization of a welding fixture design. Using a standardized fixture toolbox allowed for the parameterization of the design problem. The aim is to minimize geometry collisions within the fixture in an attempt to produce feasible design proposals that meet the design requirements. The decision space is approximated using a simulation model, where the optimization is done using a meta-heuristic algorithm, namely simulated annealing. Through empirical evaluation of sample design proposals, it is demonstrated that automation is viable for reducing repetitive tasks and initiating design solutions for welding fixture designs. Early implementation showed a reduction of design efforts to 30% during the conceptualization of design proposals, compared to manual design. Similarly, the increase of design process time cost by extensive computational time of the automated system did not impact the overall lead time of the design process.

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