Model-based Multi-Attribute Collaborative Production Cell Layout Optimization

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Abstract—**Designing the layout of a work cell remains a challenging problem due to the large search space of possible layouts which is often subjected to a variety of optimization objectives. This paper proposes a model-based methodology to aid the layout design of a collaborative work cell. This model takes into account feasibility, reachability, safety and ergonomics as constraints in the layout optimization formulation. Determining reachability and static placement feasibility is accomplished using 3D Computer Aided Design (CAD) files as inputs combined with inverse kinematics. Geometric characteristics, like bounding boxes, and assembly requirements are determined from the 3D CAD files and used in the layout optimization. Inverse kinematics is used to calculate the reach of the robots and to reliably estimate ergonomic workload of an operator in the work cell. The optimized layout of the work cell is visualized for every start and end point of an assembly task, which allows to provide task instructions to operators and could potentially be used to program the robots and cobots. The methodology is validated on a practical use case.**

Index Terms—**Collaborative work cell, Model-based design, Mixed integer linear programming, Inverse kinematics, 3D CAD files.**

I. INTRODUCTION

A current challenge in manufacturing is the design of a work cell's layout. The layout of such a work cell needs to be optimized, but is usually subjected to multiple and often conflicting design objectives such as: cost, lead time, space, operator mental load and operator ergonomics. Furthermore, the coming to market of cobots, robots that are designed to safely interact with human operators [8], makes the optimization task even more exacting due to the additional challenge in distributing tasks to either a human or a cobot, and due to the increased number of possible layouts. However, the potential economic gain in designing a good layout can be significant. In addition, a collaborative work cell, where humans and cobots cooperate to accomplish a certain task, has the advantage the operator's ergonomics and mental load can be improved as cobots can perform heavy and repetitive tasks.

While designing a good work cell is still an art, tools for evaluating work cells have already become widely used. Performance attributes like cost, space and lead time can be calculated with relative ease once a design is put forward. Additionally, more advanced tools are able to estimate the ergonomic load of the operator [6], [17]. The knowledge implemented in these tools is mostly based on surveys [19] or information measured by wearables that detect posture or muscle strain of the operator [5], [9]. These tools can be used by designers to compare, rank or weigh different work cell designs against each other.

Even though good ergonomic evaluation tools exist, the ergonomic work load is often neglected in the optimization of a work cell. However, it is an important hidden cost as people have to work longer and the average age of the work force increases. An excessive ergonomic load can lead to musculoskeletal disorders, which have a significant economic impact [4].

At least two stages can be distinguished in the design of a work cell. First, different tasks have to be scheduled and assigned to *resources*, where the term resource includes robots, cobots, machines, conveyor belts, operators, etc. Second, the geometric layout of the cell has to be determined taking into account certain goal values. The objective of this paper is to focus on the latter and reach a computer-aided and model-based approach to help the designer in laying out the geometry of the work cell, taking into account space limitations and the operator's ergonomic work load.

The main contributions presented in this paper are:

- The focus on the ergonomics of the operator during the optimization of the physical layout of a collaborative work cell;
- The usage of an inverse kinematics algorithm for robots to avoid overlap in the work cell and thus assure feasibility;
- The usage of an inverse kinematics algorithm for humans to also determine ergonomic scores for operator handlings which are taken into account during optimization.

The remainder of this paper is structured as follows: Section II describes the state of the art on both work cell optimization and ergonomic evaluation, Section III describes the optimization problem in more detail, Section IV illustrates the approach on a production use case, Section VI summarizes the conclusions, and finally Section V contains ideas for further research.

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II. State of the Art

A. Work cell optimization

In scientific literature, work cell optimization is a broad term referring to different optimization problems in which we can distinguish four main interpretations. A first interpretation is the optimization of the resource allocation of a work cell. Here, the input consists of a list of assembly steps and the output is a set of resources that is able to execute these assembly steps. The objective of the optimization problem can, for example, be the resource cost. Constraints on functionality and payload of the resources are taken into account. The approaches in [10], [14] are examples of this interpretation.

A second interpretation focuses on the optimization of the task distribution between humans, robots or cobots without assigning specific resources [3], [23], [25]. A list of capabilities of different types of resources are used as input, together with the list of assembly steps of the product. The objective is the feasibility of task distribution, while also allowing to optimize for cost or efficiency. Another objective can be ergonomic work load of the operator, again based on work load estimations, since no detailed work cell layout is known at this moment. In [25], cognitive load of the operator is taken into account during optimization.

A third interpretation is the optimization of time scheduling the assembly tasks [7], [16], [22]. A task and resource allocation is used as input and minimizing throughput time is the objective. However, also here, only time estimations are available, since the detailed layout is still unknown.

A fourth interpretation is the optimization of a work cell's physical layout which is the interpretation that is focused on in this paper. Design of work cells for human-robot collaboration has already been applied in [26], [27], where a 3D simulation tool is connected to an analytic tool for estimating characteristics like used work cell space, ergonomic load and throughput time. The result is a number of alternative work cell layouts with their respective goal values. In contrast, our approach is purely analytic and incorporates goal values, like ergonomic scores, directly into the optimization problem that determines the work cell layout, while allocation of resources is done upfront. This allows for an accurate work cell layout and ergonomic evaluation.

Finally, combinations of the four previous described interpretations have also been investigated in literature. In [10], three types of task and resource allocation are discussed: Global Task and Resource optimization, Task optimization and local resource allocation, but with resource alternatives, Task optimization and local resource allocation (optimization), with prioritized resources. The authors in [12] focus on the non-linear problem for the base placement, task sequencing and motion coordination of a robot arm and a rotating table. In [18], a broad approach is suggested that looks at task extracting, human robot task allocation and task scheduling, but does not focus on work cell layout.

B. Ergonomic evaluation

Currently, many tools exists which allow the evaluation of ergonomics by using either surveys or either wearables that either detect posture or measure muscle strain of an operator. Most of these tools focus on the ergonomics of a specific situation. For scoring the posture of an operator standing or sitting at a work station, potentially during repetitive tasks, the Rapid Upper Limb Assessment (RULA) scoring [19] can be used. Alternatively, the Rapid Entire Body Assessment (REBA) tool [15] assess postures during static or rapidly changing actions. Another tool to asses the impact of repetitive tasks, is the Assessment Of Repetitive Tasks Of The Upper Limbs (ART) tool [13]. For lifting heavy loads from different heights, the NIOSH lifting equation [29] offers a quantitative way of assessing lower back strain on the operator. Other assessment tools include the strain index [20] and the Rodgers Muscle fatigue analysis [24]. The website [17] offers online calculators to evaluate several ergonomic scores, such as RULA, the NIOSH Lifting Equation, the WISHA Lifting Calculator, the Rapid Entire Body Assessment (REBA), the Liberty Mutual Manual Material Handling Tables (Snook Tables), and the Washington State Ergonomic and MSD Risk Assessment Checklist.

III. Layout optimization

This section introduces our model-based design methodology for optimizing the layout of a collaborative work cell. First, the general problem description is given. Subsequently, the decision variables, goal function and constraints are discussed in detail.

A. Problem description

The input for our model-based design methodology consists of the assembly steps of the product, the task allocation of the assembly steps to resources, a schedule of the assembly steps, specific constraints for the work cell (e.g. the space limitations, positions where work pieces enter/exit the work cell, . . .) and the 3D Computer-Aided Design (CAD) files of both the product components and resources. The 3D CAD files are used to extract geometrical information, such as bounding boxes, from the product components and resources. Moreover, these 3D CAD files are also used to assure reachability and calculate ergonomic work load by applying inverse kinematics to the robots and human operators.

These inputs are used in the analytic formulation of the optimization problem that describes the necessary relations and physics of the components. The formulation of the optimization, which combines the scheduling information with the geometric inputs from the CAD files, is described below. The output of the problem consists of the layout of the work cell with the detailed positioning of the resource components at every start and end point of an action. Moreover, an ergonomic score as well as other performance values are possible outputs of the optimization approach, depending on the chosen optimization objective.

This optimization problem can be mathematically formulated as

$$\underset{\mathbf{x}}{\text{minimize}} \quad w_1 \cdot E(\mathbf{x}) + w_2 \cdot S(\mathbf{x}) + w_3 \cdot P(\mathbf{x}) \tag{1}$$

subject to

$$f(\mathbf{x}) = 0,$$
$$g(\mathbf{x}) \leq 0,$$

where $\mathbf{x}$ is a vector containing the decision variables related to position and orientation of the different work cell elements, $E(\mathbf{x})$ is the ergonomic score of a layout, $S(\mathbf{x})$ the space occupation of the work cell, $P(\mathbf{x})$ an additional performance indicator of interest, f and g contain the coefficients for the feasibility constraints, and w_1, w_2 and w_3 are weighting factors. Applying a weighted objective formulation does not have to be restrictive, as in many cases ergonomics is a priority (i.e. w_1 is chosen to favor $E(\mathbf{x})$, and w_2 might be expressed as an equivalent cost of occupied factory space). Multi-objective optimization, like, e.g. computing a Pareto front, is out of the scope of this paper.

The problem is formulated using discrete variables $\mathbf{x}$ and is solved using a NLIP solver.

B. Decision variables

The two main decision variables of Equation (1) are the position and orientation of the work cell elements (i.e. product components and resources) in each action. To discretize the positions, the positions are expressed on a discrete grid of size $1\mathrm{dm}$.

The orientation of each work cell element (i.e. product components and resources) in each action is described by one or more of angles around predefined rotation axis or points. For work pieces, only one rotation point is defined in the centre of gravity. For robots and operators, the rotation axes and rotation points lie at the joints, see e.g. Figure 1. The angles of the robots and operators are related to the stance of the arms and the position of the hands or end effector.

To alleviate some of the computational cost during optimization, the rotation-related information is extracted from the 3D CAD files ahead of the optimization. In this preprocessing procedure, first, the axis-aligned bounding box for each part of the assembly from the input CAD files is calculated. Second, for each robot in our resource library, the set of points which can be reached by the robot is determined by using an inverse kinematics algorithm. To limit the number of points, only points are considered that lie on a regular grid with grid size $1\mathrm{dm}$ and the origin of the grid aligned with the origin of the 3D model of the robot, see $(X_\mathrm{r}, Y_\mathrm{r}, Z_\mathrm{r})$ in Figure 1. For each point on the grid, we use the Cyclic Coordinate Descent (CCD) algorithm to (i) test whether the robot can reach the point, and (ii) find the configuration of the robot (i.e. the angles of the robot joints). The CCD algorithm tries to minimize the distance between the end effector and a target by iteratively fixing part of the rotational coordinates and using analytical formulas. More details can be found in [28], [21]. An example of such a grid of reachable points, which we refer to as the *reach cloud*, is shown in Figure 2. Each point is implicitly linked to a certain combination of angles in each of the joints. Typically, for many grid points, there are multiple combinations of angles that solve the inverse kinematics problem. For robots, angles are chosen that follow logically from the neighboring points, i.e. there are no large jumps in angles when moving from one point to its neighbor. For the operator, additionally, the angle combination is chosen

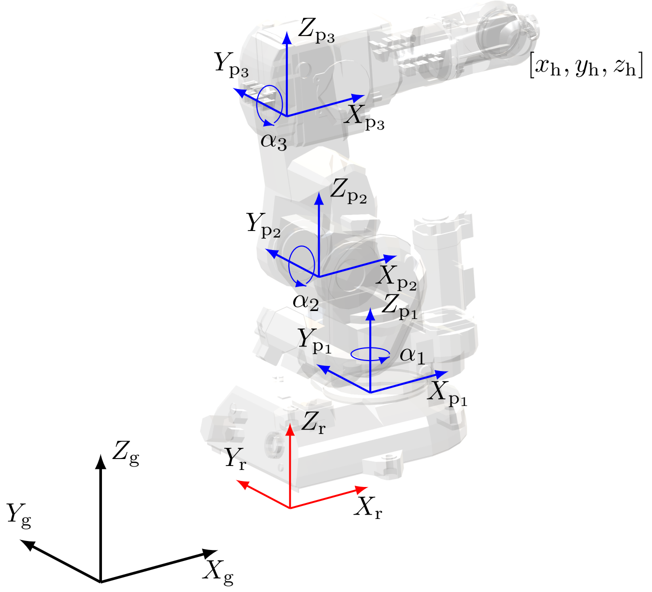

Figure 1. Example of the orientation and positioning of the robot. The robot position is expressed in global coordinates $(X_\mathrm{g}, Y_\mathrm{g}, Z_\mathrm{g})$, the position of the parts in robot coordinates $(X_\mathrm{r}, Y_\mathrm{r}, Z_\mathrm{r})$ and the sizes of the parts are expressed as the maximum coordinates in part coordinates $(X_{\mathrm{p}_i}, Y_{\mathrm{p}_i}, Z_{\mathrm{p}_i})$, for $i = 1, \ldots, 3$. Position of the “hand”, $[x_\mathrm{h}, y_\mathrm{h}, z_\mathrm{h}]$ is expressed in the robot coordinate system $(X_\mathrm{r}, Y_\mathrm{r}, Z_\mathrm{r})$ and determined by the three angles $(\alpha_1, \alpha_2, \alpha_3)$. CAD model: [1].

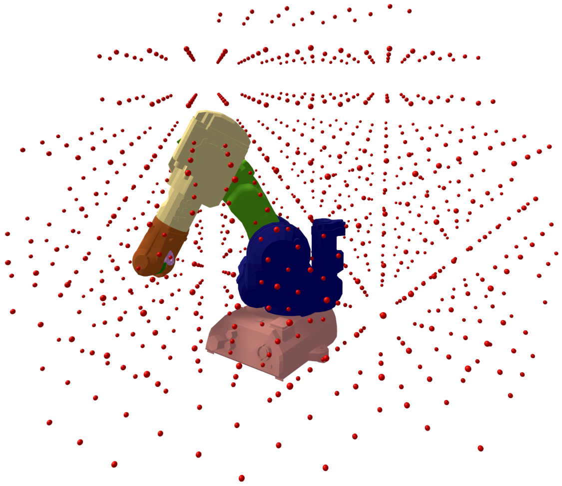

Figure 2. Visualization of a robot’s reach cloud. To generate the reach cloud, a Cyclic Coordinate Descent (CCD) inverse kinematics algorithm is used to test for each point on a regular grid of $1\mathrm{dm}$ centered around the robot whether it can be reached by the robot. CAD model: [1].

that minimize the RULA score among all possible angles that allow reaching a gridpoint, presuming the aforementioned smooth transition of angles is satisfied.

To avoid excessive calculations during the optimization, the optimization routine works with these predetermined grid points, and the corresponding position of the different parts of the robot or operator. The optimization routine returns the optimal orientation of the parts as an index that indicates the optimal grid point for each player in each action. Afterwards, this index can be linked back to a combination of angles that can be fed to the visualization routine or could be the input for the robot controller.

C. Goal function

The goal function consists of the ergonomic score $E(\mathbf{x})$, the work cell surface $S(\mathbf{x})$, and a potential third metric $P(\mathbf{x})$.

The space $S(\mathbf{x})$ is considered to be shaped as an axis-aligned box and can thus be determined based on the minimum and maximum coordinate in each of the three main directions.

To score the ergonomics, a combination of two ergonomic assessment formulas is used. First, when the operator is applying an action that does not involve picking up or placing a work piece down, only the RULA scoring system is used [19]. RULA scores the operator on its stance while working over the table and handling the different work pieces. Recall from Section III-B that the stance of the operator is defined through a grid of reachable points, where each point corresponds to a set of angles for the joints of the operator. The RULA score is defined through the same angles, so each stance point corresponds to a certain RULA score. Three angles are taken into account to compute the RULA score: the hip angle, the angle of the shoulder and the angle of the elbows, as well as the weights of the items being handled. The RULA scoring system contains many other criteria that determine the score, like wrist angles, twists, leaning and frequency of the actions. These are however not yet taken into account, and presumed to be optimal while computing the score.

When the operator is involved in picking up or placing an object down, both RULA scoring and the NIOSH lifting equation are used [29]. The NIOSH lifting equation also takes into account the vertical and horizontal positioning of the object being handled. The NIOSH score is computed from the information of the stance of the operator and through its movements as well as the weight of the parts. This is information known during the geometric optimization. As for the RULA score, twist and frequency of the movement, which are also part of the NIOSH scoring, are not yet incorporated.

A RULA score of more than 2 indicates that change may be needed [19]. For the NIOSH lifting index, a value above 1 indicates that a redesign might be useful. Therefore, we use the following ergonomics related term in the goal function (for actions involving the operator)

$$E(\mathbf{x}) = \mathrm{RULA}(\mathbf{x}) + 2 \cdot \mathrm{NIOSH}(\mathbf{x}), \tag{2}$$

where $\mathrm{NIOSH}(\mathbf{x})$ is zero for operations that do not involve lifting.

D. Constraints

The following constraints are applied to the positions of the elements in the work cell to result in physically logical behaviour. First, the positions are constraint to avoid overlap of the bounding boxes of the different elements in the work cell. Second, the vertical positions are constraint to limit the z-coordinates of the elements to the ground or table height. Third, the elements are constrained to be located within the area of the work cell. Finally, elements are constrained to move only when it is demanded by the action at hand.

The reachcloud information, as outlined in Section III-B, allows overlap and intersection testing between different work cell components and operators during optimization as well as testing of the reachability of work pieces.

Further possible constraints that might be of value to the final design, but are not yet implemented, include the orientation of work pieces when joining, safety considerations involving robots in between actions and more detailed transportation of pieces, e.g. to avoid conflicts during actions.

IV. APPLICATION

To illustrate our approach we apply our method to a simplified version of the "clinching case", which is described in detail in [14]. The clinching case considers the clinching of eight corners to a piece of sheet metal casing that has been folded in four to form a rectangular tube (see the workpieces in Figure 4).

To illustrate our method, we simplified this problem by restricting the number of corners to be clinched to four and applying a very basic, self-performed scheduling and allocation, without using optimization. Two robots and one human operator are allocated to perform the following tasks in order. First the folded sheet metal should be removed from the folding machine. Second the corners should be transported to the tube where, finally, they should be clinched by the operator in sets of two. This scheduling and allocation is depicted in Figure 3.

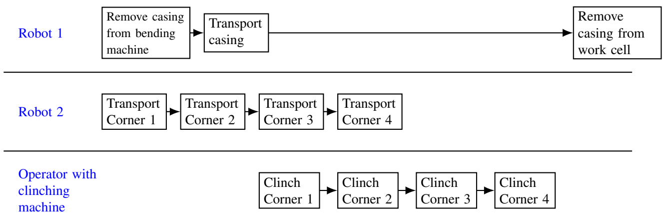

Figure 3. Allocation and scheduling of the simplified clinching case. One robot removes the casing from the bending machine and transports the casing through and out of the work cell. The second robot is responsible for transporting the corners, which the human operator clinches using the clinching machine.

All the work cell elements are depicted in Figure 4. Next to these active elements, the cell also contains three tables. The z-position of these tables is constrained to the floor, but the optimization routine is free to choose both the xy-position and the scale of the tables in every direction. Both the casing and the corners are restricted to enter the work cell at predefined locations, representing the supply of work pieces to this work cell.

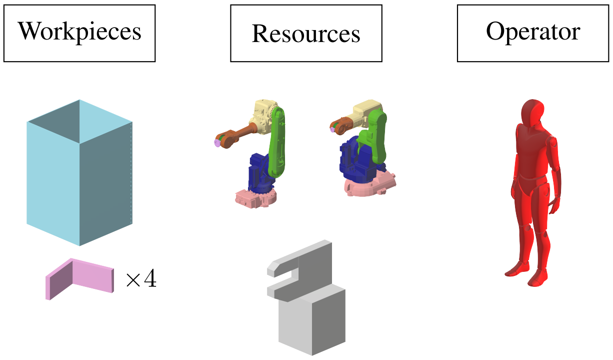

Figure 4. Different work cell elements of the simplified clinching case. There are five workpieces: four edges and one metal casing. The available resources consist of two robots and a clinching machine. Finally, we also have a human operator as a resource. (3D CAD files: [2], [1], [11])

The first (larger) robot handles the folded sheet metal, while the other (smaller) robot and human transport the corners. The corners are fed to a clinching machine, which is operated by the operator at the time of the clinching action. The square tube is held by a fixture at the time of the clinching. The different robots and work pieces are represented by 3D CAD files that are analyzed by the geometric preprocessing tool. This results in the necessary geometric information: bounding boxes, reach clouds and ergonomics scores. Together with the predetermined allocation and scheduling results, these form the inputs to the geometric optimization.

For this case, we optimize ergonomics and work cell area described by Equation (1), where we specifically want to focus on ergonomics by using weights $w_1 = 100$, $w_2 = 1$, and $w_3 = 0$ (since there are no additional performance terms). The results are returned to the 3D processing tool which results in visualization of the work cell, as depicted in Figures 5 through 8. The tool finds the optimal location of the clinching machine, the robots and the tables, as shown in the starting positions of the work cell in Figure 5.

The casing is fixed into position by the first robot, while the second prepares the corners. Note that the corners are placed by the robot on a table with the correct height, so that the operator does not have to bend his back and can pick up the corners with reasonable RULA (2) and NIOSH (0.15) score, see Figure 7. Finally, the corner is clinched to the casing by the operator in Figure 8. This action amounts to a RULA score of 3, indicating more significant strain on the operator which is due to the height of the clinching machine. The stance of the operator during clinching is determined by the interaction with the casing which is fixed to the clinching machine. Due to the height of the clinching machine, the operator has to lift the right arm higher up which results in a larger shoulder angle causing an increased RULA score. This is can only be avoided by using a lower clinching machine.

V. FUTURE WORK

Currently, our methodology assumes that the task scheduling and resource allocation are defined in advance. A first promising idea that could lead to improved ergonomics would be to relax this assumption and to link the layout optimization with the resource and task allocation, such that ergonomic work load can be taken into account on all three optimization levels. While our initial tests to integrate the three optimization levels into one mixed integer linear problem proved to be too computationally demanding for realistic cases, another possible solution would be to create a feedback loop between the layout optimization and the resource and/or task allocation and running the three optimization stages multiple times.

Related to the idea of a feedback loop, a second idea would be to use the information from the layout optimization to update the execution times estimated during scheduling and resource and task allocation. The output of the layout optimization provides all distances that must be bridged by work pieces and resources. These distances can be used to update the estimates of each task's time and the total lead time, which could potentially result in another more optimal task schedule and/or resource allocation.

A third idea is to extend the collision detection to not only test at the start and end points of the assembly tasks, but also during the execution of the assembly tasks. Such an extension could be used to further fulfill safety constraints, without the need to make the layout too conservative.

VI. CONCLUSION

This paper presents a model-based methodology to aid a designer in optimizing the layout of a collaborative work cell, allowing him to make his own trade-off between optimizing space occupation and ergonomic work load of the operator. The methodology presumes resources have been allocated, tasks have been scheduled and outputs a feasible work cell, guaranteeing no static collisions between work pieces and resources and that all the work pieces are reachable by robots and operators during their assigned actions.

The major contribution of our work is the detailed ergonomic score evaluation and the reach cloud computation of robots and cobots in the optimization routine. Furthermore, expensive inverse kinematics calculations for evaluating reachability are avoided during optimization, by calculating the reach clouds in advance. The geometric information of robots, cobots and operators, required for reachability and collision detection, is extracted from 3D CAD files. Furthermore, the input for overlap constraints, grip points and assembly direction are also extracted from these 3D CAD files, which makes the input and optimization more transparent for a designer.

Finally, to validate our model-based design methodology, we applied it on a realistic use case.

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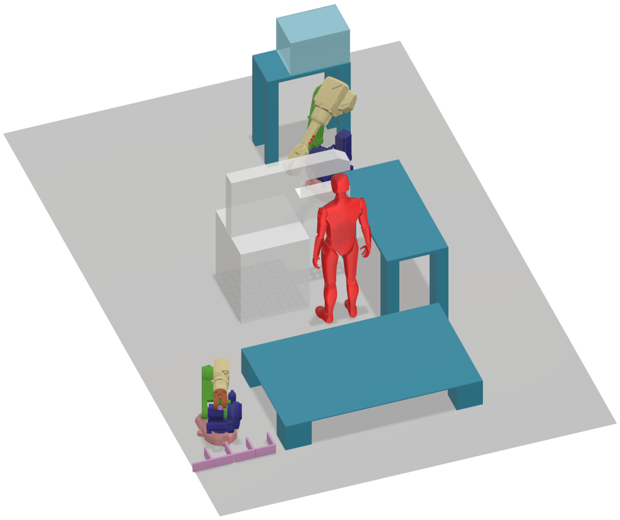

Figure 5. Start positions of the work cell.

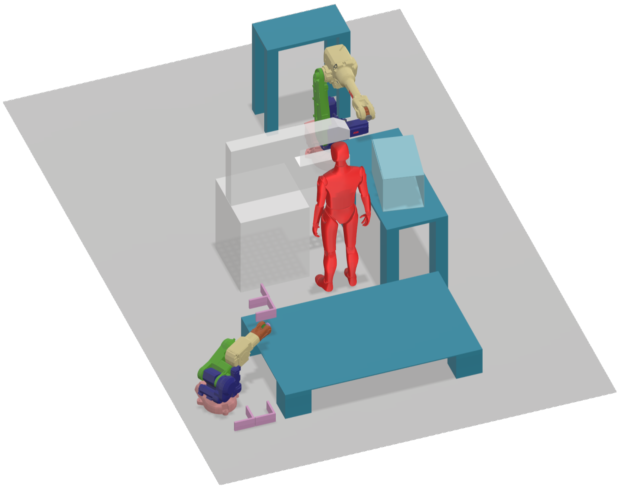

Figure 6. The corner is set by the robot.

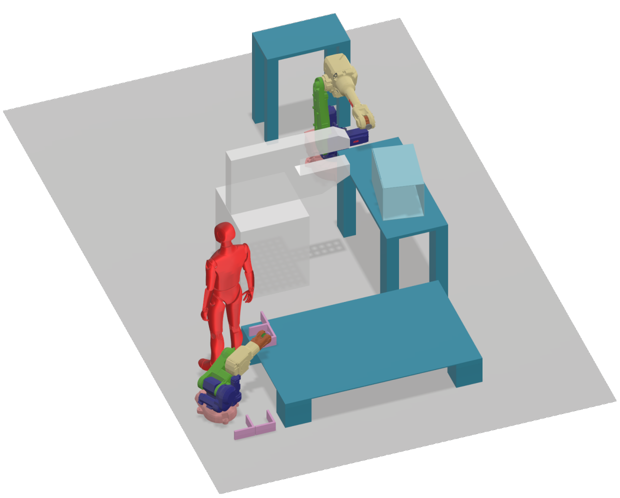

Figure 7. The corner is picked up by the operator. This action has a RULA score of 2 and a NIOSH index of 0.15.

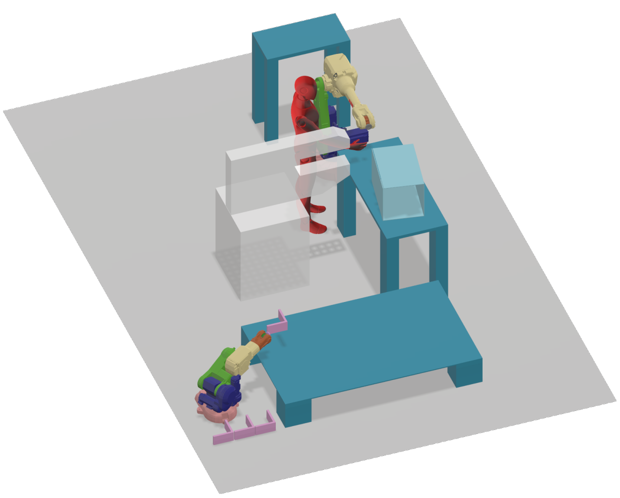

Figure 8. The corner is clinched by the operator, using the clinching machine. This action has a RULA score of 3.

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REFERENCES

[1] ABB: IRB 140 CAD model. https://new.abb.com/products/robotics/industrial-robots/irb-140/irb-140-cad ([Online; accessed October-2018])

[2] ABB: IRB 2600 CAD model. https://new.abb.com/products/robotics/fr/robots-industriels/irb-2600/irb-2600-cad ([Online; accessed October-2018])

[3] Bänziger, T., Kunz, A., Wegener, K.: Optimizing human-robot task allocation using a simulation tool based on standardized work descriptions. Journal of Intelligent Manufacturing pp. 1–14 (apr 2018). https://doi.org/10.1007/s10845-018-1411-1

[4] Bevan, S.: Economic impact of musculoskeletal disorders (MSDs) on work in Europe. Best Practice & Research Clinical Rheumatology **29**(3), 356 – 373 (2015). https://doi.org/https://doi.org/10.1016/j.berh.2015.08.002, occupation and Musculoskeletal Disorders

[5] Busch, B., Maeda, G., Mollard, Y., Demangeat, M., Lopes, M.: Postural optimization for an ergonomic human-robot interaction. In: 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). pp. 2778–2785 (Sep 2017)

[6] Caputo, F., Gironimo, G.D., Marzano, A.: Ergonomic optimization of a manufacturing system work cell in a virtual environment. Journal of advanced engineering **46**(5), 21–27 (2006)

[7] Casalino, A., Cividini, F., Zanchettin, A.M., Piroddi, L., Rocco, P.: Human-robot collaborative assembly: a use-case application. IFAC-PapersOnLine **51**(11), 194–199 (2018). https://doi.org/10.1016/j.ifacol.2018.08.257, 16th IFAC Symposium on Information Control Problems in Manufacturing INCOM 2018

[8] Couroussé, D., Florens, J.: Cobot. Enactive Systems Books (jan 2007)

[9] Diego-Mas, J.A., Alcaide-Marzal, J.: Using kinect®sensor in observational methods for assessing postures at work. Applied Ergonomics **45**(4), 976 – 985 (2014)

[10] Fasth, Å., Provost, J., Fabian, M., Stahre, J., Lennartson, B.: From task allocation towards resource allocation when optimising assembly systems. Procedia CIRP **3**, 400–405 (2012). https://doi.org/10.1016/j.procir.2012.07.069, 45th CIRP Conference on Manufacturing Systems 2012

[11] GRABCAD: https://grabcad.com/ ([Online; accessed October-2018])

[12] Gueta, L.B., Chiba, R., Arai, T., Ueyama, T., Ota, J.: Practical point-to-point multiple-goal task realization in a robot arm with a rotating table. Advanced Robotics **25**(6-7), 717–738 (2011). https://doi.org/10.1163/016918611X563274, https://doi.org/10.1163/016918611X563274

[13] Health And Safety Executive (HSE): Assessment Of Repetitive Tasks Of The Upper Limbs (The ART Tool). HSE Books (mar 2010)

[14] Herzig, S.J.I., Berx, K., Gadeyne, K., Witters, M., Paredis, C.J.J.: Computational design synthesis for conceptual design of robotic assembly cells. In: 2016 IEEE International Symposium on Systems Engineering (ISSE). vol. 1–8 (2016). https://doi.org/10.1109/SysEng.2016.7753183

[15] Hignett, S., McAtamney, L.: Rapid entire body assessment (REBA). Applied Ergonomics **31**(2), 201–205 (2000). https://doi.org/10.1016/S0003-6870(99)00039-3

[16] Lee, I.S.: Minimizing total completion time in the assembly scheduling problem. Computers & Industrial Engineering **122**, 211–218 (aug 2018). https://doi.org/10.1016/j.cie.2018.06.001

[17] Mark Middlesworth, E.: Recommended ergonomic assessment tools. https://ergo-plus.com/ergonomic-assessment-tools/ ([Online; accessed 17-December-2018])

[18] Mateus, J.E.C., Claeys, D., Limère, V., Cottyn, J., Aghezzaf, E.H.: A structured methodology for the design of a human-robot collaborative assembly workplace. International Journal of Advanced Manufacturing Technology - revised version submitted (2018)

[19] Mcatamney, L., Nigel Corlett, E.: RULA: A survey method for the investigation of work-related upper limb disorders. Applied ergonomics **24**(2), 91–99 (apr 1993). https://doi.org/10.1016/0003-6870(93)90080-S

[20] Moore, S.J., Garg, A.: The strain index: A proposed method to analyze jobs for risk of distal upper extremity disorders. American Industrial Hygiene Association Journal **56**(5), 443–458 (jun 1995). https://doi.org/10.1080/15428119591016863

[21] Olsen, A.L., Petersen, H.G.: Inverse kinematics by numerical and analytical cyclic coordinate descent. Robotica **29**(4), 619–626 (2011). https://doi.org/10.1017/S026357471000038X

[22] Qin, W., Huang, G.Q.: A two-level genetic algorithm for scheduling in assembly islands with fixed-position layouts. Journal of Systems Science and Systems Engineering **19**(2), 150–161 (Jun 2010). https://doi.org/10.1007/s11518-010-5133-y, 10.1007/s11518-010-5133-y

[23] Ranz, F., Hummel, V., Sihn, W.: Capability-based task allocation in human-robot collaboration. Procedia Manufacturing **9**(C), 182–189 (2017)

[24] Rodgers, S.H.: A functional job analysis technique. Occupational medicine (Philadelphia, Pa.) **7**(4), 679–711 (10 1992)

[25] Roncone, A., Mangin, O., Scassellati, B.: Transparent role assignment and task allocation in human robot collaboration. In: 2017 IEEE International Conference on Robotics and Automation (ICRA). pp. 1014–1021. Institute of Electrical and Electronics Engineers Inc. (may 2017). https://doi.org/10.1109/ICRA.2017.7989122

[26] Tsarouchi, P., Michalos, G., Makris, S., Athanasatos, T., Dimoulas, K., Chryssolouris, G.: On a human-robot workplace design and task allocation system. International Journal of Computer Integrated Manufacturing **30**(12), 1272–1279 (2017). https://doi.org/10.1080/0951192X.2017.1307524

[27] Tsarouchi, P., Spiliotopoulos, J., Michalos, G., Koukas, S., Athanasatos, A., Makris, S., Chryssolouris, G.: A decision making framework for human robot collaborative workplace generation. Procedia CIRP **44**, 228–232 (2016). https://doi.org/10.1016/j.procir.2016.02.103

[28] Wang, L.C.T., Chen, C.C.: A combined optimization method for solving the inverse kinematics problems of mechanical manipulators. IEEE Transactions on Robotics and Automation **7**(4), 489–499 (aug 1991). https://doi.org/10.1109/70.86079

[29] Waters, T.R., Putz-Anderson, V., Garg, A., for Occupational Safety, N.I., Health.: Applications manual for the revised NIOSH lifting equation. DHHS, U.S. Dept. of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Division of Biomedical and Behavioral Science (jan 1994)