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One-Fits-All vs. Tailor-Made: User-Centered Workstations for Field Assembly with an Application in Aircraft Parts Manufacturing

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Abstract

Field assembly of large components for aircraft, ships, trains or big machinery is often done in a rather unstructured environment, with little concern for the individual needs of the involved personnel. Confronted with a shortage of qualified personnel and a generally aging workforce, workstation designers need to put more emphasis on improving ergonomics and allowing for individual adjustments and support for a particular worker. Human factor engineering traditionally uses a "percentile-approach" to work-design, preventing an exact adjustment to the ergonomic needs of particular users. New technological advances provide opportunities for major improvements; novel assistance and information systems allow the accommodation of the needs of an increasingly diverse assembly workforce, while minimizing overall physical and mental stress.

Based on a recently developed synopsis of options for individualization of assembly workstations, an example of an application in field assembly is being presented and illustrated by a full-scale demonstrator for the assembly of large scale composite parts for the aerospace industry. The pilot-installation combines a projector-based augmented reality environment for dynamic worker-information with automated operator position tracking and field of vision positioning. Finally, a comprehensive concept, that includes other dimensions of individualization, is presented.

Keywords: Individualization; field assembly; physical / cognitive assistance; work design

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1. Introduction to assembly workstation design

The main topic of this paper is a user-centered approach to workstation design for field assembly. By means of an application in aircraft parts manufacturing, the potential of individualized workstations for improving functionality and ergonomics is illustrated. Although the "ergonomic quality" of assembly workstations in western industrialized countries has substantially improved over the last few decades, there are certain problematic work situations remaining, e.g. workstations that require strenuous postures, overhead work or have a short cycle-time and repetitive work content. With an increased awareness of the importance of the layout and physical design of workstations for long-term health benefits and motivation, ergonomic workstation design for assembly tasks has sparked renewed interest. As described below, several issues need to be taken into consideration.

1.1. Standardization vs. individualization

Also caused by the "lean mantra" of standardization, to a certain degree the focus of the ergonomic design of assembly workstations has been oriented towards accommodating a broad spectrum of employees with one standard configuration. Traditionally, human factor engineering uses a "percentile-approach" to work and workstation design for assembly line situations, which are highly standardized in shape and layout. Workstations often lack opportunities for individualization and personalization and do not permit an exact adjustment to the ergonomic needs and personal preferences of the particular user.

Currently partial solutions for workplace design with individual adjustable parameters for working height [1], material supply [2], lighting [3] as well as eligibility and information representation [4]; [5] exist. Those approaches commonly use different user needs and requirements with respect to anthropometrics and ergonomics as starting points for "individualizable" workplace design. Since rationalization and humanization are two equally important goals, it is essential to find solutions that support efficiency objectives while allowing for a higher degree of individualization. In the light of demographic developments and an increasing shortage of qualified labour, well-designed workstations are progressively more important means to attract and retain qualified and motivated employees [6].

1.2. Workstations for field assembly

Assembly workstations are designed to support the efficient assembly of parts, components and subgroups to higher-level manufactures or final products. Typically, they are rendered as single workstations, flow line workstations or field-assembly workstations [7]. Field assembly (also known as site assembly) means that a large product is assembled in a stationary setting and the assembly personnel, as well as components and tools are transported to the product. A large number of individual parts are required and the accessibility to the assembly object must be guaranteed from all sides, which requires extensive space. (comp. [7]).

While single and flow line workstations have been the object of ergonomic scrutiny, field assembly situations have gotten little attention with respect to ergonomics; in particular their adaptability and individualization. This is not surprising, since field assembly is characterized by an unstructured environment and improvization. However, empirical data shows that employees in field assembly situations often complain about the challenging environment, physical strain and health problems leading to absenteeism and a high turnover of personnel.

1.3. New technological developments and state-of-the-art individualized workstations

In an attempt to mitigate the remaining ergonomically problematic work situations in assembly, new technological developments provide opportunities for major improvements [8]; [9]; [10]; [11]. Many companies are testing and implementing assistance systems (lifting assistance, exoskeletons, cobots, wearables, augmented/virtual reality (AR/VR) systems, etc.) [12]; [13]; [14]; [15]. Besides reducing the strain on workers, the research focus is on intelligent automation and digitalization and the reduction of stress on individuals.

Recent studies concentrate on individualized digital human models and design models for assembly workstations [16], [17], individualized profile data models [18] as well as assistance systems for monitoring ergonomic parameters [19]; [20]. There is very little work known to the authors that deals with the evaluation of possible individualization dimensions and parameters, especially with respect to entrepreneurial efficacy and efficiency as well as ergonomics, organizational and user acceptance criteria. Hence, there is a demand for a systematic evaluation and selection of individualization dimensions and parameters with respect to new technological developments.

The use of modern technologies to improve ergonomics enables a fundamental advancement to a state-of-the-art workplace design with respect to the overarching goals of occupational science: “fostering of personality development and social responsibility and compatibility” [21]. Incorporating individual user requirements in workplace design will help to overcome the “one-size-fits-all” dogma and creates optimal conditions for diverse users of a work system.

2. Synoptic disposition of options for individualizable assembly work stations

The presented synopsis is a collection of current knowledge with respect to the design dimensions of individualizable assembly workstations, which has been compiled with an application for individualizable assembly assistance systems in mind. This encompasses workstation dimensions (working height, reaching area of the hands), work environment (lighting, ventilation and climate, acoustic situation) as well as other aspects as the utilization of assistance systems. The synoptic disposition of options is a first step in the systematic development of individualizable assembly workstations.

Table 1. Synopsis of possibilities for the individualization of assembly workstations [22].

Options for adjustments	Utilization for individualization	Expected benefits
1) Dimension: working height		
• Height of work surface • Utilization of work surface for seated and standing work positions	• Adjustment of optimal work height according to body height • Adjustment of optimal work height according to specific task • Change of work surface height according to defined use-time to foster switching from seated to standing work positions	• reduction of musculoskeletal strain due to avoidance of ergonomically unfavorable body positions • Efficiency improvements due to suitable working height (better gripping area, lower fatigue levels, fewer mistakes)
2) Dimension: Range of vision, gripping area, handedness		
• Length, breadth, depth, angle of the work surface • Provision of material and tools	• Automatically adjustable work surface (in breadth, depth, angle) • Provision of material and tools within the optimal gripping area • Adjustment of the provision according to handedness (right/left handedness, ambidexterity, posture of hands) • Automatic adjustment of assembly fixtures, joining stations • Handling assistants • Automatic posture control	• Reduction of physical strain by avoiding ergonomically unfavorable handling ranges, forces/ torques, e.g. no work higher than heart level • More productive work due to optimized gripping area and hence ▪ more efficient processes ▪ lower fatigue ▪ fewer errors
3) Dimension: Lighting		
• Intensity of illumination • Number of light sources • Number of additional spotlights • Color of lights • Angle of incidence • Blinding/ glare	• Automatically adjustable work station lighting (individual preferences of intensity of illumination and light color) • Adjustment of light color to time of day • Use of additional light sources for sensitive work	• Higher productivity due to individualized/ task specific lighting • Lower fatigue • Fewer mistakes • Targeted stimulation (attention, circadian rhythm) • Higher employee satisfaction/ wellbeing

Options for adjustments	Utilization for individualization	Expected benefits
4) Dimension: Ventilation and air conditioning		
• Air temperature • Humidity • Air speed • Thermal radiation • Air transfer rate	• Individualizable heating and cooling equipment • Individualizable humidifiers, dehumidifiers, ventilators • Individually adjustable shading • Increased airspeed/ temporary lowering of temperature to counter fatigue	• Avoidance of climate-related illnesses (e.g. respiratory problems due to dry air, muscle stiffening due to air drafts, etc.) • Increased individual capability and wellness
5) Dimension: Acoustic situation		
• Background noise • Noise level at workstation (dB) • Vibrations • Music	• (noise cancelling) headphones • (movable) noise barriers • Noise killer • Adjusting of (background) music/ radio at the workplace	• Avoidance of burdensome acoustic situation • Increased individual capability and wellness
6) Dimension: Use of information and assistance systems		
• Type of offered assistance (physical, cognitive, organizational, communicative) • Individual adjustability of capability enhancers (e.g. exoskeletons) • Extent and frequency of assistance systems use • Design and configuration (font size, interaction modus) • Extent of information and information granularity • Interaction/ -medium (Input/Output)	• Individually adjustable assistance and learning assistance systems • Provision of information depending upon the individual need for assistance (experienced-based provision of information: less in case of frequent use; more, e.g. after vacation; additional assistance after mistakes) • Individualized adapted interaction media (i.e. depending on the preferences with respect to the use of certain senses – optical, acoustic, haptics)	• High potential for learning and efficiency improvements due to the adjustment of the assistance to the competence level of the user and the job to be performed • Increased acceptance and intensity of use
7) Dimension: Further aspects		
• Organization of work (e.g. cycle time, target time) • Sense of security, visual privacy • Esteem, status and need for recognition • Color and material	• Individually adjustable cycle time • Individually different target times and dynamic cycle time • Workstation design, that takes individual psychological aspects into account • Taking into account the individual's preferences for the organization of work (disposition, shift planning)	• Integration of handicapped employees in synchronous work systems • Higher employee retention and lower turnover • Increased initiative, commitment and responsibility • Higher productivity

Based on Table 1, the intention is to support the experimental configuration of different individualization-constellations and to evaluate them with respect to their effects on productivity, ergonomics and user acceptance. The presented use-case from aircraft parts manufacturing is a first attempt of such an experimental configuration. As a final result, universally valid and applicable design rules and combinations of attributes for individualizable assembly systems will be developed.

3. Implementation of a pilot-workstation

The dimensions of individualization depicted in Table 1 allow for a wide range of applications and serves as the departure point for the conceptualization and implementation of a pilot workstation for the field assembly of aircraft components. The use-case chosen is the assembly of a composite structure and the specific part is a composite "wing tip device", which was also dubbed "winglet" or "sharklet". This part is assembled in a field assembly situation by placing several hundred of specifically cut pre-impregnated fiber mats (so-called "tapes") in a particular sequence with high demands with respect to position and fiber orientation onto a carbon tool. This tool provides the shape for the composite part and has a dimension of 5.500 x 2.000 x 1.000 mm and weight of approx. 800 kg and was supplied by a partner company from the aircraft parts industry that also furnished user requirements and process knowledge.

Due to its dimension and weight, the tool is stationary during assembly and cannot be adjusted with respect to height and angle. To perform the different assembly tasks, the personnel must move around the tool. For certain process steps, the workers have to bend and twist; and in order to reach certain areas they have to climb onto the tool and even lay down. To do this or to compensate for individual height differences, the workers use small ladders and stepping stools.

Work-related information and work plans are provided on a stationary PC-terminal, and certain steps need to be acknowledged at the terminal, necessitating extra trips. Recently, a large overhead screen was installed, which was an improvement, but since it cannot be seen from every angle, workers still must move in order to retrieve the information. Furthermore, certain material and speciality tools are stored centrally, creating extensive search and travel time.

Of all the possible dimensions for potential individualization presented in Table 1, it was decided to start with dimension 6 *use of information and assistance systems,* since in field-assembly situations it is one of the most problematic issues that creates inefficiencies and ergonomic problems. In field assembly, process and work-related information is often provided on paper or on stationary PC-terminals. In the presented use-case, the company is experimenting with overhead TV displays, which are mounted above the tool.

Currently, positioning information for the carbon mats is provided by a laser-beam system that projects a flickering red grid onto the tool, which is very tiring for the workers and also not intuitively understandable, especially in combination with the information provided on the TV screens. The envisioned dynamic projection system (see Fig. 1.) combines both positioning and information assistance in one system.

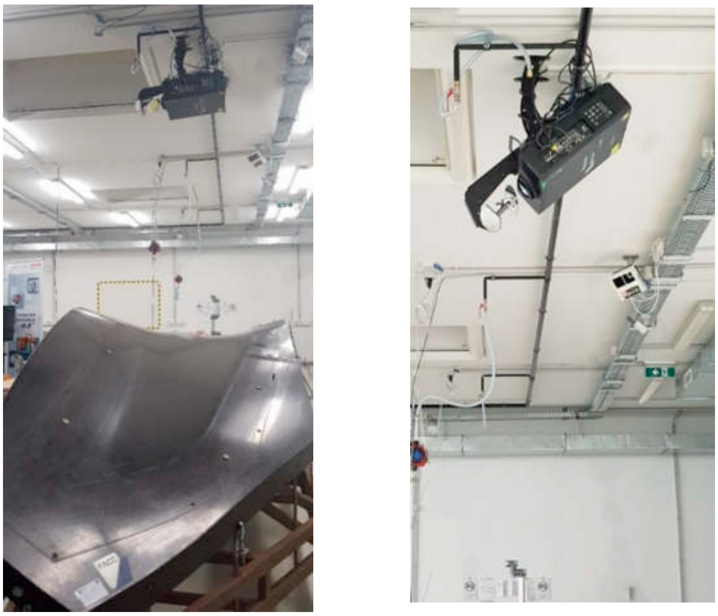

Fig. 1. (a) Overall setup of the AR projection system; (b) dynamic mirror system and TOF-camera. © TU Wien

Above the workstation, three time-of flight (TOF) cameras detect movement, differences in height as well as other visual properties. The resulting point cloud is analyzed and processed in order to control the different assistance systems that allow further individualization, i.e. the data about the body height of the worker can be used in order to adjust the height of the component. Although the TOF sensors enable the measurement of the body height of the worker, they do not produce an image of the person and hence the privacy of the person is inherently protected.

In order to display work-related information (position, shape, orientation, assembly and quality instructions, additional information, etc.) directly where the worker is located, a projector is mounted above the tool and projects directly on the tool. By using the surface of the tool as a projection area, a simple augmented reality (AR) application is created. The projector is coupled with the TOF-cameras and in combination with a dynamic projection lens system, the projection follows the worker and can always be displayed in an optimal view range. This can assist with position information for certain process steps or provide contextual information. The information is displayed directly at the particular working area or within the viewing range of the worker, giving context to the specific job.

One of the problems faced with projecting directly onto the tool is that the tool's surface is curved, distorting the resulting image (see Fig. 2.). To offset the distortion of the rather difficult geometry of the projection surface, the project team is currently working on a correction interface based on the CAD-model of the tool. Since the projection is supposed to move with the person in real-time, the requirements with respect to hard- and software are demanding but manageable.

Fig. 2. First results of the prototype augmented reality projection system © TU Wien

Fig.3. shows this 3D point cloud of the TOF-cameras, which capture the tool and the movement of the employees.

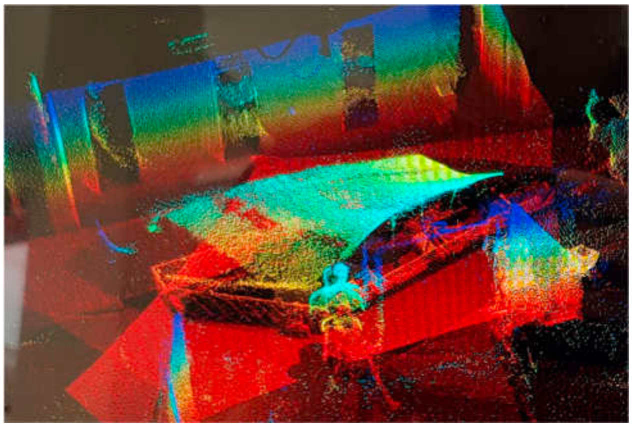

Fig. 3. Pointcloud from the winglet-tool © TU Wien

The image illustrates a current problem of detecting the range of view of the worker, since it is more difficult than originally expected to perceive the nuance of head movement that indicates the visual gaze of the worker.

4. A concept for a comprehensive user-centered pilot workstation for field assembly in aircraft parts manufacturing

The pilot-workstation for field assembly introduced in Chapter 3 is currently extended in order to implement some of the other dimensions for individualization presented in Chapter 2. Fig. 4 depicts the concept for the implementation of additional dimensions for individualization, which will be implemented step-by-step in the pilot factory of the TU Wien in order to create a comprehensive user-centered pilot workstation for field assembly in aircraft parts manufacturing.

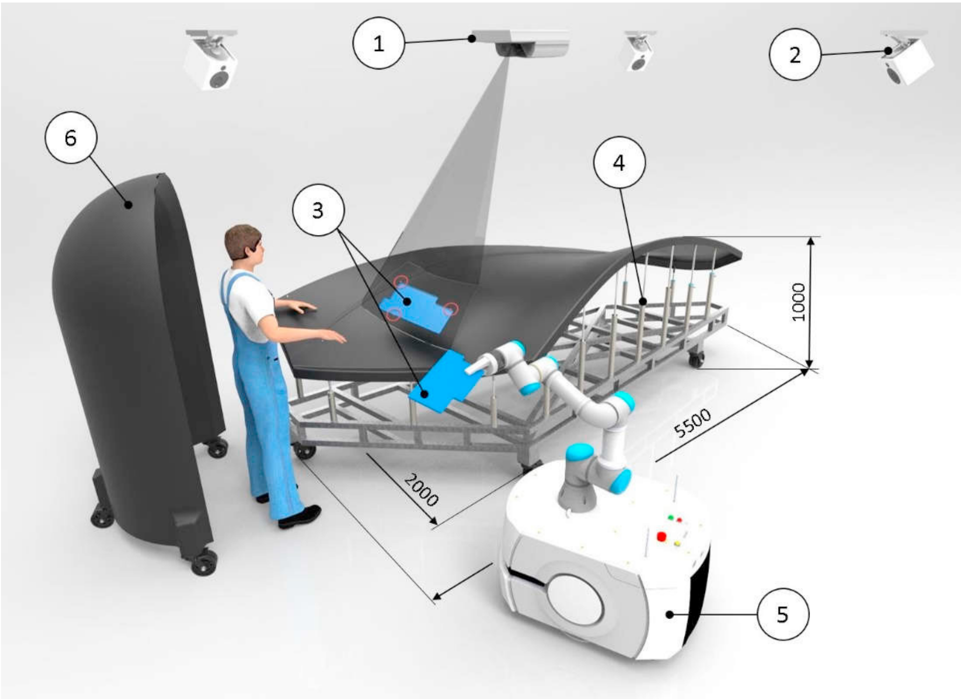

Fig. 4. Application of the individualization dimensions for a pilot workstation [22]

In addition to the augmented reality system (1 and 2) that already exists, Fig. 4. also depicts the projected outline of a carbon fiber mat (3), which will provides visual guidance to the worker in order to place the mat onto the correct position and with proper fiber orientation. The feedback from the TOF-cameras also has the potential to provide automated process and quality control.

To adjust for an individual's body height, the tool is mounted on wheels and adjusted by hydraulic cylinders (4), which enable the individual adjustment of the assembled component in height and angle. This makes it easier to reach difficult areas and reduces ergonomically problematic postures and movements.

In order to assist with material supply, an automated guided vehicle (AGV) with a built-on lightweight robot arm is envisioned (5). This enables the ergonomic provision of materials under consideration of personal preferences as handedness, gripping area, etc. Such an automated material supply will reduce unnecessary effort in getting material and prevent errors due to wrong positioning or mistaken components.

The movable noise-protection barrier (6) also has the potential to house a portable air conditioning unit that produces a micro-climate for the worker.

5. Conclusion

The synopsis of the different dimensions for individualization presented in this paper combines partial aspects of the design of individualizable workstations. It provides a foundation for their comprehensive design, which adapt to the physical and psychological characteristics and needs of the users. The synopsis is intended to be catalogue of options for the design of individualizable workstations and is illustrated on a conceptual level by means of a pilot workstation for field assembly.

The augmented reality assistance system presented in Chapter 3 is central for the targeted and automated individual adjustment of the workstations, with respect to the dimensions of height, angle, reaching area and information provision. It creates the basis for a comprehensive user-centered pilot workstation for field assembly in aircraft parts manufacturing, which is currently developed step-by-step at the pilot factory of TU Wien.

The individualization of the workstation will lead to an overall improvement of the ergonomic situation, hence improving health, wellbeing and morale. Present problems with the implementation of individualizable workstation design stem from lack of experience with actual, quantifiable effects, especially with respect to industrial implementation and utilization. First experiences clearly show that by avoiding unnecessary movement, using less effort for searching and a lower error-rate, an overall reduction of process time can be expected. Further research into the options for the implementation of physical assistance and digital interconnectedness and their effect on the central objectives of human factor engineering (productivity, ergonomics, user acceptance) is already carried out. Moreover, the implementation of individualized workstation design on the organization of work and concepts of on-the-job education and training will be investigated [23].

Against the initial expectations, the main risks are not hardware, sensors, image processing or actuators, but rather expensive integration and a lack of interoperability of hard- and software [24]. The resulting demand for additional research concerns mainly the consideration of individualization for overarching standards, basic models and platforms for the design of work assistance systems, as well as the implementation of evaluated, scalable solutions for prevalent workstations and tasks.

Furthermore, the individual adjustability of workstations is based on the utilization of personal employee data [25]. This is currently a major hindrance for implementation and acceptance, especially in Europe with its stringent data protection laws. However, with the progressive integration of digital assistance systems into our daily life as well as commonly accepted models for the protection of employee data, there is a good chance for high employee involvement during implementation resulting in broad user acceptance. However, this necessitates the establishment of new levels of trust for the utilization of personal data as well as its integration into generally applicable design guidelines.

Although the last few years have been very successful with respect to the ergonomic design of workstations for production and assembly, there is still considerable potential for improvement with respect to employee-specific adaptability and individualization. The growing consideration of individualization as a factor of workstation design is a valuable step towards humanization and increasing the attractiveness of production work. In order to succeed, intensive research is necessary to guarantee a successful industrial application.

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