Response to Reviewers

Manuscript ID: applsci-1008375
Type of manuscript: Article
Title: A smart algorithm for personalizing the workstation in the assembly process
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Received: 4 November 2020
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Submitted to section: Mechanical Engineering,
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Dear Reviewer,

Thanks very much for taking your time to review this article. I really appreciate all your comments and suggestions! Please find my itemized responses in below and my revisions/corrections in the re-submitted files (using "Track Changes" function).

Thanks again!

Comments and a summary of the revision

In the Introduction section (row 74-75), authors said that the smart application of the proposed algorithm provides improvement of product design? How?
Rows 74 and 75 refers to cited paper [24] and not our proposed algorithm or better proposed assembly system. In the paper [24] the authors stated that in most cases, DfA method only focuses on the optimization of the product design, and missing to provide a holistic view of the assembly line, workstations, assembly tasks, etc. Because of that, they proposed a holistic approach to overcome the abovementioned weak points and to optimize the assemblability of complex mechanical products, by taking into account all the aspects involved in the manual assembly (Material, Method, Machine, and Man). So this paper is relevant because they use holistic approach to product design (4M approach) and the analogy to the paper is our holistic approach to system design (smart workstation, smart algorithm, implementation of tool and technologies, inclusion of ergonomics) and not directly to product design. We apologize for our awkward expression and not properly clarified the sentence in row 74-75. In the article this part is now corrected (rows 83-86), so there is no more misunderstanding.
In addition, a summary of the sections constituting the paper must be added at the end of Introduction, nevertheless some information can be found on the beginning of succeeding sections.
Thank you for the suggestion, we have added a summary of the structure of the article (rows 168-174). This paper is structured as follows: Section 2 focused on the presentation of the smart assembly workstation, smart algorithm and case study description. The section 2.1 includes

presentation of the smart manual assembly workstation and its main implemented technologies and its operational functions. Next subsection presents the smart algorithm in details and subsection 2.3 includes workstations`, products`, and workers` characteristics involved in case study. Section 3 presents results and discussions about time and error analysis and ergonomic evaluation of the workstations. Section 4 further summarizes the final findings of the study in conclusion.
For anthropometric features, authors use height and gender. As far as I know, anthropometric features can be specified according to gender, but gender is not an anthropometric feature.
That is correct, gender is not anthropometric features. We have corrected this in the article so now is clear that gender is not an anthropometric feature (rows 244-249). As anthropometric features in the study, we use directly just body height, but indirectly there are other significant anthropometric features that we used, such as elbow height, eye height, and shoulder-grip length. We wanted to use directly as few data as possible, due to data storage and the law on personal data protection (GDPR, [34]), so we wrote down all indirectly used anthropometric features in such a form that they functionally depend only on gender and body height. For more detailed description of functional dependency see the answer of the question about empirical equations and recommendations.
Why the proposed algorithm is considered "smart"? This is the algorithm that, according to the given input (workers' ID and product types and assembly complexity), adapts the smart workstation (height of the working bench, lighting, grab containers and assembly nest/rotation table) according to the data already entered in the system database. Please clarify.
In the article we rely on facts/definition stated in [30], which says the functions of SMSs (smart manufacturing systems) are as follows: Self-sensing function (capturing the data and the critical information from the environment), Self-organizing function (the capacity of solving the emergent requirements), Self-deciding function (data-driven decision making process in manufacturing), and Self-adaptive function. Self- adaptive function operates the behavior of SMSs' elements, which are based on the real-time sensing data and information. Through the different algorithm and rules, self-adaptive behavior of SMSs is considered as continuous learning or life-long learning. As a primary intelligence level, adaptivity implies the capacity of acting on rules "If- Then-Else" (rows 179-187). It can be said that our proposed assembly system is a smart system with a self-adaptive function. It is true that our system does not yet learn on its own, but we have considered the primary intelligent level as the basis for the development of the algorithm, as our algorithm acts on rules "If-Then-Else".
In chapter 2.1. (row 192-194) as well as in chapter 3.1. (row 306) authors mentioned empirical equations and recommendations. What are these equations? Could you list and explain which equations are in question? How you get them? Or, are those taken from the literature that is not cited?
Thank you for pointing that out. Equations and recommendations are cited next to the fig. 2, when the explanation of dependency of influential parameters are given (rows 241-260). For better understanding, we cited the literature again in chapter 2.1 (row 279) and 3.1 (row 391) and here is more detailed explanation. Using a smart algorithm we control the height of the workbench, lighting, grab containers with parts and rotation of the assembly nest. The anthropometric characteristics of the worker that the algorithm takes into account is body height (with standard deviation), and

indirectly the hand range, elbow height, eye height, and shoulder-grip length [31-33], and additionally the gender of the worker.

In the case of the smart algorithm, the main guideline was to adapt the smart manual assembly workstation to the individual worker and that the minimum possible amount of data (which is "publicly" visible) should be entered into the algorithm due to the personal data law already mentioned. We achieved that by writing down all the necessary anthropometric characteristics of the workers in functional dependency on their body height and gender, through empirical equations.
We form the empirical equations on the basis of gender, reference values of (average) body height, elbow height, and shoulder-grip length from [31-33 p. 33-51]. The dependency is linear. The "if-then-else" statements of algorithm calculates the final height of the work bench as follows:

- From gender and body height via empirical equation the algorithm calculate elbow height.
- According to the recommendations of [33 p. 53-54] then from elbow height subtracts 50 mm, thus obtaining the optimal working height of the table (working height 1).
- However, in the further procedure we must also take into account the complexity of the assembly. By entering the assembly complexity (normal, heavy, precise), the workbench stays at working height 1 (normal) or is raised (precise) or lowered (heavy) according to recommendations from the literature [32, 33 p. 54-56] to obtain working height 1.1.
- Finally, the height of the product along the z-axis is taken into account. When the product exceeds a height of 100 mm, the workbench is lowered by 100 mm and the optimal working height (working height 1.2) is maintained

For illumination, we used the Photometer phone application to describe the relationship between the data sent to the reflectors (value between 0 and 250) and the illuminance (from 0 to 2000 lux). Data were obtained indoors, the windows were dimmed, and the other indoor lights were turned off. Data were captured for each reflector separately (left, right) and for both together, respectively. Recommendations on optimal work lighting were obtained from the Slovenian Law and Standards [35, 36]. Recommendations regarding intensity of the light depending on the complexity of the assembly were obtained from [33 p. 295-317].
The following is a description of data acquisition for grab containers - distance and inclination. The recommendations from [33 p.64-66] was followed for setting the inclination of the grab containers. Using experiments, we determined the relationship between the data sent to the linear actuator (0-180) and the distance or angle of inclination as is stated in [33]. For the distance of grab containers, we followed the recommendations [32, 33 p. 67] on reach envelope, and accordingly sent data to the linear actuators that control grab containers. The recommendations were also checked by the drawing reaching zones to the smart manual assembly workstation (Fig. below).

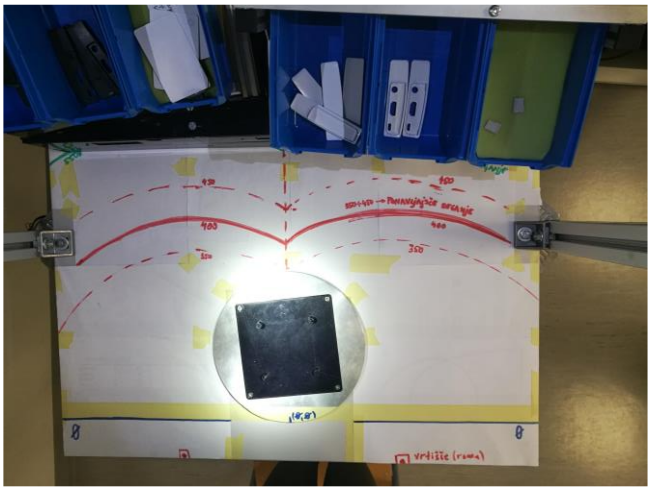


Fig: Reach zones.

And finally the determination of rotation of the rotatable table. Determining the direction of assembly or the orientation of the product at the assembly nest mainly depends on the choice of the base part of the product and the structure of the product. Usually, the determination of these characteristics depends on the experience and expertise of a group of people (product architect, assembly planner, ergonomist) [Demoly, F. et al. An assembly oriented design framework for product structure engineering and assembly sequence planning. *Robotics and computer-Integrated Manufacturing*, **2011**, 27(1), 33-46. 10.1016/j.rcim.2010.05.010.]. As stated in [Agrawala, M. et. al. Designing Effective Step-By-Step Assembly Instructions Assembly Instructions. *ACT Transactions on Graphics*, **2003**, 22(3). 10.1145/882262.882352] most objects have a set of natural orientations or preferred views. These orientations maximize the number of important features that are visible. In our study, we determined the structure of the product and the basic part on the basis of expert knowledge (professor of handling and assembly), on the above definition, and on the principle that the product should always be assembled from the direction where the worker has the greatest field of vision. This means that during the assembly process, the worker must see the place/location where he will assemble the current part.

How did you determine the values of the data you enter into the database on which the customization of smart assembly is based? In particular, the location and angle of a grab container and rotation of the rotary table / assembly nest. How did you determine the optimal direction of an assembly operation?

Thank you for the questions. Please see the full answer to those questions in the detailed explanation of the previous question.

“Case study methodology” is somehow an inappropriate title for the section 2.2. Through this section, I cannot see which scientific methods you will use for your case study so the word “methodology” cannot be used properly. The methodology should show which methods, tools and techniques we will use in proving or rejecting certain hypotheses. Perhaps you can use some other title, for example: “Case study information”, or “A short review of data for the case study”…

Thank you for suggestion. We change the title of the section 2.2 on “Overview of the case study”. As we add some sections in the article, the new section is 2.3 Overview of the case study.

Please add a new section where you describe the newly created smart workstation in a little more detail. What does it all entail? Which technology you use on it? Why? How the table,

shelves, containers, lights, etc. within the workstation are managed, powered? Are there some drawbacks noted or reported by workers, as safety issues due to moving elements, increased noise, strain on human vision…

We add section 2.1 Smart assembly workstation (rows 193-221) with detail description of the workstation. Content added in the article is write below.

When choosing the technology for the construction of a manual assembly workstation, the main guide was the low price and availability of the products. We used two Raspberry Pi (RPI) controllers for the manual assembly workstation control system. Two RPI controllers were used because we wanted to build a modular manual assembly workstation. The code is written in the Python programming language. The desired current hardware states on manual assembly workstation are written in the Microsoft SQL Express database. There the hardware states are recorded by the program LPM at each step of the assembly. The Raspberry Pi controllers are connected to the base via the network and send a motion signal to the appropriate hardware when the hardware state changes.

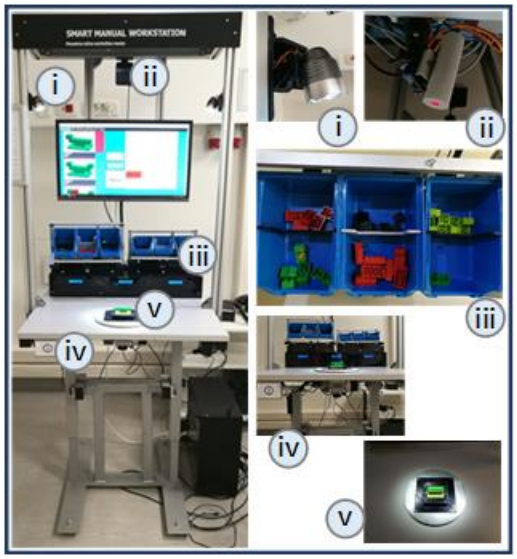


Fig: Smart manual assembly workstation with implemented tools.

We have illuminated the work surface with additional adjustable lights (i) due to the possibility of adjusting the intensity and direction of the light beam. The lights are controlled by a PWM signal, which enables the control of light intensity. The lights have their own 12 V power supply. The lights are mounted on a two-axis stand with RC servomotors. These are connected to Raspberry Pi via the RC servo motor / I2C interface card.



i: Additional lighting.

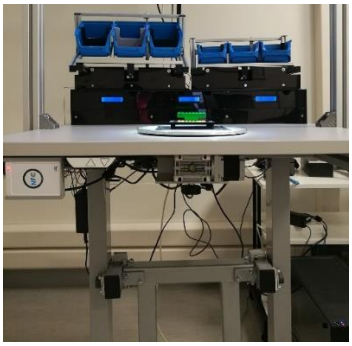
The laser pointer (pick-by-light (ii)), which points to the area in the buffer, is also mounted on the same stand and connected in the same way.


ii: Pick by light technology.

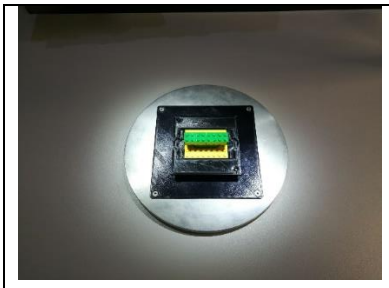
The storage of parts contains two separate containers (left and right: LZ, DZ) each with 6 sections (LZ1-6, DZ1-6) driven by a linear servo motor. They are also connected to the Raspberry Pi controller.


iii: Left storage with 6 sections containing different parts and pick by light laser beam shown LZ2 section with dark green Lego blocks.

We used adjustable table (iv) to raise the work surface on the appropriate height for each worker. The switches for lifting the table were connected to Raspberry Pi via a relay board. The table had its own power supply by plugging it into a socket.


iv: Height adjustable table.

The rotatable table (v) has a stepper motor and a 24 V power supply. The stepper motor is controlled by the Arduino controller via the stepper motor interface.

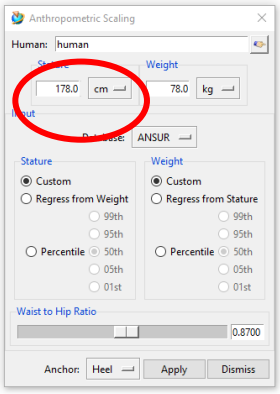


v: Rotatable table with assembly nest.

For safety reasons, movement is limited to slow speeds and low power motors are used to avoid injury. RC Servomotors generate typical noise, which could be reduced by using high-quality motors. Replacing these motors with better motors would also increase the accuracy and repeatability of laser and light positioning.

Why you use a predefined avatar (male; height:1774 mm) as a virtual human, and not for example human with the mean height (1780 mm)?

In the simulation model, we analyzed predefined avatars performing assembly on workstation adjusted to it (him) (table height, grab containers distance, tilt of the grab containers, etc.), so that we obtained relevant data for a male person with body height 1774 mm. However, given that the average height of the workers who participated in the study was 1780 mm, we subsequently did a simulation with an avatar of this body height as well (Fig. 7). We imported a smart manual assembly station of the correct table height, grab containers openings and tilt into the simulation model Jack (this was previously modeled in SolidWorks 2018) in .jt format (without further formatting, so the workstation is unfortunately in violet color – but color doesn`t impact the result, only the esthetics). We then added an avatar and assigned a body height of 1780 mm (fig. 1 below).



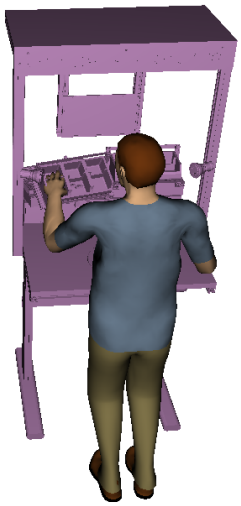


Fig. 1: Avatar with body height of 1780 mm in simulation environment.

Then an ergonomic analysis and a range analysis was performed as shown in the figures 2 (below). It can be see, that the result of the analysis of forward reaches are the same (comparison of results from figure 11 in the article, row 473 and figure 2 below) for predefined avatar (1774 mm) and avatar with body height of 1780 mm, because in analysis the adjusted workstations for each avatar was used.

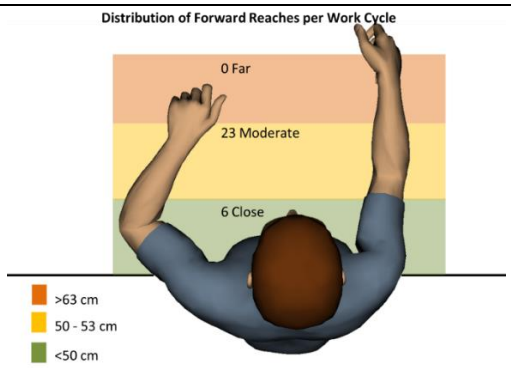


Fig. 2: distribution of forward reaches per work cycle on smart assembly workstation, worker`s body height = 1780 mm.

In the third figure (Fig. 3, below) the reach envelope of avatar is presented. It gives us the result that all grab containers are within reach, which means that the workstation is ergonomically suitable for performing manual assembly in the long run without any consequences for health.

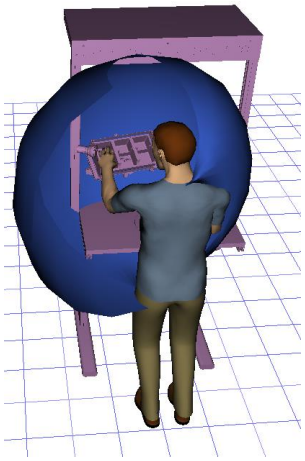


Fig. 3: Reach envelope.

In the article we changed the avatar body height to 1780 mm (as the height of the average experiment participants), as you suggested, because the analysis shows the same results (rows 376-377).

In row 308. you mentioned “labels that are colored red” on figure 8? I don’t see the red labels. Is it important to be presented on picture?

Thank you for you observation, this is our mistake, instead of red colored label, we use bold text in the figure. This mistake is appropriate corrected in the text of the article (rows 393-394). The labels are important, because they represent the data (information) to facilitate the interpretation and understanding how the smart assembly system works.

In the conclusion (row 437) you said that “…research has shown that the assembly of simple products can be carried out without errors”. How? According to table 2, errors occurs during the assembly of both of your product (P1 that is more complex and P2 that is a less complex product).

Thank you for the observation. It’s true, you figured it out correctly. Our conclusion was too hasty. It needs to be states that assembly of the product with digital instructions on smart assembly workstation can be carried out with **less** errors than on traditional one. And as we stated before, for future work the AR instructions need to be implemented, and analysis need to be made to figured out if non-error assembly is possible. The conclusion is corrected in the article (row 525).

In my opinion, the subject of the manuscript is very timely and widely described in scientific journals, which is why the literature review seems to be poor. Addition of certain

number of recent literature is obligatory. For example, paper "Utilization of Industry 4.0 Related Equipment in Assembly Line Balancing Procedure", Processes 2020, 8, 864, presents only one of reported custom made visual guidance solutions incorporating I4.0 related equipment, nevertheless only limited number of these solutions are mentioned to exists, in rows 78-87. Paper „Assembly system configuration through Industry 4.0 principles: The expected change in the actual paradigms". IFAC-PapersOnLine 2017, 50, revealing consequence during transformation to Industry 4.0, which could strongly impact on the actual assembly paradigms, including in manual assembly. The paper „Information-level real-time AR instruction: a novel dynamic assembly guidance information representation assisting human cognition", The International Journal of Advanced Manufacturing Technology volume 107, pages 1463–1481(2020), could presents as leading point in future research, as AR is emphasized…
Thank you for underlining this deficiency. We added new proposed literature (and some additional) in the section Introduction and extended this section for more detailed literature review.
Please check the text by native English speaker. Already in Abstract, there are sentences which are difficult to follow. Minor typing errors are found.
Thank you for pointing this out. The article was grammatically checked by native English speaker, and hopefully all minor typing errors were corrected as well as sentences improved.