A decision making framework for Human Robot Collaborative workplace generation

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Abstract

The Human Robot Collaborative (HRC) workplace design and the automatic task allocation can significantly decrease the time of a new set-up or a cell’s reconfiguration. This paper proposes a method for an HRC workplace layout generation and the preliminary assignment of human and robot tasks. A decision making framework is proposed in order for the location of all components in the available layout space to be decided upon. The evaluation of the alternative HRC workplace layouts is based on multiple criteria. The system has been integrated with a user interface into a 3D simulation tool and tested on an automotive industry case study.

Keywords: HRC; Search Algorithm; Multiple Criteria; Workplace generation; Design.

1. Introduction

The Human Robot Collaboration is viewed positively by today’s production firms, since it inspires their keeping up a favourable production cost, through the combination of both human skills and robot capabilities. The HRC workplace design and task allocation is a critical issue for the throughput increase and the cycle time reduction. When a process changes, an easy way of deciding a new layout is required for the cycle time improvement and the time reduction for re-design and reconfiguration.

The workplace layout design and optimization has undoubtedly been receiving considerable attention by researchers and experts in the last years [1], [2], [3], [4], [5], [6] and [7]. The problem has been also addressed as “the facility layout problem” [1], [2] and [3]. The HRC task allocation and coordination has also received the researchers’ attention [8], [9], [10], [11], [12], [13], [14] and [15]. The role of Digital Human Models (DHMs) has been also examined for the ergonomics analysis and workplace design [16].

Concurrently, there are numerous 3D commercial simulation tools that help the workplace designer in the preliminary stages of design, including the simulation of both humans and robots (e.g. eM-Workplace, Siemens PLM, 3D Automate, Visual Components etc.).

This paper investigates the problem of the HRC workplace design. The proposed method inspires to help designers and engineers with designing an HRC workplace, in its preliminary phases, by considering a large number of layout alternatives (Fig. 1). To this effect, a decision making framework is developed for the generation of alternative HRC workplaces and the initial task allocation. The main advantage of this framework is the evaluation approach that is based on multiple criteria.

Fig. 1. HRC workplace and task allocation Problem Overview
New criteria, depending on the specifications and requirements, can be integrated into this framework. The main questions to be answered during an HRC design, initially, have to do with the location of the passive resources (working tables, fixtures etc.) and active resources (humans and robots) given a task and secondly, with the number and type of active resources to be selected for a task.

The research contribution of this study, in comparison to the existing works, is summarized as follows. The concurrent modelling of human and robot tasks, as well as the taxonomy of the existing resources, in a unified model, is innovative. The evaluation of an HRC workplace layout, given multiple criteria, such as ergonomics, investment cost, robot reachability, minimum floor space etc. is quite similar to that of the designers’ experience. The incorporation of the resources’ suitability check, given the skills of humans and robots, for a specific task, is also a part of the decision to be made. Last but not least, the integration of the proposed decision making with 3D simulation models, in order for the use of spatial representation techniques to be overcome, enables the layout overview and a valid solution to be had in a short time.

2. Approach

A generalized model is proposed for the existing active and passive resources (Fig. 2 (a)). A pool of resources includes the active and passive ones. The active resources comprise humans and robots, whilst assembly tables, fixtures etc. constitute the passive resources. The suitable grippers and tools are the latest layer of active resources, when assembly components and parts belong to passive resources. The HRC workload (Fig. 2 (b)) is decomposed in a number of processes. A process involves a group of tasks (high level activities), which constitute a group of operations (low level activities) [17].

The first decision point of the proposed framework is the location of the passive resources in fixed or random 3D positions (Fig. 3). For a passive resource position in x, y and z axes, the next passive or active resource should be located in all the positions available except for the occupied ones. The next decision point is the allocation of the suitable active resources for a specific task. The location of the assigned active resources is the latest decision point. The rotation around the x, y and z axes is considered being fixed for all the resources.

The evaluation of the HRC workplace layout alternatives is based on the estimation of multi-criteria values for each alternative. The criteria that have been implemented are:

- The floor space in the working area;
- The Robot’s Reachability to Passive Resources;
- The Ergonomics;
The Investment cost.
The criterion of the floor space (FS) refers to the occupied space by an active or passive resource for a specific task. This is estimated by taking into account the x and y directions and is expressed by the following equation:

$$FS = (x_{max} - x_{min}) \times (y_{max} - y_{min})$$  \hspace{1cm} (1)

Where:
- \(x_{max}, y_{max}\): The maximum values of x, y positions for passive or active resource;
- \(x_{min}, y_{min}\): The minimum values of x, y positions for passive or active resource.

The robot’s capability of reaching the parts’ positions is the next criterion used. This criterion checks if the part that is laid on a passive resource is inside the robot’s work envelope. The relationship used for this estimation is:

$$E_{Reachability} = \begin{cases} true, & \sqrt{(x_{p} - x_{b})^2 + (y_{p} - y_{b})^2 + (z_{p} - z_{b})^2} \geq WE \\ false, & \sqrt{(x_{p} - x_{b})^2 + (y_{p} - y_{b})^2 + (z_{p} - z_{b})^2} \leq WE \end{cases}$$  \hspace{1cm} (2)

Where:
- WE: The robot’s work envelope is the range of movement, measured in meters;
- \(x_{b}, y_{b}, z_{b}\): The robot’s base frame position on the x, y and z axes respectively;
- \(x_{p}, y_{p}, z_{p}\): The part’s mass center position on the x, y and z axes respectively.

The ergonomics of the human tasks are also evaluated by considering only a convenient position on the height (z axis) of the human hands. When the parts to be assembled are closer to the human, the estimated factor is decreased. The estimation of this criterion is based on the following equation:

$$E_{z} = \begin{cases} 1.3 - z_{p}, & \text{if } z_{p} < 1.3 \\ 1.3, & \text{if } z_{p} > 1.7 \\ 1, & \text{if } 1.3 \leq z_{p} \leq 1.7 \end{cases}$$  \hspace{1cm} (3)

Where:
- \(E_{z}\): Ergonomics factor;
- \(z_{p}\): Position of the part on the z axis, measured in meters.

The experimental estimation of the most convenient positions of the parts is estimated from 1.3 to 1.7 meters (height).

The estimation of the ergonomics factor constitutes an initial rough analysis of human tasks ergonomics. Further analysis on ergonomics is possible in the 3D simulation environment by considering more important aspects of ergonomics, such as human age, muscles strain, fatigue etc.

The investment cost criterion is the last one used in the evaluation of alternatives. It concerns the cost of the active and passive resource for the specific alternative HRC workplace layout. The target investment cost should be kept as low as possible. The following equation is used for the investment cost estimation.

$$C_{Investment} = \sum_{k=1}^{N_{R}} C_{R} n_{R}$$  \hspace{1cm} (4)

Where:
- \(C_{R}\): Cost of active or passive resource;
- \(n_{R}\): Number of active or passive resources;
- \(N_{R}\): Maximum number of active and passive resources.

Since the multiple criteria values are estimated for each alternative, they are normalized and weighted for the final ranking. The normalized calculation for each alternative is between the value 0, for the worst alternative and 1 for the best alternative. The alternative with the maximum normalized value is selected as the final one.

The proposed decision making framework has been implemented as a viewer in the Process Simulate 3D simulation tool, utilizing the Tecnomatix libraries (Fig. 4). This graphical interface has been designed and integrated into this platform and enables its interaction with the decision making tool through web services. The viewer provides the user with information, such as the cell dimensions in width, length and height. The tasks, the suitable active and the passive resources are also required as input. The alternative HRC workplace layout is visualized in the 3D simulation environment. The simulation of the assigned HRC tasks is also possible in this environment, along with the further evaluation of the layout alternative.
3. Case study

The proposed methodology has been applied to a collaborative scenario from the automotive industry. The case study concerns the assembly of a vehicle’s rear axle with the axle wheel groups. The assembly sequence of this case is described in [21]. The HRC workplace layout of this assembly case study is generated with the proposed decision making tool. The HRC model described in section 3, is applied to this scenario as follows. The list of tasks, suitably active and being involved with task passive resources, in this case study, are visualized in Table 1. The user fills the dimensions of the cell in the viewer with x=5m, y=5m and z=5m.

Table 1. Data input for Rear axle assembly case.

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Suitable Active Resources</th>
<th>Involved to Task Passive Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load gripper 1</td>
<td>Robot or Human</td>
<td>Gripper loading table</td>
</tr>
<tr>
<td>Pick up axle</td>
<td>Robot or Human</td>
<td>Axle loading table</td>
</tr>
<tr>
<td>Place axle</td>
<td>Robot or Human</td>
<td>Axle assembly table</td>
</tr>
<tr>
<td>Unload gripper 1</td>
<td>Robot or Human</td>
<td>Gripper loading table</td>
</tr>
<tr>
<td>Load gripper 2</td>
<td>Robot or Human</td>
<td>Gripper loading table</td>
</tr>
<tr>
<td>Pick up wheel 1</td>
<td>Robot or Human</td>
<td>Wheels loading table</td>
</tr>
<tr>
<td>Hold wheel 1</td>
<td>Robot or Human</td>
<td>Axle assembly table</td>
</tr>
<tr>
<td>Pick up screw driver</td>
<td>Human</td>
<td>Human working table</td>
</tr>
<tr>
<td>Pick up screws</td>
<td>Human</td>
<td>Human working table</td>
</tr>
<tr>
<td>Install screws</td>
<td>Human</td>
<td>Axle assembly table</td>
</tr>
<tr>
<td>Pick up wheel 2</td>
<td>Robot or Human</td>
<td>Wheels loading table</td>
</tr>
<tr>
<td>Hold wheel 2</td>
<td>Robot or Human</td>
<td>Human working table</td>
</tr>
<tr>
<td>Install screws</td>
<td>Human</td>
<td>Human working table</td>
</tr>
</tbody>
</table>

The button on the viewer, upon being selected by the user, generates the HRC workplace layout. The user can select the same button as many times as are necessary to yield a good result. As an example, four different alternatives are visualized in Fig.5.

The final layout is selected on the basis of the highest value of the multi-criteria evaluation process (Fig. 6).

4. Discussion and conclusions

The need for easy and fast set-up or reconfiguration of an HRC workplace, keeps up with the need for increased production rate, decreased cycle time and cost. This proposed framework enables designers and engineers to easily evaluate and select or reject proposed workplace layouts for the human robot collaboration in production.

The proposed method for HRC workplace generation and task allocation, provides certain advantages such as the generalized unified model for active and passive resources, including both humans and robots, as well as working tables, fixtures etc. Another important advantage is the fact that multiple criteria are used for the evaluation of the alternative solutions. This has shown that an HRC workplace layout can be generated upon the criteria defined by the user and depending on the requirements and specifications. Last but not least, the results have shown an improvement on the use of 3D simulation tools for the automatic workplace generation and simulation, through the integration of graphical interfaces for a direct interaction with the user. In this way, the user can easily understand if the generated solution is also satisfactory.

5. Future work

The above results have brought about some issues for future improvement. In this direction, more criteria for the decision making algorithm can be considered. A more complete ergonomics analysis evaluation, including factors estimation such as fatigue, muscle strain etc., is given in an example. Automatic path planning modules will also be considered for future research to enable a more automatic solution for 3D simulation. KPIs, such as the time to completion measurement will be also possible with the integration of such tools.
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