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A Morphology of Human Robot Collaboration Systems for Industrial Assembly

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Abstract

In recent years, the number of hybrid work systems using human robot collaboration (HRC) increased in industrial production environments – enhancing productivity while reducing work-related burden. Despite growing availability of HRC-suitable manipulation and safety technology, tools and techniques facilitating the design, planning and implementation process are still lacking. System engineers who strive to implement technically feasible, ergonomically meaningful and economically beneficial HRC applications need to make design and technology decisions in various subject areas, whereas the design alternatives per such subject area are plenty – combining aspects to a challenge of increased complexity. In this paper, the heuristic procedure of morphological analysis is applied to establish a description model that can serve as both a supporting design guideline for future HRC applications of value-adding, industrial quality as well as a tool to characterize and compare existing applications. It focuses on HRC within assembly processes, and illustrates the complexity of HRC applications in a comprehensible manner through its multi-dimensional structure. The morphology has been validated through its application on various existing industrial HRC applications, research demonstrators and interviews of experts from academia.

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Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Human-robot collaboration (HRC) is on the advance, not only in academic research, but also in productive real-world application. Whereas manufacturing systems are already mechanically assisted, semi- or even fully automated to large extent, assembly process areas generally remain permeated of manual operations [1]. In recent years, robot manufacturers have brought a range of power- and force-limited robots to market which are capable of working in the immediate surroundings of humans.

This brings up the opportunity to deploy such robots into process areas such as assembly [2]. Here, they serve as assistive machines that carry out certain tasks in close conjunction with their human counterparts and thereby increase or improve e.g. capacity, ergonomics or quality of a process. Hence, through combining strengths of robots such as accuracy and endurance with strengths of humans such as cognition and versatility in a joint environment [3], human-robot collaboration (HRC) emerges.

A HRC work system for assembly portrays a demanding complex planning and design task [9] that involves qualitative and quantitative considerations and trade-offs. Depending on

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a given target set, multiple decisions with regard to system layout, technology, flexibility, collaboration and safety have to be taken and iterated. To ease this design task while outlining the design options at the current state-of-the-art, and at the same time enable feature-based comparison of HRC scenarios, a description model based on morphological analysis is being proposed. It incorporates all aspects relevant for their characterization. The outcome of its use is a HRC system whose design is considerate of current technical and conceptual options.

2. Related work

Existing taxonomies and classification schemes with relevance for human-robot collaboration in industrialized assembly systems derive from the more generic human-computer interaction (HCI) as well as human-robot interaction (HRI) – both of which are not exclusively focused on articulated robot technology for the use within industrial environments. In addition, applied research has published classification work for industrial HRC in particular, e.g. [8].

Scholtz [4] outlines the systematic differences between HCI and HRI in terms of multiplicity of systems to interact with, the physical nature of a robot, the dynamics of a robot, the interaction environment, which is more demanding and rich in external influences, and, finally, the ability for autonomy. Core of his work is the definition of interaction roles for HRI that vary between five levels – from an uninvolved bystander to a responsible supervisor.

Yanco and Drury [5] [6] develop a taxonomy for human-robot interaction (HRI) that covers eleven descriptive dimensions for HRI applications, which include types of tasks and their criticality, the external appearance of the robot, human-robot team compositions, information for decision support, human-robot proximity, interaction levels and roles as well as autonomy levels. The framework is applicable to all conceivable implementations of HRI, e.g. in space flight, warfare, human rescue, but also industrial environments. While encompassing important conceptual characteristics for human-robot collaboration in assembly, it lacks relevant information on technical design and implementation.

Onnasch et al. [7] propose an interaction taxonomy that classifies HRI with regard to the actual interaction, the robot and team criteria. Within those categories, ten descriptive dimensions have been developed and arranged into a *Canvas* style representation to allow graphical depiction of HRI applications from diverse fields of application and their subsequent comparison. While being comprehensive on the conceptual matters of HRI, the model also blanks out technical implementation aspects.

Bauer et al. [8] follow an inductive approach in order to classify HRI scenarios by analyzing 21 actual implementations of HRC within assembly environments – in both industry and research. The classification scheme includes, beyond qualitative aspects of task, technology in use and level of collaboration, also quantitative information on e.g. cycle times and work piece dimensions. In addition, it is able to categorize safety aspects of HRI, detailing characteristics on workspace monitoring, robot-inherent safety features as well as tool-related safety features.

Wang et al. [9] provide a classification framework that builds upon existing classification models with regard to temporal and spatial elaboration, agent multiplicity and autonomy. It adds characteristics which are specific for the concept of *symbiotic HRC*. Symbiotic HRC is shaped by intuitive or multimodal programming and natural input, immersive collaboration and a high degree of context dependency. Major system elements identified for classifying an HRC scenario are actors, work environment and work pieces/operations.

Existing research work is not considered fully holistic from an industrialization perspective, as it does not consider economic and other quantitative aspects. Also, many technical and safety-related-specifications - which might seem irrelevant for the before mentioned authors' respective academic focus - move very much into spotlight when trying to bridge the gap between academic HRC scenarios and industrial application.

3. Development of the morphology

Based on the identified drawbacks, the authors propose a framework that is able to characterize both academic and industrial HRC applications. A major asset of the morphological analysis [10] [11] as a method for describing complex systems, like a HRC application, is the integration of all significant features and characteristics and their potential attributes. Thus, a picture of the application, both holistic and generic, is created. A particular application can be classified, allowing a simplified illustration of the correlations between all existing options to conceptualize a HRC application and its specific design.

The proposed morphological framework consists of five dimensions (see Fig. 1), 41 attributes and a total of 169 characteristics. It takes into account research findings as well the authors' practical experience in designing HRC applications within research and industry projects. While the sequence of the dimensions does not reflect a rating in terms of priority or importance, it reflects the notional process of the design of a HRC application. As HRC should not be implemented as an end-in-itself, it starts with a qualitative objective and economic framework conditions that will have to be met.

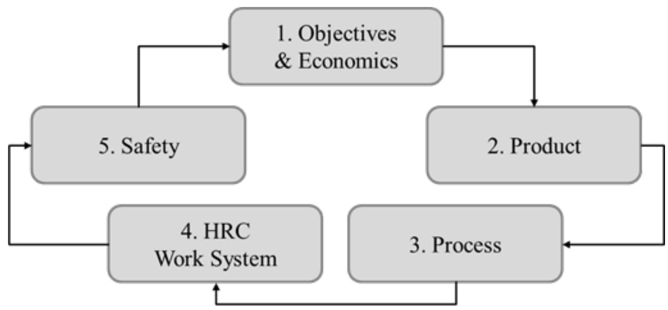

Figure 1: HRC morphology sections

It then considers product specifications as prerequisites and requirements for the design of the collaborative work process. The further procedure then, to large degree, determines the specification of the physical HRC work system. The setup in its entirety ultimately requires a safety concept and safety measures to be taken. As an iterative process, the scenarios developed have to be tested against the qualitative and quantitative objectives and, if necessary, revised.

3.1. Objectives & economics

While the eligible superordinate objectives pursued by implementing HRC are manifold, research illustrates that cost improvements (e.g. reduction of assembly cost per piece) or increase in productivity (e.g. increase of system output per time unit) are the primary targets of companies when adopting HRC. Improving flexibility over other means of automation, reducing work related burden or increasing the internal degree of innovation play a subordinate role for manufacturing companies [8] [12].

If economic targets are met, to large degree depends on the system's required investment and the degree of substitution of manual labor or increased productivity. Although costs for lightweight robots, which are frequently used within HRC, are lower than for industrial robots, experience shows that the cost for implementing a HRC application in total is approx. four times higher than the base cost for the pure manipulator [13]. This includes engineering, tools and fixtures, re-arrangement of the work system and safety equipment. Here, the investment cost (attribute 1.2) can be considered both a target value that should not be exceeded or an actual value. Thus, it is evident that amortization of the investment into HRC is facilitated when the work system will be highly utilized (1.3), e.g. in 3-shift-operation around the clock, and the service delivered by the robot is used more frequently due to higher repetition/lower tact time (1.4), and the remaining lifespan of the product produced is rather long (1.6). Otherwise, a low tact time can also impose a challenge in terms of robot speed.

The attributes included in this section derive from [14], where an exemplary HRC profitability calculation is outlined.

3.2. Product

Product characteristics influence automation capability of a task or at least the complexity of automation. In general, smaller and lighter products are preferably used for HRC applications, for safety reasons on the one hand, for investment reasons on the other hand. Amongst robots that are meant for HRC by default, such as collaborative lightweight articulators, FANUC CR-35iA with an official payload of 35 kg [15] is the most capable representative.

Other product characteristics determining automation capability include symmetry, stability, sensitivity and its provision [16] [17]. Symmetry (2.3) can be pronounced rotational, areal, partly or complex. In general, a symmetric part has less requirements regarding its exact orientation at the joining location, accelerating the process. Unstable, flexible parts (2.4) will likely require more sensory support during manipulation, if they can be manipulated reliably at all. Sensitivity of a component can speak for or against its handling by a robot (2.6) – depending on whether human or robot are better capable of dealing with the specific requirements.

Material provision (2.6) can range between separated materials that have to be picked from constant locations, which eases their presence verification and localization by the robot to bulk material that might require high-end vision systems for localization and separation (2.7). Product specification also determines the potential manipulation principles (2.8) and the required technology, that can be pronounced *mechanical* (e.g. electrical two-finger gripper), *pneumatical* (e.g. vacuum gripper), *magnetic*, *adhesive* or *other* very specific tooling.

Remark: Blue backed boxes in Table 1-5 indicate "true" characteristics for the use case in paper section 4.

Table 1: HRC morphology section 1: Objectives & Economics

#		#	Attribute	Characteristic				
1	Economics	1.1	Superior HRC objecti	*Cost improvement*	*Productivity increase*	*Flexibility increase*	*Ergonomics improvement*	*Innovation*
		1.2	Investment	$I \leq$ *EUR 50.000*	*EUR 50k* $< I \leq$ *EUR 100k*	*EUR 100k* $< I \leq$ *EUR 150k*	*EUR 150k* $< I \leq$ *EUR 200k*	$I >$ *EUR 200k*
		1.3	Productive hrs/week	$h \leq 40$	$40 < h \leq 80$	$80 < h \leq 120$	$h > 120$	
		1.4	Tact time	$T \leq 10$ *s*	$10 < T \leq 20$ *s*	$20 < T \leq 60$ *s*	$T > 60$ *s*	
		1.5	Availability	$V \leq 80$ %	$80 < V \leq 85$ %	$85 < V \leq 90$ %	$V > 90$ %	
		1.6	Process lifespan	*< 1 yr*	*1-3 yrs*	*3-5 yrs*	*5-7 yrs*	*> 7 yrs*

Table 2: HRC morphology section 2: Product

#		#	Attribute	Characteristic				
2	Product	2.1	Dimensions	$D \leq 1$ *mm*	$1 < D \leq 100$ *mm*	$100 < D \leq 1.000$ *mm*	$D > 1.000$ *mm*	
		2.2	Weight	$m \leq 1$ *kg*	$1 < m \leq 10$ *kg*	$10 < m \leq 20$ *kg*	$m > 20$ *kg*	
		2.3	Symmetry	*rotational*	*areal*	*partly*	*complex*	
		2.4	Stability	*rigid*	*easily ductile*	*flexible*		
		2.5	Sensitivity	*insensible*	*party sensible*	*entirely sensible*		
		2.6	Staging	*single pick-up position*	*sorted and oriented*	*sorted and partly oriented*	*bulk (no entangling)*	*bulk (entangling)*
		2.7	Object detection	*mechanical*	*capacitive*	*inductive*	*optical*	
		2.8	Manipulability	*mechanical*	*pneumatical*	*magnetic*	*adhesive*	*other*

3.3. Process

Several attributes from the Process section are strongly related to the nature of collaboration and require considerate selection to achieve a work system highly accepted amongst workforce. Type of interaction (3.1) refers to the commonality of goals of human and robot as well as their temporal and spatial relation [6]. In isolation, physically fenced-off robots and humans work separately in proximity, but independently from each other. In co-existence, robots still operate independently from humans, but are un-corralled [7]. In synchronization, robots and human share a joint goal, but operate the workstation alternately [8]. In cooperation, they operate the workstation simultaneously, but do not manipulate the same object (product) at the same time [7] [8]. Full collaboration involves a common goal, overlapping workspace due to collocation and simultaneous manipulation of the same object – collision between human and robot is most likely in this scenario [18]. Beyond assembly, HRC can be applied also in neighboring process areas such as manufacturing or logistics if the nature of available tasks shows potential (3.2). For assembly in particular, HRC can involve all supporting processes that are required - such as dosage of auxiliary materials or cleansing of surfaces (3.3). For a full list of sub-tasks belonging to assembly refer to [19].

The involvement of humans in collaborative task fulfillment can vary vastly. The implemented scheme largely follows [4]. Especially in isolation and co-existence, human workers can be considered as uninvolved bystanders who only require knowledge about the robot's purpose and its potential dangers.

Operators can operate the system in terms of starting it up or adjusting it slightly, whereas teammates are those who actually cooperate or collaborate within the production task. Programmers are responsible for set up, programming and repair of the system. Supervisors are responsible for making decisions that impact the before mentioned roles. An individual can take on multiple roles at the same time.

Task-allocation (3.8) refers to the superordinate paradigm according to which available jobs and tasks are distributed between the available resources, i.e. human and robot. Schröter et al. [20] propose process building blocks and standard motion times to enable time-optimal task distribution.

Takata et al. [21] developed a methodology that considers cost-optimality in task allocation. Müller et al. suggest consideration of capabilities when deciding on who is doing what [22]. A multi-criterion approach that considers capabilities to optimize time, cost and quality based on [23] is outlined in [2].

Table 3: HRC morphology section 3: Process

#		#	Attribute	Characteristic				
3	Process	3.1	Type of interaction	*Isolation*	*Co-existence*	*Synchronisation*	*Cooperation*	*Collaboration*
		3.2	Process area	*Manufacturing*	*Assembly*	*Logistics*	*Quality control*	…
		3.3	Sub-processes	*Insertion*	*Assembly*	*Hand over / Take over*	*Checking*	…
				Dosage	*Cleansing*	*Packaging*	*Static work*	
		3.4	Product variance	*none (standard product)*	*low variation*	*high variation*	*individualized products*	
		3.5	Required accuracy	$d \leq 0,1$ *mm*	$0,1 < d \leq 1$ *mm*	$1 < d \leq 2$ *mm*	$2 < d \leq 3$ *mm*	$d > 3$ *mm*
		3.6	Force regulation	*required*	*not required*			
		3.7	Interaction role	*Bystander*	*Operator*	*Teammate*	*Programmer*	*Supervisor*
		3.8	Task-allocation	*time-optimal*	*cost-optimal*	*quality-optimal*	*capability-optimal*	*multi-criteria*
		3.9	Team multiplicity	*n robots > n humans*	*n robots = n humans*	*n robots < n humans*		
		3.10	Pacemaker	*Robot*	*Human*	*other device*		

Table 4: HRC morphology section 4: System

#		#	Attribute	Characteristic				
4	System	4.1	Kinematics	*Gantry robot*	*SCARA*	*Articulated robot*	*Parallel robot*	
		4.2	Robot workspace	$R \leq 500$ *mm*	$500 < R \leq 1.000$ *mm*	$R > 1.000$ *mm*		
		4.3	Space requirements	$A \leq 1$ *m²*	$1 < A \leq 5$ *m²*	$A > 5$ *m²*		
		4.4	Installation	*upright*	*pendent (horizontaly)*	*pendent (vertically)*		
		4.5	Spatial flexibility	*stationary*	*relocatable*	*linearly travelling*	*track-guided*	*autonomously guided*
		4.6	Tool flexibility	*none*	*configurable tool*	*multi-purpose tool*	*tool changing system*	*adaptive tool*
		4.7	Power supply	*wired*	*autonomous*			
		4.8	Interface to human	*mechanical*	*acoustical*	*optical*		
		4.9	Interface to robot	*electronical*	*mechanical*	*acoustical*	*optical*	
		4.10	Design	*functional*	*caricaturized*	*zoo-morph*	*humanoid*	
		4.11	Programming	*code based*	*intuitive*	*hand-guided*	*gesture based*	*automatic programming*

Table 5: HRC morphology section 5: Safety

#		#	Attribute	Characteristic				
5	Safety	5.1	Safety principles	*Safety-rated stopp*	*Hand guidance*	*Speed/distance monitoring*	*Power & force limitation*	
		5.2	Workspace monitoring	*mechanical*	*optical*	*inductive*	*tactile*	*none*
		5.3	Spatial proximity	*avoiding*	*leading*	*appraximating*	*touching*	
		5.4	Collision detection	*Engine currents*	*Force-torque sensorics*	*pneumatic*	*capacitive*	
		5.5	Sensoric standard	*safety-rated sensors*	*non-safety rated sensors*	*combination*		
		5.6	Certification	*Self-certification*	*External certification*	*no certification*		

The concept of team multiplicity (3.9) derives from [7]. More than one robot might be required, if the range of tasks designated to the robot can not be executed by one robot alone due to constraints in time, flexibility or space.

3.4. System

All known types of robot kinematics come into question for use in HRC. Articulated robots, in fact, are the most widespread manipulators within HRC applications as [8] shows.

Different models vary in terms of payload, accuracy, reach etc. In many factories, floor space is vastly limited, so minimum space occupation (4.3) can be achieved by alternative modes of installation (4.4) such as a pendent mounting.

While especially articulated manipulators are flexible in terms of accessibility of desired target points within their work space, further flexibility for changing tasks, higher product variance or increased utilization can be achieved through spatial flexibility (4.5) and tool flexibility (4.6). Well-known means to increase spatial flexibility of a robot that are also in use within HRC are hand-pushed trolleys, linear axes as well as autonomously guided vehicles (AGVs). On the tool side, configurable tools, multi-purpose tools, tool changing systems as well as adaptive tools such as the FESTO MultiChoiceGripper or VERSABALL® are available.

Communication between robot and human (4.8) and vice-versa (4.9) can take place through various channels. The characteristics are derived from Onnasch et al. [7]. Of highest practical relevance is electronic communication to the robot, either through simple sensoric input or, especially in networked factories, IP-based protocols. Optical communication is most common to the human operator – e.g. through signal lights, a teaching pendant, a touch-screen or a wearable devices. The design of the user interface within HRC is of upmost importance for user friendliness and acceptance. Beyond very practically designed robots (4.10), some models follow different design paradigms. Fong et al. [24] distinguish between functional, anthropomorphic or humanoid (human-like), zoo-morphic (animal-like) and caricatured robots. An example for a caricatured collaborative robot is RethinkRobotics® Baxter, who adopts single characteristics of humans such as two-armedness and a simplified face through which it is able to express the actual operational status of the robot. Mori et al. found that exterior design and appearance of a robot have tremendous effect on its positive or negative perception by humans [25].

3.5. Safety

ISO 10218-2, ISO/TS 15066 and other standards and guidelines regulate safety in HRC. Four safety principles (5.1) are outlined: safety-rated stop, speed/distance monitoring, hand guidance and power/force limitation [18]. The first two try to avoid collision before they occur and therefor require sensors for monitoring of the workspace (5.2). The latter two accept the possibility of collisions and therefor require sensors for collision detection (5.4). Collision avoidance or detection systems should ideally be safety-rated (5.5) to be able to achieve a CE-certification (5.6), which is a prerequisite for commissioning any kind of machine in Europe.

4. Application of the morphology

The presented morphology was developed based on an extensive literature review and own project experiences. To validate its comprehensiveness and evaluate its comprehensibility, it was presented and discussed in an expert panel with manufacturing companies which already have HRC applications in place.

It was also used *deductively* as a guideline in the design of an HRC application in the electronics industry, whereby the authors were able to *inductively* test its feasibility and completeness. In this application, a HRC retrofit into an existing assembly system that post-processes and packs approx. 700.000 circuit boards per year has been implemented. In the initial situation, two workers operated the system. Through the implementation of HRC, the number of operators could be reduced by one. Due to constraints in reach, two robots had to be implemented in order to be able to execute all tasks.

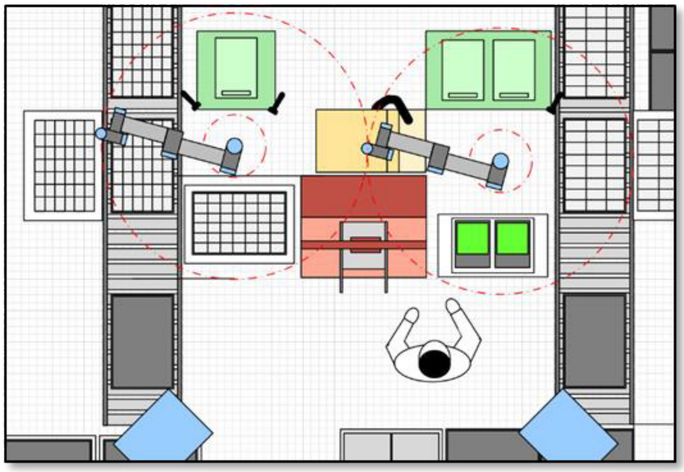

Figure 2: HRC Assembly Work System in Electronics Industry

Robots take care of inserting, cleaning, scanning and packaging electronic modules, while the operator remains responsible for complex assembly. Two workstations are provided for cooperation. Work pieces have to be handled with care to avoid stress entry. Therefore, flow grippers were implemented and are complemented by a regular suction pad for tray handling through a triangular flange. Robots implemented are lightweight and functional in design. The worker was trained with regard to the workflow to act as a teammate to the robot and to operate the robot, i.e. conduct minor adaptions. The robot receives information electronically from the MES system and from local binary sensors. It indicates its status to the worker optically through both a touch screen that. is also used for intuitive programming, and a signal light (red, yellow, green).

Both robots are operated with reduced power and force and detect collisions upon occurrence through monitoring motor currents. Additionally, overlapping motion ranges of human and robot are monitored by light fences as these are the only areas where human and robot approximate each other frequently and intendedly. These Light fences detect when both agents are present, further reducing traversing speed of the robot.

Boxes backed blue in Table 1-5 indicate the “true” characteristics for this HRC scenario.

5. Conclusions and outlook

The proposed morphology meets the expectation of characterizing both conceptual and technical aspects, and also quantitative and qualitative aspects of HRC applications. Influencing factors for feasibility and profitability also become obvious to its user. It can easily be adopted to other industries and conditions. Through the active use of the morphology as a design and characterization tool, the consideration of essential aspects can be ensured. Thereby, implementation of HRC applications that match requirements of all stakeholders is facilitated – at first try. From a scientific standpoint, additional experimental application of the morphology and its current design will have to be undertaken to prove its feasibility empirically. Since this morphology is supposed to be a lively system, such experiment will also support the continual addition of new knowledge and experience in order to keep it up to date and relevant.

Acknowledgements

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