A Roadmap for the Future Design of Human-Robot Collaboration

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Abstract:
Human-robot collaboration systems are a new and interesting approach in the science of robotics. Collaborative robot systems can be used without protective fences in direct interaction with humans. For ongoing developments in human-robot collaboration, further improvements in a multitude of disciplines and research areas are necessary. The scope of interdisciplinary research work in this context is enormous and the scientific field is, due to the high level of interdisciplinarity, quite complex. In the debates within the Ladenburg Discourse* on human-robot collaboration, it was agreed that guidelines for future research and development work would be very useful and would enable researchers to structure and position their work in this wide field. Duplications and redundancies could be avoided, and synergies and cooperations could be promoted. For those reasons, an extended set of thirteen theses is formulated. This paper describes these theses, as a summary of the Ladenburg Discourse, with the intention to provide a roadmap for human-robot collaboration.

Keywords: Robotics, Human-robot collaboration, Design methodology for human-machine systems, Security and safety of human-machine systems, Ergonomics, Human Factors

1. INTRODUCTION

The available literature on the state of the art of science and technology in human-robot collaboration (HRC) is diverse and characterized by professional articles, dissertations and conference contributions. Most of them focus on specific aspects of HRC. Many of these papers are strongly application-oriented and describe, for example, a concrete realization of HRC; others are more generally and have a wider impact. As an example, the often cited considerations on taxonomy in the HRC of Onnasch et al. (2016) should be mentioned here. However, there is a lack of a structured knowledge base on HRC that could provide a basis for future research and development in this field. Müller et al. (2019) describe the current state of development and present an excellent overview of existing HRC concepts and applications in the broad and comprehensive presentation of a manual. In Buxbaum (2020) a variety of individual concepts in the HRC environment will be highlighted, which were discussed by experts at the Daimler and Benz Foundation as part of the Ladenburg Discourse 2019. Many singular works in different fields of science and application were analysed and examined for similarities and differences in approaches. The scientific fields involved included engineering technology, in particular mechanical engineering and robotics, industrial engineering and management as well as electrical engineering and computer science due to the thematic orientation. Scientists from the fields of ergonomics, health care, psychology and human factors were involved. The circle of experts was supplemented by ethicists, technical philosophers and physicians as well as by users and application planners from industry and various service sectors.

In the discussion of the various topics, it became clear, that different approaches often lead to comparable results, depending on the task, thematic objective and area of expertise of the researchers and users. Furthermore, findings from other disciplines are sometimes transferable. It was agreed, that guidelines in the form of an interdisciplinary theses paper on the scientific orientation of the work would be very helpful in the actual situation. So, during final discussion of the discourse, some theses were pre-formulated and it was decided to elaborate them afterwards.

Based on a framework of technical, economic, psychological and ergonomic approaches, a comprehensive package of thirteen theses will be presented in this paper. Those theses shall deliver a base and a structure for future research and development work in the field of HRC. Researchers and users in the HRC should be able to assign their respective work to one or more of these theses selectively or structurally and thus classify their contribution to the development of HRC in the large field between the above-mentioned scientific fields.

2. POINTS OF VIEW ON HRC

2.1 Ergonomic Point of View

The idea of a catalogue of theses on future developments of HRC originates from Wischniewski et al. (2019), where the following seven theses are stated from an ergonomic perspective.

(1) Simplify programming of robotic systems.
(2) Adapt the operating characteristics of the robotic systems to the qualifications and competences (and needs) of the employees.
(3) Flexibilizing safety technology.
(4) Develop interaction principles for robots in need of help (failable automation).
(5) Focus on social isolation through increasing use of robotic systems.
(6) Enable ad hoc task allocation beyond MABA-MABA lists.
(7) Ensure transparency and expectation conformity.

2.2 Technical-Economic Point of View

In industrial applications, a technical-economic perspective is particularly relevant, which addresses the following properties of rationalization and feasibility.

(1) Economically efficient robots are usually huge, strong and fast. HRC robots, on the other hand, are often small, weak and slow. The structural design must be reconsidered.
(2) The effort for security is considerable and is often in no reasonable proportion to the benefit.
(3) An HRC system must be able to be configured and programmed directly by the people who use it. This aspect is already important for reasons of acceptance.
(4) An artificial intelligence is required, which in many cases - despite some successes in partial areas of the AI - does not yet exist.

Kuhlenkötter and Hypki (2020) raise the question where teamwork with robots and humans can work out and focus on both, the technical and the economic aspects. Even with representable benefits, every human-robot collaboration solution often requires considerable investments in the planning and equipment of the HRC scenario, which initially leads to increased expenditure on personnel and technical - and thus ultimately financial - resources.

2.3 Psychological Point of View

In existing HRC applications, the cooperation between humans and robots often is rather artificial. Task distribution is usually determined by engineers and is often oriented on technical objectives of the respective application. From a psychological perspective, the question arises, how this collaboration should be structured, in order to achieve as natural collaboration as possible between humans and robots. Approaches to doing so are as follows.

(1) Anthropomorphic machine design:
Roesler and Onnasch (2020) argue that an application of anthropomorphic features to the design of the robot is appropriate to make collaboration in the HRC more intuitive and effective. Anthropomorphic design features are mentioned there: Form, communication, movement and context. The idea is that a transfer of human-like characteristics to robots supports an intuitive and socially situated cooperation between humans and robots and increases acceptance. Potential fields of tension are also mentioned, such as the phenomenon of the "Uncanny Valley".
(2) Integration of cognitive models into the machine:
Russwinkel (2020) proposes to integrate knowledge about collaboration into robots as cognitive models. This should enable them to communicate implicitly by deriving interaction requirements and support possibilities through observation:
- To enable robots to interact with humans as "third hands" or "clairvoyant eyes", they must be able to anticipate what the requirements of the situation are, what their contribution could be to the achievement of goals with flexible task allocation, and how joint action can be synchronized. For this they need a model to understand the common goals, the interaction partner and the action environment as well as a world model with general laws.
- Cognitive models enable robots to behave in such a way that the human interaction partner anticipates what the robot intends to do. For example, an anthropomorphic robot could focus its "gaze" on a workpiece to be gripped and at the same time detect whether the human eye has also focused on this workpiece, on the robot, or on the environment in order to derive its own behavior from it.

2.4 Human Factors' Point of View

Häusler and Straeter (2020) represent the human-robot collaboration as a system in which the human cooperates with an autonomous technical system and describe this cooperation as a problem of the human-automatic interaction. The phenomenon and the demands on the interaction between robots and humans are known and researched from other technical fields, especially in the field of automation of aviation and in the process industry. The possibility of transferring knowledge from these areas should therefore be examined.

From the perspective of human factors, the following error zones could be better solved by targeted HRC design than in conventional high-safety systems.

(1) Deskilling:
HRC design requires a competence-focused work design. The technical possibilities should enable an individualised solution that allows tasks to be assigned to people according to the current level of competence.
(2) Carelessness:
If tasks usually perform reliably, it indicates to the operator that his efforts - permanent monitoring and active control, e.g. by own estimations and extrapolations - are unnecessary. It would therefore be preferable if the HRC design could change roles: At first the human is acting. This can be realized target-oriented. The machine monitors, warns and intervenes where necessary.

(3) Inactivity

A supervising operator, who has to understand the critical situation and be able to solve the problems in an emergency, is not encouraged in his everyday job. The operator is underchallenged and not demanded in his possibilities of attention and perception. At the same time his capacity of attention does not allow him to permanently monitor the technical system. This leads to focusing on other things.

Management of complexity is an important prerequisite for maintaining competence, responsibility and active involvement. This requires a number of approaches to questions, which are presented here as examples:

- How can work processes be sensibly simplified so that the interrelationships and effects remain recognisable to the human?
- How can buffers be installed that allow the work process to be stopped and continued without negative consequences?
- Is the human worker allowed to make mistakes that can be corrected in the process?
- How can the robot react towards mistakes by the human?
- How can human and robot synchronize their actions and plans?

Answers can possibly be provided by transfer from the aviation industry. With their experiments on the concept of the one-man cockpit (reduced crew), the major aircraft developers are heading for a pilot-robot collaboration. The solution approaches should take better account of the three error areas mentioned and not simply replace humans with more technology and a further increase of complexity.

2.5 Ethical Point of View

The ethical perspective provides the basis for the evaluation of technical changes in our world. In this context, the development of HRC scenarios and their ethical evaluation are at the forefront. According to Remmers (2020) it is a matter of the scope of safety measures, of legal aspects and last but not least of the question which types of activities remain for humans and how human capabilities and burdens change in these constellations. It must be considered how interactions between humans and robots take place, who assumes which role, and whether these interactions are comfortable and intuitive for humans.

Bendel (2019) refers to moral machines and describes the difference between normal machines and machines that have been given a form of morality. The task of machine ethics is to create moral or immoral machines to explore, improve, and eventually release them into the world where they can provide benefits or do harm. He speaks of moralizing the machines, which causes a fundamental change in the behavior of the machine.

3. ROADMAP FOR THE FUTURE DESIGN OF HRC

As a roadmap for the future design of HRC a couple of theses on the above-mentioned perspectives of ergonomics, technology, economic efficiency, psychology, human factors and ethics is both meaningful and feasible. There are also overlaps in the perspectives leading to a reduced, common set of theses. The aim is to create a compendium of research on HRC in the coming years. This should not be too narrowly defined, because it might be necessary to expand the scientific fields.

3.1 Thesis 1 – Rethink Safety Requirements

In many cases, the safety requirements for HRC systems used in industry, appear to be inappropriately high. Restricting the motion speed of robots in collaboration scenarios is certainly the right approach, but the actual specifications for maximum speed values must be questioned. If in other accepted safety regulations, e.g. a safety distance of less than one meter to an entering or passing train in any well-attended station with a mostly distracted audience is accepted, the current limitation of 250 mm/sec in HRC applications (with instructed personnel) seems inappropriate. In addition, this also limits productivity and the question of economic effiency arises. Even the employees often mention, that the robots run much too slowly. It is self-evident that any danger to employees must be ruled out in any case. Less rigorous safety requirements are common in the healthcare sector (Keibel (2019)). Obviously, double standards are applied here. Divergent safety requirements should at least be standardised.

3.2 Thesis 2 – Flexibilization of Safety Technology

The flexibilization of safety technology is encouraged by Wischniewski et al. (2019) from an ergonomic perspective and it is argued that the increased flexibility associated with HRC should be exploited. The concept of flexibility must be redefined. IoT solutions in particular will play an important role in the future (Bruce-Boye et al. (2020)). At the same time, efficient process flows should be guaranteed. This requires new security concepts that can keep pace with the increasing requirements of flexible HRC. At the same time, conventional safety technology must be further developed. Of course, any danger to employees must be excluded under all circumstances.

3.3 Thesis 3 – Re-Questioning Structural Design

Robots in industrial production are often required to have high power reserves, be fast and have a large operating range. This is essentially motivated by economic considerations. Moreover, there are reports that there are a number of cobots that are no longer in use due to insufficient economic efficiency (Wöllhaf (2020)). Actual cobot systems of leading manufacturers are indeed mostly small, slow and can only move small payloads. These aspects should be taken into account when designing future cobots in order to achieve better economic efficiency.

Surdilovic et al. (2018) discuss concepts for heavy-duty robotics and show approaches for the optimization of structural design with regard to power and range of collaborative robots. This way is to be pursued further for a successful development in HRC.

Increasingly anthropomorphic designs are required to improve acceptance. Such as Roesler and Onnasch (2020) indicate, new challenges arise, if anthropomorphic design,

in terms of form, communication, movement and context, can promote acceptance and cooperation. In addition to the phenomenon of the "Uncanny Valley" and the problem of expectation conforming design, the tension between functionality and anthropomorphism creates a central problem. This should be also taken into account in the structural design.

3.4 Thesis 4 – Simplify Configuration and Programming

A major problem in the construction of HRC systems is that engineers and installers generally still have relatively less experience with collaboration scenarios and furthermore those scenarios are usually not set up with usability in mind. They rather have a technical problem-solving character. Ideally, cobot programming and teaching should also be possible by the operator. HRC can only succeed in the long term if there are specified recommendations for action, guidelines and corresponding training courses for plant planners and project planners in the foreseeable future. It is to be demanded that the users must be able to carry out configuration and programming of the cobot directly. Therefore, the human-machine interface must be redesigned to be user-friendly. The consideration of aspects such as acceptance, perceived safety and attention control play an important role in this context. Overstrain is to be avoided.

Wischniewski et al. (2019) focus on the ergonomic perspective of the configuration and also demand from this perspective that the training of the HRC systems must be made possible by the respective user. This means that the user's qualification must be increased; ideally, in addition to his tasks in the production process, the user also has a technical responsibility for the cobot equipment.

3.5 Thesis 5 – Adapt Cost Effectiveness Analysis

HRC often requires an increased expenditure of personnel and technical resources. The planning and implementation process involves uncertainties. A classic ROI assessment fails. An important point of criticism is that a short-term ROI is difficult to illustrate in many cases, because a comprehensive and overarching calculation system that is proven by experience and facts does not yet exist. Simple and general approaches of the classical profitability calculation for automation applications fail. In addition to the undoubtedly quantifiable investment and engineering costs on the one hand and the changed production costs on a short time frame on the other hand, various other cost evaluations are very difficult, highly inaccurate and often have to be made with assumptions that can hardly be put to the test. The following questions play a central role (Kuhlenkötter and Hypki (2020)):

- Do different economic criteria apply in start-up and ramp-up scenarios or during production peaks?
- What is the value of investing in future technologies?
- How can ergonomics improvements be fully evaluated in order to increase productivity and address the demographic change?
- How can expenses for higher qualification requirements for employees and savings in the area of additional training to maintain competence (e.g. sim-ulator training in aviation) be included in the profitability calculation?
- What values do motivating, development-friendly workplaces have?

Only by a comprehensive consideration – with the necessary meaningful, perhaps even courageously far-sighted assumptions for the above mentioned criteria – a motivation for HRC solutions is given. However, numerous implementations in the research and industrial landscape provide the necessary motivation for the use of HRC.

3.6 Thesis 6 – Think of HRC as a Socio-Technical System

Gerst (2020) discusses normative concepts and practical orientation models of a participative work design between humans and robots in an HRC system and shows approaches for a successful interaction of both interaction partners in the team. In this HRC team mechanical and human abilities are combined in an appropriate way. The power and accuracy of the robot on the one hand, and the intuition and intelligence of the human being on the other hand. In a socio-technical system, the question of when humans accept a robot that works right next to them is also crucial. Here the "perceived usefulness" is particularly decisive, this aspect had the greatest influence on the willingness to use a robot in a study by Bröhl et al. (2017).

Bendel (2020) describes the human-robot collaboration as a socio-technical system and discusses aspects of the proximity between humans and machines, but then also highlights cooperative interactions, access to shared resources and work on the common object. Humans and robots merge to form a productive overall system, which in turn essentially combines strengths and avoids weaknesses.

Wischniewski et al. (2019) address in this context the aspect of social isolation, which could increase through increased automation by the use of HRC. An interaction of human and robot as a team should combine machine skills with human abilities. Aspects such as proximity, physicality and interaction are to be considered and system solutions that counteract social isolation are to be preferred. In order to remedy the shortcomings of conventional design approaches for socio-technical systems, which are predominantly oriented towards technical possibilities, HRC must be designed by humans and their abilities and skills and not vice versa.

3.7 Thesis 7 – Counteract Deskilling

Experiences from the aviation industry have shown, that an unilateral use of machine capabilities - e.g. for precise aircraft control or for calculations and predictions - contributes to the loss of important manual and mental skills on the human side that are essential in an emergency (Häusler and Straeter (2020)). This lack of use and exercise of human skills in work activity must be compensated by costly additional training. The development of deskilling through the use of automation could be counteracted by making the distribution of tasks more flexible. This requires a machine, that monitors the human operations, give alerts to deviations and errors and intervenes in the

event of serious deficiencies. Flexibilization can therefore be the key to counteracting deskilling.

On the other hand, however, the "mental workload" must be brought into focus in order to assess and adjust available attention or resources within the human mental processes. These resources are countered by task requirements such as task difficulty, task priority and situational contingencies. In addition to make the distribution of tasks more flexible, application-specific concepts must be developed to promote and maintain human competencies in work activities. Leaving this to the respective operator would imply, that he would have to be enabled to overcome production pressure and his own comfort and to have an awareness of his own need for practice in relation to important skills.

3.8 Thesis 8 – Answer Ethical Questions

The argumentation in favour of HRC often asserts that, in contrast to classical automation, human work does not disappear but is rather supplemented and expanded. In fact, employees in such scenarios often get the impression that they are constantly working on their own abolition.

Furthermore, a cobot has the technical possibilities to monitor the human in collaboration. Obviously the aspects of privacy and data protection are getting more important; what happens to such data and who has access to it subsequently? In addition to aspects of technical ethics, there are also aspects of information ethics and privacy. There are a number of ethical challenges, such as the final clarification of responsibility and liability. Questions of machine morality also need to be clarified.

3.9 Thesis 9 – Enhancing Flexibility in the Distribution of Tasks

Any definition of the distribution of tasks between human and robot raises the question, what effect has the allocation of tasks on the quality of the activities assigned to the human. Remmers (2020) shows that the allocation in most current HRC scenarios is mainly determined by the capabilities of the robot and is therefore oriented towards technical rather than ergonomic aspects. Wischniewski et al. (2019) demand a task allocation that can be done ad hoc and flexible. One approach to combining the different abilities of humans and robots is to use MABA-MABA lists ("Men are better at – Machines are better at"), in which the abilities of humans and machines are compared, evaluated and linked (Price (1985)). However, this results in a constant allocation of tasks, which does not permit a flexible reorganisation of tasks. When the allocation of tasks is made more flexible, solutions must be found in the area of conflict between self-determination and technical heteronomy that focus on the people as decision-makers for the allocation of tasks. An ad hoc task allocation, which is initiated by the human being, is in any case preferable to a choreography given by the machine.

3.10 Thesis 10 – Ensure Expectation Conformity

Wischniewski et al. (2019) require from an ergonomic point of view that robot actions must be transparent and comprehensible for humans so that they are following the rules of expectation conformity. In view of the demand for more flexibility in the distribution of tasks, expectation conformity and transparency are an important prerequisite. With flexible task allocation, there are significantly fewer repetitions in the processes as a direct consequence. This could delay or even complicate learning effects in humans and consequently increase the probability of safety-relevant disruptions. Ideally in order to the expectation conformity, humans should be able to recognize - in the process - what the robot will do next, for example by external signals, such as lights or audio. As an alternative to signalization, Sen (2020) suggests to use suitable movement types or path planning for the robot movements, which make it possible to increase the ability to predict the movements of the robot and having good awareness of the situation.

3.11 Thesis 11 – Achieve Higher Functionality via AI

Today, there is a great potential of sensors that can be used to enable robots to record their environment very accurately and in real time. In theory, the evaluation of many different sensor signals could provide the robot with a representative world model so that it can act appropriately on the basis of this data and learn from it. In practice, however, the processing of these sensor signals in the robot controller is carried out procedurally. Thus, the programmer already decides which options the machine will have in operation by providing ready-made routines. Here, approaches from computer science, such as self-learning algorithms, rule-based systems, neural networks and 5G communication must find their way into future HRC applications in order to make cooperating machines adaptive and intelligent. Rules are to be created by machine ethics as default, knowledge is available by access to the Internet at any time and unlimited. A clever combination of rules, knowledge and learning will be essential for the entry of the AI into the HRC.

3.12 Thesis 12 – Increase Anticipation of Automation Technology

For a cognitively less complex coordination by anticipation it is important that robots are perceived in collaboration as deliberately acting "beings". In order to convey to the collaborating human an intentionality - i.e. an arbitrary purposefulness of movements and actions of the robot - the robot has to be designed anthropomorphous in form, movement, communication and context (Roesler and Onnasch (2020)). This simplifies the anticipation of robot behavior for humans by using the mirror neuron system. Since morphological designs arouse expectations (e.g. ears suggest auditory receptivity of the robot), design and function should match in order not to arouse false expectations of the robots ability to interact. Human similarity not only increases the perception of the intentionality of the robots actions: It can also promote acceptance, empathy and willingness to cooperate. However, the connection is not linear. Therefore, collaborative robots should be designed and developed iteratively and human-centered. Gerst (2020) argues that human-like robots could be perceived in collaboration as drivers or "actors" who work better and faster

and are superior to humans. He considers the danger that humans attribute a stubbornness or consciousness to the robot. This can limit the willingness to collaborate with the robot. Anticipative skills on the part of the robot are also required, especially for the realization of a flexible task allocation or in dealing with critical situations. Russwinkel (2020) defines the necessity of integrating mental models into robot control, e.g. for the realization of cognitive abilities or interactive learning processes.

3.13 Thesis 13 – Think of HRC as Key Technology

The increasing digitalization in many areas of society will also lead to a progressive use in non-industrial fields of application in robotics. Examples include care robotics, medical technology applications and rehabilitation applications. The prerequisites in these fields of application are in some cases comparable with the "drivers" of HRC. Usually high structural costs, personnel-intensive activities as well as power-intensive or monotonous tasks are mentioned. Through the development of suitable, collaborative robots, powerful sensors and intelligent control technology, HRC can also be a key technology for non-industrial applications. Aspects of interoperability as well as a clean definition and consistent application of standards are essential in order to transfer progressive development results to other interdisciplinary areas.

4. CONCLUSION

If researchers and developers orientate their work on the future design of HRC in an overall context on the thirteen theses presented here, this can spur communication between research groups and lead to valuable synergies. The theses are intended to facilitate a common understanding and open up an insight into related fields of research. Scientists and practioneers from all the interdisciplinary fields mentioned above can coordinate their work more easily on this basis. The common goal of an economic, intelligent and, above all, human-centered HRC can be achieved.

Any discussion on the extension of these theses with the aim of completion, adaptation or correction is possible and desired.

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