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ASSEMBLY

Human Hybrid Robot: a new concept for supporting manual assembly tasks

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Abstract Due to the volatile conditions in today's production, flexible assembly systems are required. However, current plants are often custom-made which are designed for a fix product spectrum. Especially for the assembly of unique products or products with a small-scale lot size and large-scale lot size with a high diversity of variants, many manufacturing steps are difficult or non economic to automate. Thus, a large part of the manufacturing processes is to be performed manually. These can be supported by assistance systems, but appropriate systems are seldom available. A new approach for supporting manual assembly tasks is the hybridization of biological and technical systems, a so-called "Human Hybrid Robot" (HHR). The kinematic chains of human, machines and tools are configured task-depended in serial and parallel arrangement. By doing so, the individual skills are used optimally. Main focus of this concept is improving the assembly accuracy and error prevention to boost the overall quality of the assembly processes. This paper presents the theoretical concept. Possible applications and realization of exemplary components are outlined to show the potential of HHR.

Keywords HHR · Human robot integration · Hybrid kinematics · Assembly · Assistance system · Human–robot-cooperation/interaction

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1 Introduction

Producing companies are confronted with various challenges nowadays. Due to the globalization the number of competitors is rising. Simultaneously, the customer requires individual products for their specific demands which results in a higher product variance. The obvious solution is one production line for each product variant which is only cost-efficient for high production rates [1]. A flexible production line can be used for several product variants. However, the complexity of the production systems as well as their planning effort is much higher. Flexibility is often enabled by humans [2]. Especially for single item production, low volume production and high volume production with a wide range of variants, the assembly process for complex or small size products is still done manually or semi-automated. Simple support systems can already be observed in industrial applications, e.g. for monitoring assembly positions [3]. Yet, the production quality and productivity is highly dependent on the physical constitution of the employee.

This paper introduces a novel concept for Human Hybrid Robot (HHR) which supports the industrial assembly. The main idea is the merging of technical and biological systems to a hybrid system. Thereby, the advantages of the robot and human can be fully exploited. In the following chapters the state of the art and the new approach with its functionality is presented. Finally, based on the concept of HHR exemplary components of a HHR system are illustrated.

2 Current approaches

Assembly includes operations for handling, joining, checking and adjusting as well as utility operations like cleaning [4]. Current technical solutions for assembly are automats, telemanipulators, balancers, exoskeleton, manual workplaces and manipulators based on the concept of human-robot-cooperation.

2.1 Manual workplaces

In manual workplaces all tasks are performed by human which is supported by suitable mechanical, electrical and pneumatic hand tools (e.g. screwdriver). The advantages of human are high flexibility, learning ability, adaptability and mobility [5]. Their disadvantages are high operating costs and low endurance. The human should perform tasks with low degree of repetition and high complexity. Current researches mainly address the design of ergonomic workplaces with respect to an optimized workplace organization and workflow [6, 7] as well as the development of assistance systems [8, 9]. For example, by using augmented and virtual reality the necessary information for the manual assembly can be displayed for the worker [10]. Age-differentiated design of workplaces for the application of touch screens is addressed in [11].

2.2 Robots/automats

Technical systems for automated solutions (robotic systems) for industrial application are standardized and free programm-able industrial robots (e.g. Kuka, ABB and Stäubli) with serial and/or parallel kinematic chains. Those robots can be used as a stand-alone machine [12], in cooperation with other robots and humans [13, 14] or with automated machine tools [15]. Exemplary topics in the field of robots are the development of more flexible automation systems, new robots based on combination of known kinematic chains [16, 17] and the improvement of the human–machine-interaction. Currently, the human–machine-interaction mainly addresses the human motion recognition and interpretation [18, 19]. New robots are designed as portable or mobile robots to be more flexible in respect to their operating space [20]. Furthermore, the robots are enabled for an efficient production of individual product variants and to perform multiple assembly processes by changing tools [21]. Usually, those robots execute simple or repetitive tasks within a restricted and monitored work area [22]. Common barriers for automated systems are high investment costs [23], low facility flexibility [23], low adaptability to a variance of input variables and small learning effects. On the other hands, low operating costs [24] and high endurance are advantages [25].

2.3 Balancer and telemanipulator

Balancers are widely used for the transportation of the workpiece between the workplaces [26]. In comparison to industrial robots which are overseen by the operator, the motion of the balancer is directly given by the human. Therefore the balancer can be seen as a support tool. Especially in cases of dangerous environments or inaccessible area, telemanipulators are used [26]. Here, human commands are transmitted by electronic, hydraulic or mechanical linkages for controlling the robot. The research in the field of balancers and telemanipulators addresses for example a more flexible and intuitive design, integration of current systems in manual processes as well as integration of systems for haptic perception [19, 27, 28].

2.4 Exoskeleton

Exoskeletons increase the force and mobility of the user. The support can be limited to individual body parts, e.g. hand or upper extremity [29, 30], or can support the whole body [31]. Typical applications include the area of agriculture, rehabilitation and military [29, 32, 33]. The motion of the exoskeleton is directly controlled by the motion of the user which can be perceived by implemented sensors. Aside from pressure [34] and force/torque sensors [30] which directly measures the interaction between human and exoskeleton, other non-invasive sensors like EMG-sensors [29] and hardness sensor of muscle [35] are used to detect human signals directly. Simultaneously, visual signals can provide relevant information to the human operator [36]. The kinematic chains and actuators of the exoskeletons determine the fidelity of motion in respect of the human movements. These must be adjusted individually to the user, e.g. with regard to the kinematic arrangement and number of degree of freedom, fixing points and actuator positions.

2.5 Human–machine cooperation

Main idea of the human–machine cooperation is sharing the work between human and machine in a common workspace [14]. Here the human and robot collaborate to carry out assembly tasks together. The research in the field of human–machine cooperation, interaction and collaboration addresses the design of corresponding workplaces, new technologies and assistance systems for production [37–40]. Highest priority is always the safety of the operator which can be achieved by different safety measures. A solution is the strict separation of machine and human in their workspace (e.g. by a fence) or in time [14]. More possibilities for security measures are the use of global, stationary sensors to monitor the production environment using optical methods or separating the workplace by light barriers and light curtains. Advanced systems can already dynamically divide environments in multiple zones without physical barriers [41–43]. A first approach for a spatial and temporal cooperation on a workpiece is shown for the application of welding operations [44, 45]. Another approach is the torque-controlled Light-Weight Robot III which yields under the human motion [46].

3 Human Hybrid Robot

The principal idea of Human Hybrid Robot (HHR) is the integration of human, robot and tool in a hybrid system. Main objectives are

- quality assurance,
- error prevention and
- increasing the accuracy

without compromising its changeability. Naturally, the individual advantages of human and machine such as sensory abilities and support of force, endurance as well as mobility should be maintained.

Based on the approach, the necessary technical aspects like configuration and control structure for the implementation are described in the following. Finally, possible benefits are addressed in comparison to current solutions.

3.1 Approach

The approach of HHR will further close the gap between the free programmable automats and the manual workplaces. Basic idea is to support manual assembly tasks by intelligent hybrid systems. Hybrid systems consist of serial and/or parallel kinematic technical modules of robots and tools as well as biological systems of humans (see Fig. 1). The human is an indispensable part of the hybrid system. Consequently, the human characteristics must be considered for configuration and design of the hybrid system.

The temporal and spatial merging of biological and technical systems is the essential idea of the HHR concept. Each system has individual characteristics and behaviors. Due to merging, the technical and biological system interact with each other. Through intelligent combination, the hybrid system can benefit from their individual abilities. Thereby the capability of the overall system can be optimized and the respective deficits of humans, robots and tools can be minimized. To achieve the merging of all systems a holistic approach is required for the development process which can include the design, the modeling and the control of the Human Hybrid Robot. The behavior of the human and the assembly process specify the input parameters. The technical kinematic chains are to be designed according to these requirements, e.g. axis and orientation of movements. Obviously, human, robot and tool must be integrated in a common control system.

The error prevention and quality assurance are indispensable requirements for the assembly. Reliable methods

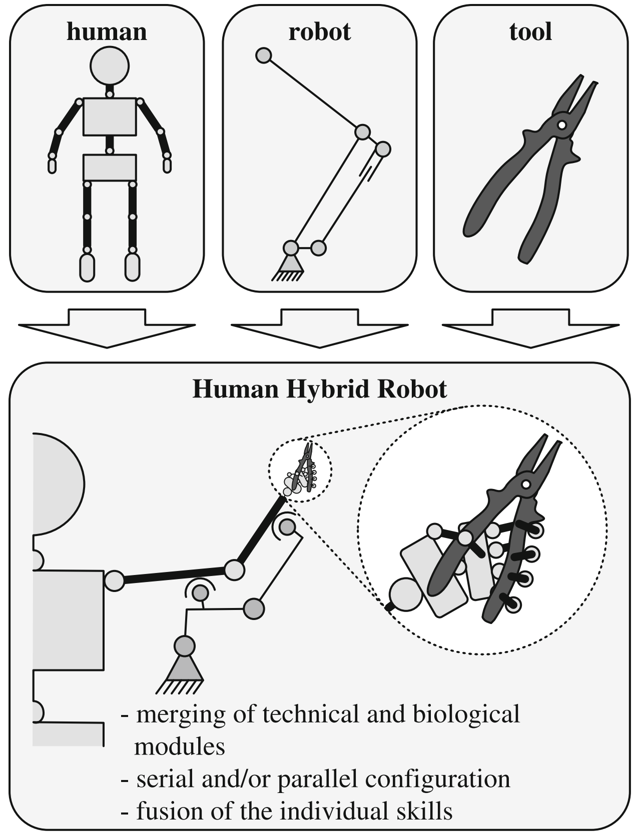

Fig. 1 Concept of Human Hybrid Robot

such as Poka-Yoke [47, 48] and ideas of the 6S-concept [49] seem to be appropriate for the implementation. These aspects must be considered for the HHR design. Therefore, appropriate sensors for monitoring and documenting the assembly process and/or self-adjusting and self-constraining systems can be used.

For a cost-effective operation, the Human Hybrid Robot should be adaptable for a wide range of applications. This requires the ability to change the system according to temporary distinct conditions, e.g. in respect to the operator and the assembly task. Consequently, modularity, standardization and reconfigurability are important issues which must be considered in the HHR development process [50–54].

3.2 Configuration

For an adaptable Human Hybrid Robot, a highly flexible system setup with respect to the product, processes and human is necessary. The required flexibility can be enabled by a pre-designed construction kit which includes modules with standardized interfaces. The construction kit should allow an ad hoc configuration and reconfiguration of the assembly system.

The human characteristics and the assembly process determine the design and configuration of the Human

Hybrid Robot (see Fig. 2). For example, the human has highly developed sensory abilities which allow him to move precisely. These abilities can be used in the application, e.g. as inputs for the control system or as a device for handling small components. The body size and the physical condition have a big influence on the design of the mechanical parts. Primarily two aspects can be determined: the size of the technical kinematic systems as well as the number and coverage of supported extremities. In this content, the technical scope of operations is to be adjusted according to the knowledge and the work experience of the operator. Furthermore, the size and mass of the workpiece define the guidelines for the actuators and structure of the HHR. The composition, e.g. surface, and the diversity of product variants determine the tool design and the associated handling equipments.

The process characteristics and their predefined process chain have a superior impact to the distribution of tasks. The process chain consists of a sequence of elementary functions (tasks) which can be executed by human, machine or tool or by their combination. On the one hand, a series of different tasks has often to be done by one HHR which may needs reconfiguration. On the other hand, small changes can also enable the HHR to execute similar tasks. For a cost efficient and task-depended configuration, the segmentation of the HHR into combinable modules is a logical solution.

The approach of a construction kit system is essential for a reasonable combination of the modules. The modules in the construction kit can be divided in

- biological and technical modules,
- tools and
- further optional modules (e.g. lighting or assembly instructions).

The human (e.g. arm and hand) represents the biological module. The passive or active technical modules can be arranged serially and/or parallelly to the kinematic chain of the biological modules. Passive systems often use bearings or springs. Active systems can include powered exoskeletons, industrial robots and powered manipulators. Robots with different kinematic chains, human, drives and tools, can be combined by standardized interfaces. For the interface design, the functions for force, data and energy transmission as well as the connected systems have to be considered. The interfaces can be classified with respect to their linkage between

- human–technical module,
- technical module–environment,
- technical module–workpiece and
- technical module–technical module.

However, the degree of standardization is influenced by the variation of the modules and products. Therefore, different designs for interfaces are possible.

In addition, every module is categorized in terms of characteristic criteria, e.g. maximal load, work area and function. This standardization enables a systematic task and human dependent configuration of the HHR.

3.3 Control structure

In current human–machine-systems, the robot control system is mainly designed to operate the robot without endangering humans. So far, the cooperation is strictly separated in time or work environment [42]. The human movements are observed by sensors, e.g. global and stationary sensors like safety fence, light barrier and camera systems as well as local tactile, visual, acoustic and

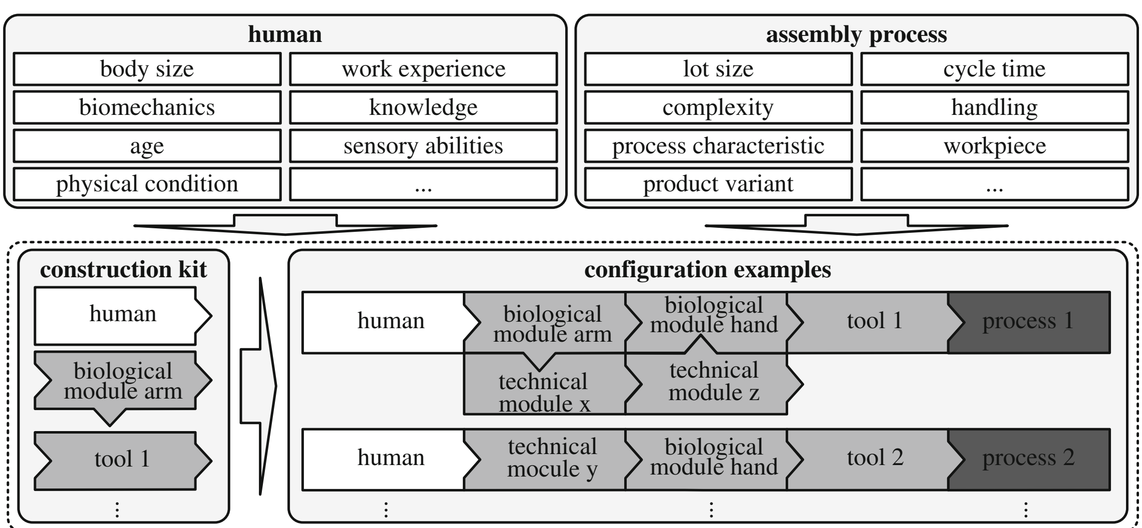

Fig. 2 Task customized configuration

capacitive sensors [42, 55]. The sensors detect unauthorized disturbances like humans in the work area of the robot and stop the robot in case of possible collisions (Fig. 3a). The temporal and spatial integration of human, robot and tool in one system, results in a higher degree of interaction between those systems (Fig. 3b). The motor skills of the human are not only part of the control, but they are also responsible for the command variables of the robot. Thus, the human is on top of the control hierarchy. In addition, the human cognitive abilities allow him to respond to different tasks and situations. Appropriate sensors detect human movements and gestures. The resulting measurement variables are analyzed and interpreted by the control algorithms which control the robot and tool accordingly. It is to be emphasized, that the human can also act as an actuator for assembly processes. Consequently, this factor must be considered in the control design. In this content, the human, machine and tool are directly connected with each other.

3.4 Advantages

The consolidation of individual abilities yields different economic, technical and social benefits. The human sense organs allow the operator generic gusto, olfactory, visual, auditory, tactile, vestibular and trigeminal perception of the environment and the current situation. The acquired information is automatically processed and evaluated by the operator. On this basis, further actions can be decided. Sensors allow quantitative and/or qualitative characterization of process parameters which assists the operator in his decisions. Force support is an additional advantage of the HHR. The modularity of the HHR enables flexible and task-adapted configuration. In short, economic and technological benefits arise primarily by supporting manual operations to increase assembly quality, higher availability and productivity of the employee. Especially against the background of demographic change, the result of an improved ergonomic design of the workplace and the associated lower burden of the employee are social benefits.

Table 1 summarizes the main difference and common characteristics between the current assembly systems and the HHR. The choice of the suitable assembly system is primarily dependent of the lot size and the complexity of the assembly task. The merging of technical and biological systems is also the principal idea of exoskeletons. For this reason, exoskeletons can be used as a module in a HHR system. However, exoskeletons cannot execute assembly tasks without tools. Additional modules are crucial to fulfil the HHR functionality which are derived from the demands for quality assurance, error prevention and assembly accuracy.

4 Exemplary applications of HHR

In the following, the potential of Human Hybrid Robots will be illustrated with two different applications: unergonomic or heavy physical work in aircraft production and assembly of micro products.

4.1 Execution of unergonomic or heavy physical works in aircraft production

Often, employees execute unergonomic or heavy physical assembly activities, e.g. assembly of floor, wires and huge components in the aircraft production. Due to missing or inadequate auxiliary or support tools, the risk for long-term effects like injuries or chronic muscle and skeletal disorders is rising [56]. For supporting heavy loads, several technical systems are developed, e.g. balancer [57, 58].

The concept of HHR in this application is a technical system to support unergonomic and heavy physical activities (see Fig. 4). Arms and neck are particularly strained in case of overhead work. This problem can be avoided by supporting and holding the arms and head by technical systems which are attached to the upper body. Thus, the

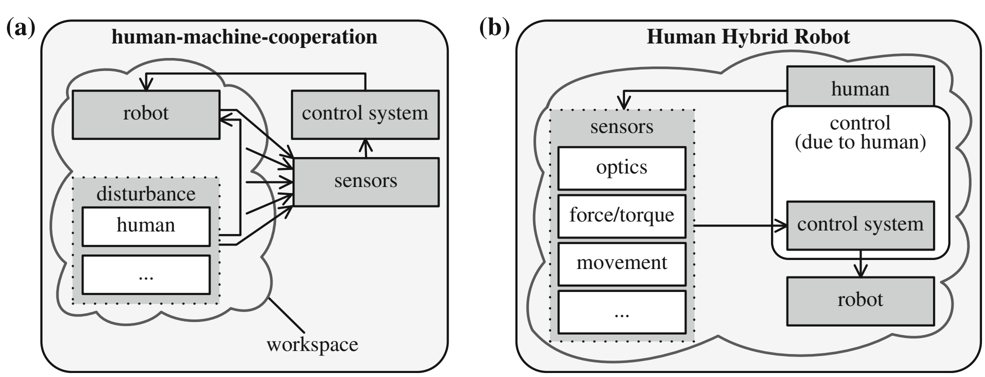

Fig. 3 Logic diagram of **a** human–machine-cooperation and **b** Human Hybrid Robot

Table 1 Characteristics of assembly systems

Characteristic	Approach						
	Manual workplaces	Robots/ automats	Telemanipulator	Balancer	Exoskeleton	Human–robot-cooperation	Human Hybrid Robot
Performing tasks	Human	Machine	Human controls machine	Human handles machine	Force support by machine	Cooperation between machine and human	Integration of human and machine
System boundary	–	–	Separated	Separated	Hybrid	Combined	Hybrid
Design	User-individual and process-oriented	Process-oriented	Process-oriented	Process-oriented	User-individual	Process-oriented	User-individual and process-oriented
Flexibility	Adaptable to product and operator	Low product variance and (simple) tasks	Product variance limited by tools and kinematics	Product variance limited by tools	Product variance limited by tools; adjustable to small range of physique	Product variance limited by tools; user-independent	Adaptable to product and operator by changeable system
Lot size	Low–medium	Medium–high	Low	Low–medium	Low	Low–medium	Low–medium
Human support	Hand tools	Automated production	Hazard avoidance, increase accessibility	Guiding and carrying support	Support of force, endurance, mobility	Taking over workload	See exoskeleton + increasing of accuracy, quality improvement, error prevention
System setup	Custom-built for a single or flexible application	Custom-built	Custom-built	Custom-built for a single or flexible application	Custom-built	Custom-built for a single or flexible application	Modular construction kit

weight of the arms, the technical modules and tools is carried by the operator. To extend the maximum work payload and endurance as well as to ease the burden on the backbone, a technical kinematic system for the complete body is possible. In this case, stresses and forces are transmitted to the ground.

In the case of assembly task near the ground level, the knees and the back of the operator are particularly stressed. Stooping, crouching or sitting on knees are often the only possible postures. Standing or seating postures with arms in front of the upper body are more ergonomic [59]. To obtain these postures, the HHR can act as an extension of the arm which can be classified as a serial kinematic system.

4.2 Workplace for micro assembly

Micro assembly is characterized by several specific economical and technological trends. The most prominent trends are increasing complexity and advancing miniaturization with smaller tolerances of products [2, 60]. Simultaneously, different sizes, shapes and new materials lead to a higher diversity of variants. Therefore, the assembly processes like handling, adjusting, positioning, joining, measuring and checking have to be performed in six degrees of freedoms [2]. Because of small lot sizes and a high product diversification a flexible assembly system seems to be the most suitable production system.

For assembly of products with sizes from few micrometers until several millimeters a precise motion coordination and a "steady hand" are necessary. In addition, skills for the manipulation with tools, e.g. tweezers and magnifiers, are required. These skills can be learned and improved through work experience. Furthermore, a high level of concentration is often needed and to be maintained over long time periods. In summary, the capability of the operator significantly decides the product quality. To reduce the requirements for the operator without compromising the product quality, a technical support system such as a Human Hybrid Robot is maybe helpful. This system can also minimize the strain on the operator and speed up his learning curve.

Figure 5 shows an implementation of a workplace for micro assembly. The HHR fulfills the objective of stabilizing and securing the posture. Furthermore, tools, equipments and workpiece are arranged to secure an optimal accessibility and organized assembly sequence.

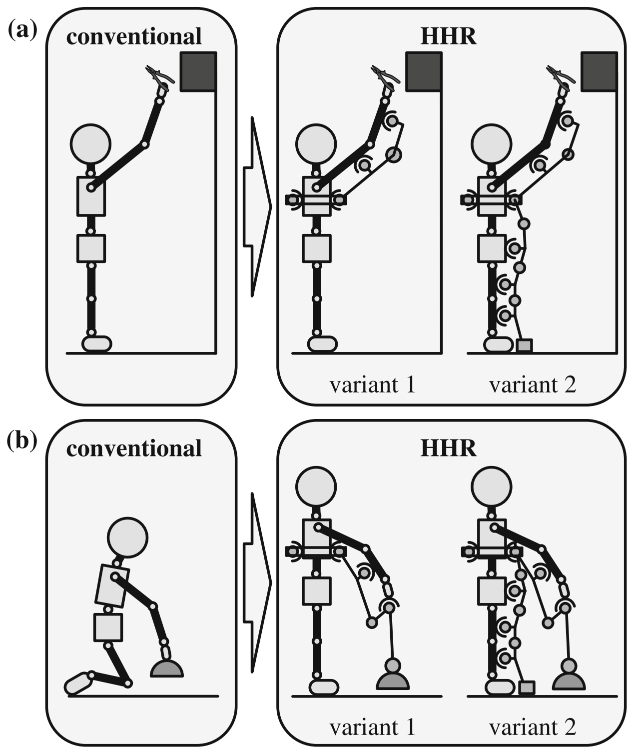

Fig. 4 Exemplary tasks. **a** Working over head and **b** working on ground

Methods for process monitoring and quality management can be integrated, for example Poka-Yoke mechanism.

Besides passive devices, active support systems for the employee can be implemented. An obvious application is an active damping mechanism for compensating the trembling of hands and arms. Another possibility is an active adjustment system of the workpiece according to the operator motion.

5 Exemplary HHR modules

As mentioned, a Human Hybrid Robot consists of several modules which are coupled by standardized interfaces. Modules are systems with one or multiple functions which interact with other modules or the production environment by defined interfaces [61]. Exemplary technical modules are shown in Fig. 6.

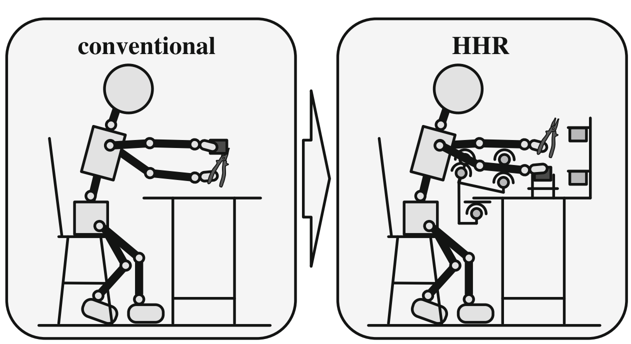

Fig. 5 HHR for micro assembly

A passive orthosis is used for the linkage between the human arm and the guiding mechanism which is mounted on the workbench (see Fig. 6a. For the current design, the kinematic chain of the technical module consisting of the orthosis and the guiding mechanism restrains the arm movement of the operator. As illustrated in Fig. 7, the result is a slightly smaller work area of the HHR workstation compared to a conventional manual workstation. However, the kinematic chain of the technical module possesses enough degrees of freedom to maintain the necessary motion range and motion trajectories as well as a steady arm posture within the work area. Therefore, the accuracy of the assembly process can be increased.

The human can control the tool directly (e.g. screwdriver) or indirectly through a mechanical, electrical or hydraulic linkage. For the assembly process, the tools can be attached to the technical modules or the production environment. They can also be held by the operator. An example for an indirectly controlled tool is shown in Fig. 6b. Here, an actuated rotary axis is mounted on the workbench and its velocity as well as its rotation direction are regulated by the operator. The motion and torque of the rotary actuator is transmitted to the workpiece carrier by a mechanical interface. The workpiece carrier with a vacuum cup is designed to hold small workpieces with smooth surfaces like lenses with a diameter >4 mm. The offset of the vacuum cup can be manually adjusted by a set screw.

To extend the number of applicable types of workpieces, different workpiece carriers have to be considered. Furthermore, the workpieces should be quickly exchanged to reduce the non-productive time during the assembly process. Figure 6c shows a possible design of the mechanical interface. It consists of a upper and a lower platform which can be mounted on the workpiece carrier or technical modules. The position of the upper platform with respect to the lower platform is defined by three carbide balls and six carbide rods with an overall stiffness of 875 N/μm [63]. Three permanent magnets on each side of the interface provide a holding force of 40 N [62] allowing the interface for low force applications such as handling small workpieces as well as for a precise and fast manual exchange of workpiece carriers.

Components for process monitoring and error prevention can also be integrated in the modules. For sensitive workpieces, a compliant mechanism can be implemented in a tool to reduce the force induced by the operator. In case of the orthosis, motion with overshoot can be avoided by mechanical stops.

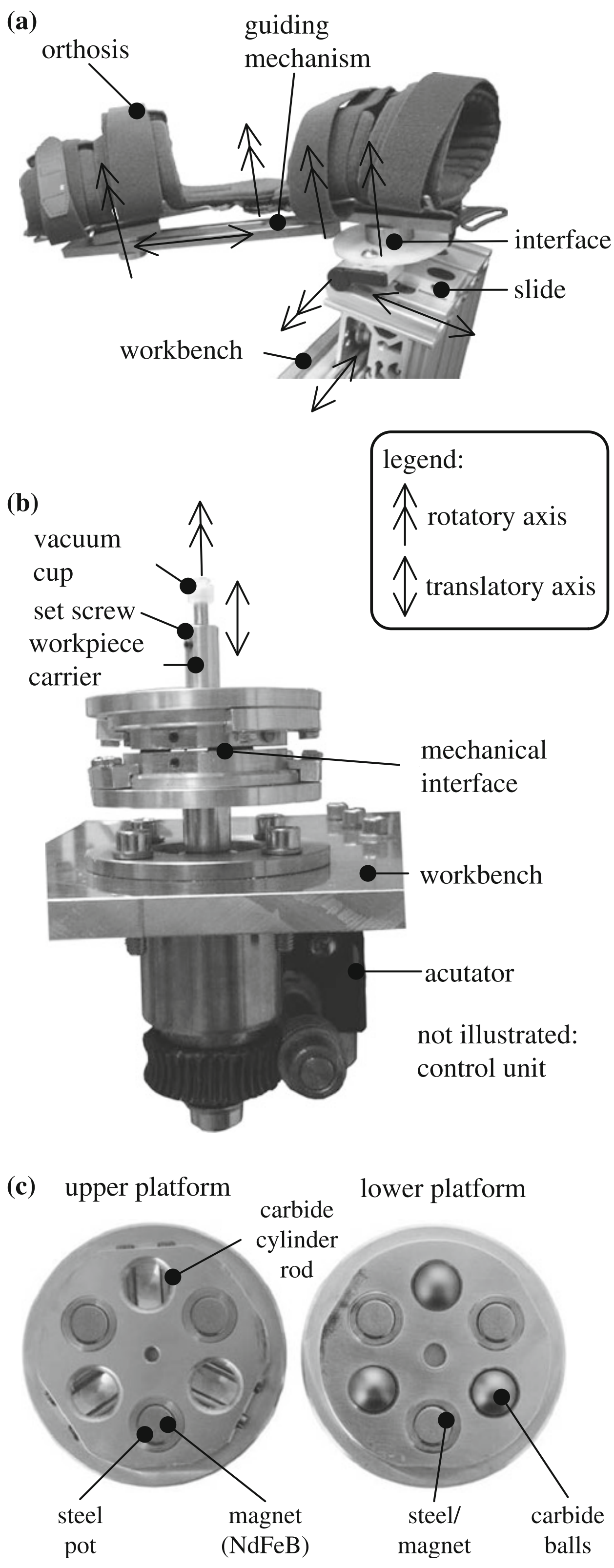

Fig. 6 Exemplary system modules **a** technical kinematic chain, **b** clamping device and **c** mechanical interface [62]

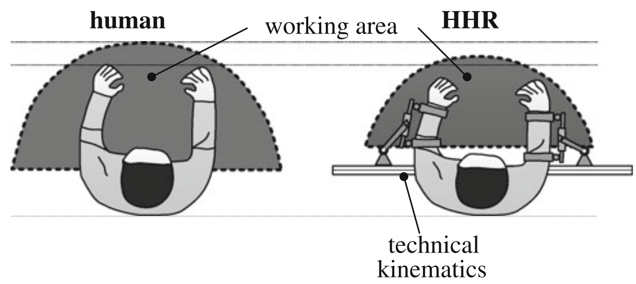

Fig. 7 Work area of a conventional manual workstation and a HHR workstation

6 Summary and outlook

In view of the demand for higher product quality and increasing individualization, technical support systems have to meet the requirements for manual assembly processes. One approach is the so-called Human Hybrid Robot which can be characterized by the hybridization of biological and technical systems. The temporal and spatial task-depended merging of different kinematic chains does not primarily focuses on increasing the force and mobility of the operator, such as current telemanipulators and exoskeletons. Rather, the HHR supports manual tasks to optimize the assembly accuracy, quality assurance and mistake proofing by integrating process-based methods and mechanisms.

A HHR can be designed to avoid unergonomic working positions for the assembler. It can also be used for complex assembly tasks such as handling micro parts. To maintain the adaptability of the HHR under volatile production conditions, high modularity is to be considered for the design of a HHR. On this basis, a first design of exemplary technical modules and a mechanical interface is presented. Further experimental studies will show their feasibility. More modules will be developed to extend the range of application for industrial assembly processes. The concept of HHR can also be implemented for other areas of application such as machining processes or in medical field, whose requirements and procedures are similar to those of assembly.

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