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Simulation-Based Diversity Management in Human-Robot Collaborative Scenarios

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***Abstract*—**In this paper, the influence of diversity-related factors on the design of collaborative scenarios is analysed. Based on the evaluation, a framework for simulating human-robot-collaboration is presented that considers both human factors as well as the overall system performance. The implementation of the model is shown on a real-life scenario from industry and validated in terms of traceability, safety and physical limitations. By comparing scenarios that consider diversity with those only meeting system performance, an overall understanding of individually adapted human-robot-collaborative workspaces is reached. A diversity-related guideline for human-robot-collaborations provides a summary of the research and aids in optimizing future applications. Finally, limitations and future amendments of the model are discussed.

***Keywords*—**Diversity, human-machine-system, human-robot-collaboration, simulation.

I. Introduction

HUMAN-robot collaboration fills the gap between automatic assembly and manual assembly. It defines a direct interaction between humans and specifically designed robots [1]. Those so-called collaborative robots assist humans to fulfil particular tasks in predefined workspaces. Combining the skills of both, robots and humans, enhances productivity and enables to respond flexibly to variable degrees of automation [2], [3]. However, in order to fully exploit the potential of collaborative work, following aspects need to be considered with respect to the diversity of the collaborating personnel: Firstly machine selection and mounting, secondly task distribution and thirdly task execution [4].

Purchasing, mounting and programming collaborative robots allow a number of possibilities to meet individual human factors [5]. For example, there exist a large number of collaborative robots on the market varying in appearance, height, weight, payload, programming interface and safety functionality. Dependent on the capabilities of the human and the collaborative robot, a task can be distributed differently between the two partners. In addition, the task execution in terms of position and velocity can be adapted not only to the anthropometry of the personnel but also to their physical and psychic capabilities. In this sense, workspace, handling range, range of vision, illumination, configuration of peripheral equipment, position of tools and workpieces as well as business requirements need to be considered. The decision on purchasing and using a specific machine should not only be made based on fulfilling the task but also on the person collaborating with it.

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II. Diversity-Related Factors in Collaboration

Diversity-related studies mainly concentrate on so-called inner dimensions, i.e. personal characteristics that usually do not change during a lifetime [6]. These include age, gender, physical and psychic abilities, sexual orientation, religion and ethnic origin. In this paper, the influence of the first three dimensions is analysed in order to answer following questions:

- Which movements are necessary to fulfil the task?
- How much space and time is available for specific tasks?
- How often are specific tasks repeated?
- How heavy are production loads?
- What is the distance between individual workstations?
- What is the interdependence between individual tasks?

More specifically, it is investigated how much diversity-related factors influence individual working methods. As employees with varying diversities may develop different approaches to fulfil specific tasks, the analysis might lead to a required transformation of steps in the production process (e.g. height, weight or distance adjustability).

III. Simulation Framework

TABLE I
Model Parameters

Symbol	Human factors	Symbol	Machine factors
h_H	human height	p_M	mounting position
r_H	motion range	r_M	workspace
v_H	velocity	v_M	velocity
a_H	acceleration	a_M	acceleration
t_r	reaction time	m_M	payload
p_s	psychic abilities	F	forces

As digital human models only consider anthropometric data [7], such as height or motion range, a framework for simulating collaborative tasks needs to be expanded by including diversity-related factors [8]. A simulation model for collaborative tasks additionally considers parameters such as reaction time, physical and psychic abilities as well as forces applied (Table I). Thus, a collaboration model combines the functionalities of a digital human model as well as that of a machine model in terms of geometry and motion data [9]. Furthermore, it incorporates a numerical behaviour model of a human in order to represent behavioural changes resulting from mental or physical stress and a Boole's probability model of the sensor system in order to represent malfunctions of the control and regulation loop [10]. The latter is especially essential to validate the system's functionality in terms of safety for the operator (Fig. 1).

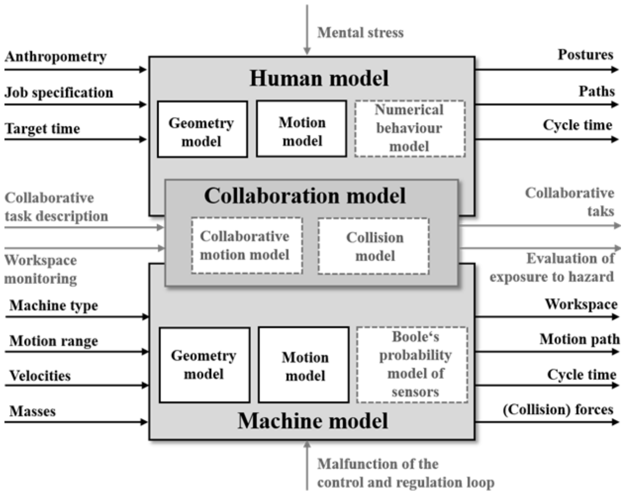

Fig. 1 Collaboration model with inputs and outputs

Collaborative tasks are tasks consisting of both discrete and continuous parts, i.e. the system states, e.g. moving, stopping, collaborating, are discrete (resulting from the monitoring behaviour of the system) whereas the motion behaviour of individual collaborative partners is continuous (Fig. 2). Following on from this, the simulation model was defined as a hybrid model using the modelling approach of DEV&DESS (Discrete Event and Differential Equation Specified System), introduced by [11]. A hybrid system with DEV&DESS is defined by a 11-tupel

$$\text{DEV \& DESS} = \begin{pmatrix} X^{discr}, X^{cont}, Y^{discr}, Y^{cont}, \\ S, \delta_{ext}, C_{int}, \delta_{int}, \lambda^{discr}, f, \lambda^{cont} \end{pmatrix} \quad (1)$$

where X^{discr}, Y^{discr} are the sets of event inputs and outputs, X^{cont}, Y^{cont} are the sets of continuous inputs and outputs, $S = S^{discr} \times S^{cont}$ is the set of states, $\delta_{ext}, \delta_{int}$ are external and internal state transition functions, $\lambda^{discr}, \lambda^{cont}$ are event and continuous output function, f is the rate of change function, and C_{int} is the state event transition function.

The hybrid collaborative model was implemented in MATLAB® based on the MatlabDEVS-Toolbox developed by the Computational Engineering and Automation research group at the University of Wismar [12]. The toolbox uses a modified discrete event simulator for simulating hybrid models that solves ordinary differential equations between individual state events to generate a continuous model behaviour. Thus, the toolbox also includes the extensions of the DEVS-theory by [13] to simulate the dynamic behaviour of hybrid models.

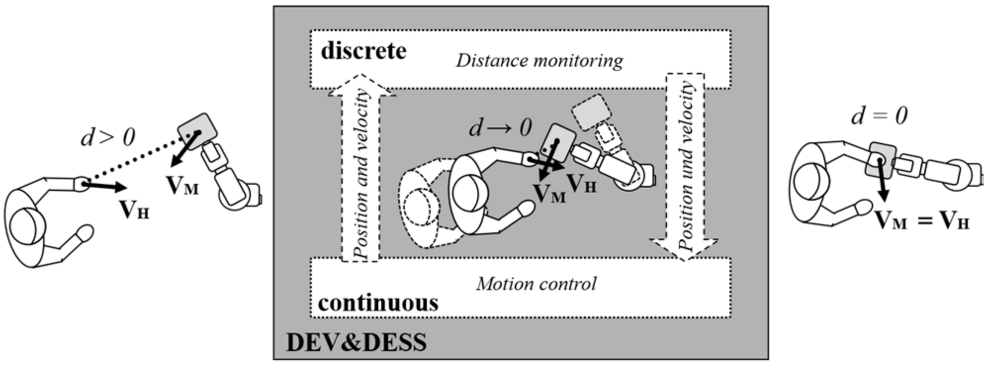

Fig. 2 Collaboration model as a hybrid model with DEV&DESS

IV. Model Implementation

A. Operating Principle of the System

The implementation of the model is presented on an industrial application in the food and beverage industry. Fig. 3 shows a robotic cell for unloading baking trays. Breads on baking trays stored on oven racks need to be manipulated on conveyor belts for further processing. One oven rack can keep up to 10 baking trays and is of a height of almost 2 m. In average, 12 breads, each of 750 g, are loaded on one tray resulting in an overall weight of 13,5 kg per tray.

The design of the application needs to meet requirements of an ergonomic manual operation in cases of a change between automatic and manual production (e.g. changing product volume, maintenance or failure). Thus, baking trays shall be either manually or automatically removed from oven racks. In the second case, racks are manually moved in docking stations in order to position them in the working range of an industrial robot.

B. Cycle Time Analysis

A direct comparison of automatic and manual operation shows that the robot takes more time in unloading a fully loaded oven rack than the operator (Table II). But yet the physical stress on the personnel in conducting the task needs to be considered too.

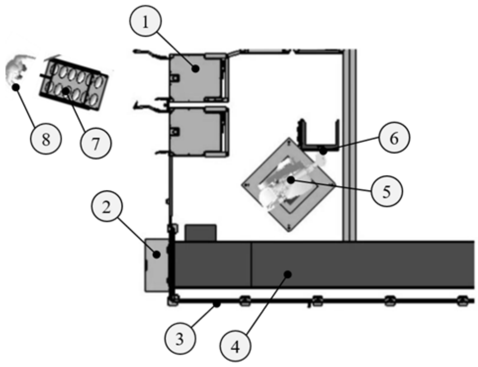

Fig. 3 Robotic cell for unloading baking trays (1 docking station, 2 manual unloading station, 3 safety fence, 4 conveyor belt, 5 industrial robot, 6 gripper, 7 oven rack, 8 operator)

TABLE II
COMPARISON OF AUTOMATIC AND MANUAL PRODUCTION

Characteristics	Automatic production	Manual production
Cycle time per rack	488.5 s	336 s
Oven racks per shift[a]	47	68
Breads per shift[a]	5,640 (6.3 t)	8,160 (9.2 t)
Utilisation	460 s break	no breaks

[a]considering an 80%-utilisation of the robot as well as the operator

C. Ergonomic Analysis

The objectives of the analysis were cycle time as well as human related ergonomics [14]. Three different kinds of people worked at the workplace. The characteristics of the personnel in terms of gender, height and weight are given in Table III.

TABLE III
CHARACTERISTICS OF THE PERSONNEL

Gender	Height percentile	Weight percentile
male	50^{th} (179 cm)	50^{th} (79 kg)
female	100^{th} (185 cm)	31^{st} (60 kg)
male	1.2^{nd} (160 cm)	98.3^{rd} (100 kg)

In case of maintenance or failure, not everybody of the present persons can handle the task of unloading the trays. Fig. 4 shows a RULA-analysis (Rapid Upper Limb Assessment) for unloading baking trays in different heights of an oven rack. With the help of the screening tool, biomechanical and postural loading on body parts such as neck, trunk and upper limbs can be assessed [15]. As bending is required to reach the lowest trays, an analysis is also conducted for the legs of the operators. Fig. 4 shows that the first two people are able to reach even the highest baking trays, whereas the third person has difficulties in reaching the top tray. The unloading of a tray in the middle of the rack is no problem for any of the persons, whereas unloading the lowest trays causes endangering postures for all three of them.

Besides reachability of trays, physical stress resulting from pushing oven racks and lifting of trays are evident. Pushing a fully loaded oven rack corresponds to a mass of almost 200 kg [16] and can be completed by all three persons according to a stress analysis based on [17] – even though the task is not recommended for women as well as for people over the age of 40. Furthermore, severe physical stresses resulting from frequent lifting and carrying of loaded baking trays are encountered. Considering an 80%-utilisation of the operator, manual production leads to a manipulation of 680 trays per shift, resulting in a manipulation mass of 9.2 t within 8 hours. The analysis based on [18] shows a high risk potential for all of the operators conducting this task. Thus, the physical stress on the personnel is only acceptable as long as the robot takes over the task of unloading the baking trays.

D. Optimisation

By adapting not only the layout of the robotic cell but also the task execution and distribution in cases of changing between automatic and manual operation, the trade-off between cycle time and physical stress of the operator are met.

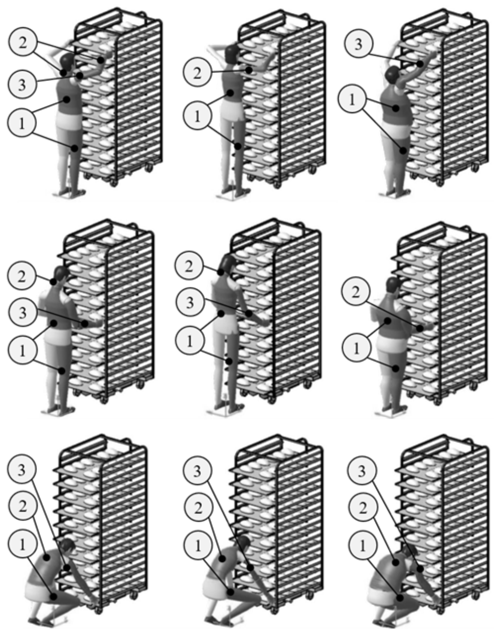

Fig. 4 RULA-analysis of reaching baking trays by different people (1 normal posture, 2 unhealthy posture, 3 endangering posture)

TABLE IV
REDUCTION OF OVERALL TRAY WEIGHT

Characteristics	initial conditions	optimized cond. for male operators	optimized cond. for female operators
Tray weight	4.5 kg	4.5 kg	4.5 kg
Breads weight	0.75 kg	0.75 kg	0.75 kg
Breads per tray	12	12	7
Tray weight incl. breads	13.5 kg	13.5 kg	9.75 kg
Lifting operations	680	200	200
Breads per shift	8,160 (9.2 t)	2,400 (2,7 t)	1,400 (1.95 t)

In order to achieve an ergonomic reasonable physical stress, lifting operations need to be reduced to a number of 200 per shift while at the same time reducing the overall load per tray for female operators to a number of seven breads per tray. This leads to a physical stress of 2.7 t for male and 1.95 t for female operators (Table IV). Furthermore, it should be considered that only people with a height percentile more than 50 should operate at the workstation for manipulating trays out of the oven rack.

Looking at the layout of the robotic cell, there would be space for adding two more docking stations for oven racks (as shown in Fig. 5). By adding two more docking stations, the break for the operator can be expanded from 7.5 minutes to almost 30 minutes. Considering operation times for manipulating oven racks from and in the docking stations as well as walking between individual robotic cells, this leads to a possibility to work at seven workstations parallel. This leads to a much higher production volume compared to pure manual production while reducing physical stresses at the same time (Table V).

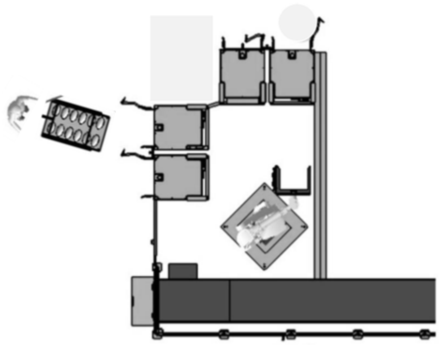

Fig. 5 Robotic cell with additional docking stations

The economic efficiency of the robotic cell becomes especially evident if workstations are multiplied and the physical stress of operators is limited. Furthermore, the reduced production volume in cases of pure manual production can be compensated by the high production volume of automated production.

TABLE V
COMPARISON OF AUTOMATIC AND OPTIMIZED MANUAL PRODUCTION

Characteristics	Automatic production	Manual production
Workstations	7	1
Breads per shift	39,480 (44.1 t)	male: 2,400 (2.7 t) female: 1,400 (1.95 t)
Physical stress	no overload	no overload

V. CONCLUSION

This paper shows the impact of integrating diversity-related factors in the planning and simulation of automation systems. By adapting system parameters, such as task distribution or task execution, the overall productivity can be increased and at the same time physical stress on operators can be reduced.

An exemplary simulation-based analysis on a robotic workstation for unloading baking trays was conducted, highlighting recommended actions for reducing the physical stress of operators. By reducing the overall manipulation weight by either reducing overall lifting operations or overall weights to lift, physical stress could be reduced by 70%. Furthermore, it is important to consider, that there is a difference in physical stress between men and women of about 30%. Thus, overall loads have to be reduced when women operate on same workstations as men.

Future research focuses on implementing a numerical behaviour model of operators as well as a Boole's probabilistic model of sensors. These models can either be defined on the basis of Failure Mode and Effects Analysis (FMEA) or on probabilities of errors. While the former deliberately integrates errors and combinations of errors in the production process, errors in the latter scenario are mainly based on probabilities. As both approaches have disadvantages such as limited errors based on imagination on the one hand and long simulation times on the other hand, the implementation in the collaborative model has still to be evaluated yet.

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