

Complexity-based task allocation in human–robot collaborative assembly

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Abstract

Purpose – Over the past years, collaborative robots have been introduced as a new generation of industrial robotics working alongside humans to share the workload. These robots have the potential to enable human–robot collaboration (HRC) for flexible automation. However, the deployment of these robots in industrial environments, particularly in assembly, still comprises several challenges, of which one is skills-based tasks distribution between humans and robots. With ever-decreasing product life cycles and high-mix low volume production, the skills-based task distribution is to become a frequent activity. This paper aims to present a methodology for tasks distribution between human and robot in assembly work by complexity-based tasks classification.

Design/methodology/approach – The assessment method of assembly tasks is based on the physical features of the components and associated task description. The attributes that can influence assembly complexity for automation are presented. Physical experimentation with a collaborative robot and work with several industrial cases helped to formulate the presented method.

Findings – The method will differentiate the tasks with higher complexity of handling, mounting, human safety and part feeding from low-complexity tasks, thereby simplifying collaborative automation in HRC scenario. Such structured method for tasks distribution in HRC can significantly reduce deployment and changeover times.

Originality/value – Assembly attributes affecting HRC automation are identified. The methodology is presented for evaluating tasks for assigning to the robot and creating a work–load balance forming a human–robot work team. Finally, an assessment tool for simplified industrial deployment.

Keywords Automation, Lean automation, Human–robot collaboration, Industry 4.0, Cobots, Assembly

Paper type Research paper

1. Introduction

Conventional heavy load industrial robots, even though being immobile and hard to reconfigure, are the backbone of a great proportion of industrial automation (Malik and Bilberg, 2017). They are applied in various areas of value addition in a manufacturing landscape to boost productivity. But when it comes to assembly work they are not practical.

Assembly work refers to a set of sequential activities of joining geometrically defined parts, components and software resulting into functional products. The primary characteristics of assembly work that differentiate it from manufacturing are the large number of parts, many variants, frequent disruptions in the production process and shorter cycle times. Given these reasons assembly systems have traditionally been remained in the hands of humans and away from mainstream automation. Today, for manufacturing of discrete products, assembly is considered the most labor-intensive process.

However, manual ways of production are not able to cope with the challenges of mass customization and globalization. The increasing market challenges are much of the drive toward extending levels of industrial automation in manual work in the form of human–machine collaboration (HMC). The dream

combination of humans and machines working together is now being realized through collaborative robots that tend to share the workload of their fellow humans. This new generation of industrial robotics, offering opportunities to form human–robot work teams, is called collaborative robot or cobot.

A collaborative robot (Figure 1) is a mechanical device endeavoring direct physical contact with fellow humans (Krüger et al., 2009). The concept of lightweight collaborative industrial robots was first presented by (Peshkin and Colgate, 1996) and is aimed to offer human–robot interaction by enabling safety, easy mobility by its lightweight structure and flexibility by ease of reconfiguration. Cobots together with required safety devices create opportunities to exchange the strengths and weaknesses of machines with their fellow humans creating workspaces exhibiting the right amount of automation (Müller et al., 2016). The balanced-automation is formed at the splendid intersection of flexibility of manual operations and efficiency of machines.

When implementing a collaborative robot in a manual assembly cell for sharing work-tasks between human and robot a challenge is the right work-load distribution. This challenge is associated with the complexity of assembly operations that keep humans as a need. If identified rightly, those manual tasks can be separated from less ergonomic, repetitive tasks and can be assigned to the robot.

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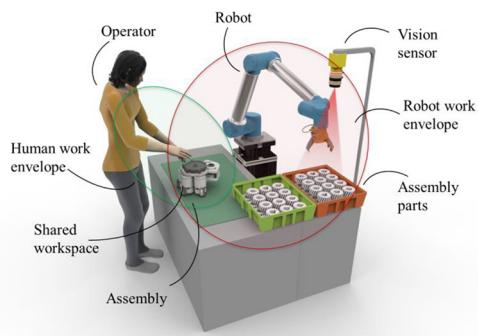
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Figure 1 Human–robot collaboration

Traditionally, this is done through *gut-feeling* without any structured methods available. Alternatively, there are complex mathematical models to verify the robot application for a given task, but these methods are contextual and complex for industrial application. Further, the significance of skills based workload distribution is important because the ironies of automating everything that can be automated and assigning the leftover tasks to humans have been discussed by Norman (Norman, 2015). A structured quantification of tasks for their ease of automation would make it possible to prioritize the tasks based on their automation potential in an assembly process thereby simplifying the work-load distribution.

A task, in assembly, is defined as the manipulation of robotic or human arm required to reach a target and execute an action (e.g. grasp, insert and release) (Pellegrinelli *et al.*, 2016). It is possible to distribute assembly tasks into three sub-phases or operations i.e. grasping the object, transport to a desired position and assembly (Krüger *et al.*, 2014). The information content of these tasks is what we refer to as assembly complexity.

The methodology presented is based on the evaluation of the physical properties of the parts and its assembly task description. Based on the scoring, the tasks are assigned to a human and robot. The numerical quantification will allow to prioritize the value adding and simple tasks for automation. The quantification will also help in formulating logic for automated workload balancing techniques.

2. Literature review

Norman (2015) in his work on the human side of automation highlighted the notion of uniqueness of skills acquired by humans and machines that define their strength and weakness to accomplish a task. The superiority of humans over machines is recognized at pattern recognition, dealing with the unexpected and setting high level goals, however, at the same time humans are considered not good at performing repetitive tasks with high accuracy and at vigilance activities.

A classical theory of evaluating human-machine capabilities for functional allocation was presented by Fitts *et al.* (1951) and is often referred to as MABA-MABA list (men-are-good-at, machines-are-good-at). Fitts, together with his colleagues built a report to discuss the challenges and opportunities of human-machine interaction to improve air navigation system. The report summarized the bests of humans and machines in eleven

points (Figure 2). Besides the later criticism (de Winter and Dodou, 2014) Fitts' report is still considered as the classical theory of functional allocation in human-machine collaboration.

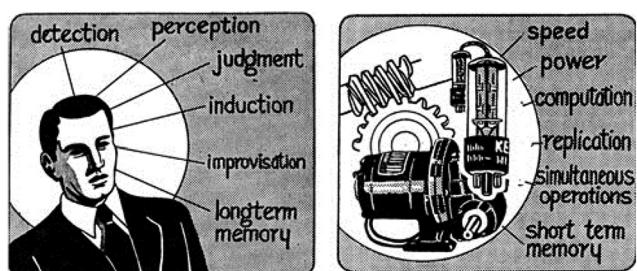
Later, the complexity and error prone nature of HRC systems, both for the system designer and the operator, was highlighted by Sheridan and Parasuraman (2005). According to (Parasuraman and Wickens, 2008), when making man – machine system, the two should be complementary resources rather than conflicting resources. Hancock (Hancock and Scallen, 1996) takes it further as the problem of task allocation arises when both the human and the machine are able to perform the task.

Design for assembly (DFA) methods give a good understanding of the attributes that affect the assembly quality. It is also recognized that factors in DFA methods influence differently for manual and automated assembly (Eskilander, 2001). Early researches on use of robots for assembly were made by Boothroyd (1984), Owen (1985) and identified the part/product attributes for ease of robotic assembly. Yet those studies are not taking care of human robot collaborative environment and the factor of lightweight robots as preferred for HRC environment with low payload capacities and limited grippers.

Fasth *et al.* (2010) developed a methodology named DYNAMO++ to determine task automation from total manual to totally automatic. Tan *et al.* (2010) formed a strategy of task allocation in HRC by task analysis approach. The work was done with a cable harness assembly in a prototype cellular manufacturing system. HRC was evaluated for productivity, quality, human fatigue and safety priorities. However, the physical properties of components were not discussed, and the tasks categorization was limited to cable harnessing. Another methodology was presented by (Teiwes *et al.*, 2016), assigning a score to various assembly tasks identified in MTM methods for automation. The scores were based on experimentation and were limited in application.

Antonelli and Bruno (2017) distributed the tasks in HRC by a decision matrix that evaluates weight, possibility to grip the part, displacement, and required accuracy to develop a dynamic task distribution method. However physical features of components, besides weight, are not considered.

Bänziger *et al.* (2017) discussed various robotic skills required to perform tasks in automotive assembly lines. Robotics skills (pick, place, move along path, navigate, wait, handle/apply tool and trigger) were identified from MTM codes and were further added with six additional skills (position, hold, align, apply force, and apply force along path).

Figure 2 MABA-MABA list for human–machine interaction

The method for planning human–robot shared tasks presented by [Michalos et al. \(2018\)](#) derives part attributes of weight, size and flexibility from CAD data and forms a concurrent method of layout and task planning in human–robot interaction for automotive sector. FlexHRC ([Darvish et al., 2018](#)) offers a dynamic or on-the-fly task sharing method to decouple human–robot action planning from robot motion planning. Another recent study ([Bänziger et al., 2018](#)) uses standardized work descriptions for automated procedure generation through simulation model. The simulation calculates production parameters as a function of human–robot task allocation. [Chen et al. \(2014\)](#) discussed system tradeoff between time and cost when scheduling tasks between human and robots and formed a quantitative method based on mathematic model.

3. Tasks distribution method in human–robot collaboration assembly

This chapter describes the attributes that determine potential of robotic automation for assembly tasks in a human–robot collaborative work fashion as shown in [Figure 3](#). These attributes are aligned with previous studies of detailing assembly process complexity ([Samy and ElMaraghy, 2012](#)) and factors contributing to DFA methods for ease of assembly ([Leaney and Wittenberg, 1992; Boothroyd and Alting, 1992](#)).

For each assembly task the evaluating attributes are divided into three basic categories i.e. part, process and workspace related attributes. Part is the entity or material that is integrated into a subassembly to gradually complete the final product. The two types of part-dependent attributes are the physical characteristics and how the part is fed into the assembly station. The next category is process which is further classified into mounting and joining methods involved. Each of these attributes are then divided into factors which is a range of various possibilities for an assembly scenario. Each factor is given a numerical rating. The rating is made on a scale of 0 to 1, where 1 defines the tasks with highest automation potential and

0 defines the lowest automation potential (see Chapter 4). The scores for each factor defining ease of HRC assembly are the results from authors' experimentation with collaborative robots for industrial applications. In an industrial research project to identify the potential of collaborative robots in assembly, the authors evaluated and developed HRC assembly workstation at a manufacturing company. A collaborative robot was used in each case for automation of the repetitive tasks. Subsequent, lab experimentation and comparison with relevant literature helped to refine the scores.

The aggregate automation score for each task is the mean value achieved against all the attributes defining suitability of the assembly task for human or for the robot. As humans and robots are having unique and similar capabilities, the rating divides the tasks as human tasks, robotic tasks, and robotic or human tasks.

The process of evaluating task complexity for HRC automation starts by decomposing the product into parts and components each of which defines an assembly task. Each task is then compared for its various attributes with the automation rating. The scores derive a decision-making arena where all tasks with scores above 50 per cent are recognized as recommended for automation, while all the tasks less than 50 per cent score are assigned to the operator. This also considers that none of the individual attribute must fall below 50 per cent. The automation potential for each attribute is calculated as:

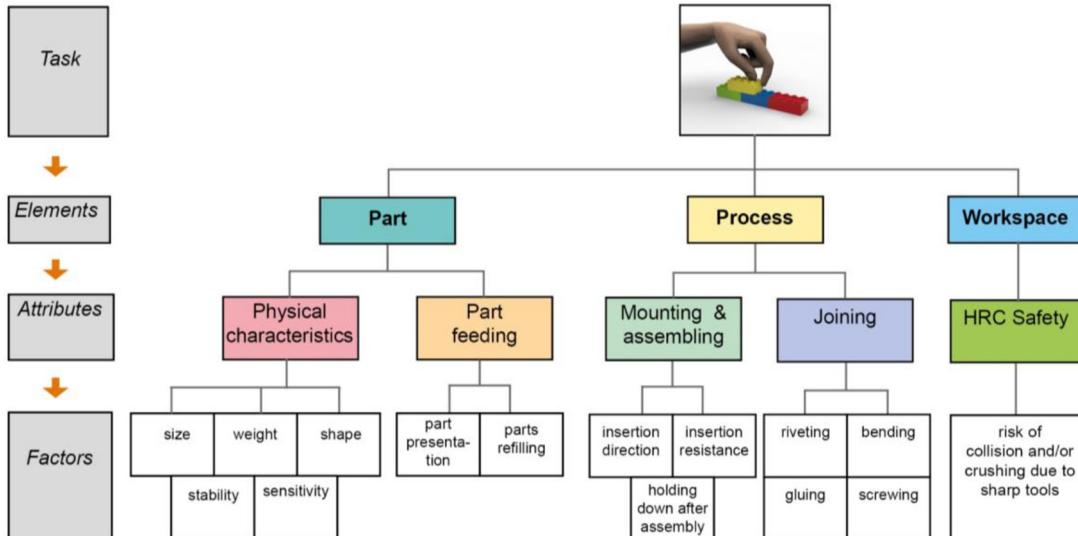
$$P_{\text{attribute}} = \frac{\sum J \text{ attribute}}{J} \times 100 \quad (1)$$

The aggregate score for each component is calculated as:

$$HRC_P = \frac{\sum P}{P_{HRC}} \times 100 \quad (2)$$

Where P is assembly score achieved in each factor considered for HRC task evaluation and P_{HRC} is sum of the number of all the factors used in HRC potential.

Figure 3 An assembly task and its components for HRC complexity evaluation



The final task assignment needs to take care of assembly precedent constraint and task times. The task times can either be calculated by using stopwatch and are generally known for manual processes when starting such an evaluation. For pick and place tasks with a robot, the time can be tested with a real robot or by using a virtual simulation. By having times of all tasks, the final task assignment is done using the logic as shown in [Figure 4](#).

4. Attributes affecting human–robot collaboration automated assembly

The following chapter presents various assembly attributes and their rating for evaluation of automation in an HRC scenario.

4.1 Graspability of parts and components

Graspability is the ability of a robot to securely pick the component from its home-location and move it to the point of placement or delivery. The accuracy and success of pick-tasks is based on the factors of size, weight, and geometry of the component to be moved.

4.1.1 Size and thickness

Size (or the major dimension) of an assembly component is the largest nondiagonal dimension of its outline when projected on a flat surface ([Figure 5](#)). It generally is the length of the part. The thickness of a cylindrical part is its radius while for a non-cylindrical part the thickness is described as the maximum height of the part with its smallest dimension extending from a flat surface ([Boothroyd, 1994](#)). A part is considered too large to be handled by a collaborative robot if the grasping feature is larger than the maximum gripping size of commercially available general-purpose robot-grippers. Additionally, very large parts that can obscure the movement of the robot during task performance can be challenging. The experiments showed that the task performance becomes hard if the maximum dimension of the part is more than half of the reachability radius of the robot. A part is too small to be handled by a robot if the part has not enough surface available for effective grasp by the gripper.

4.1.2 Weight

The allowable component's weight for robot manipulation is robot's payload capacity minus gripper's weight. A heavy component will increase the kinetic energy of the robot during manipulation increasing safety risks for the fellow human. This makes lightweight components easier to automate. The two extremes observed are the parts with less than 1 kg (which are convenient for most robots and grippers) while above 8 kg the manipulation becomes difficult for a collaborative robot, especially in HRC workspace.

Figure 4 Assembly task assignment logic for human and robot

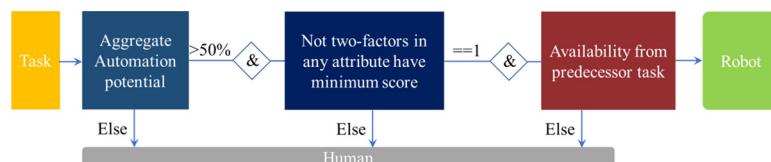
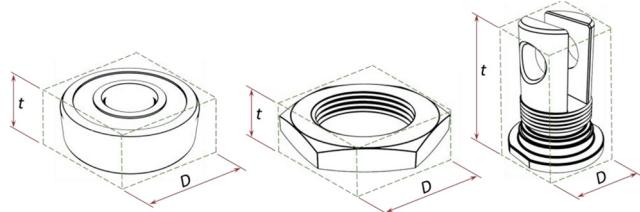


Figure 5 Size and thickness of parts as attributes for automation assessment by a robot



4.1.3 Shape of the components

The geometrical symmetry and shape of the assembly components would influence the grasp of a component in required position and orientation by a robot. The shape-suitability of a component for manipulation by a robot is defined by the grasping feature(s) and enough surface area available to securely grasp the component. Owing to various types of grippers and gripping methods available, it is a complex criterion for generalizing robot-potential for a task performance. However, there is a direct correlation between the cost of the gripper and its flexibility ([Figure 6](#)). The shape-based evaluation would entirely be contextual and the available gripper options. To ensure accuracy and repeatability in assembly, a general purpose two finger grippers would give satisfactory results in most cases.

4.1.4 Stability

A component is flexible if it cannot maintain its shape during handling and causes the robot gripper to not function properly ([Boothroyd, 1994](#)). This kind of components can better be handled by humans because of humans' hand adaptability.

4.1.5 Sensitivity

The components that are fragile or have surface that may get damaged by the surface of the gripper. The more sensitive the surface is the more task-specific gripper would be needed.

The scores for various part characteristics and their associated factors are given in [Table II](#) with their rated complexity [Table I](#).

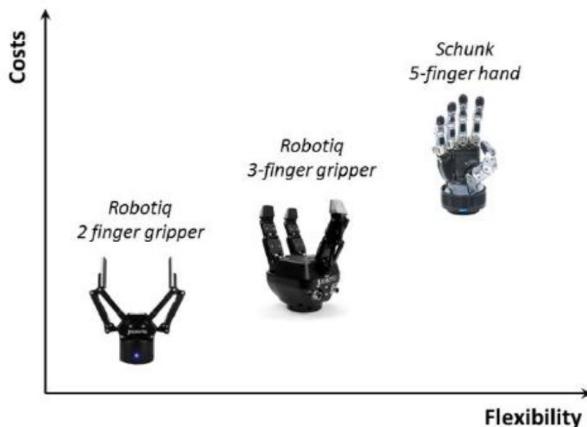
The HRC potential for part structure can be calculated by:

$$P_{\text{part}} = \frac{\sum_{1}^{\mathfrak{J}_p} \text{part}}{\mathfrak{J}_p} \times 100 \quad (3)$$

where P_{part} is a potential score for part feeding attributes and \mathfrak{J}_p denotes to number of part related attributes.

4.2 Feeding mechanism

The robot or human, for an assembly operation, need to be aware of the location and orientation of the part to pick it in the required

Figure 6 Cost vs flexibility of robot grippers

Sources: Krüger *et al.* (2009); Malik and Bilberg (2017)

Table I Part attributes for HRC assembly

No special gripper required	Component		
	Size and thickness	Custom-made gripper required to handle the part	Part may obstruct robot movement
1.0		0.75	0.25
Weight			
<1 kg	1-3 kg	3-8 kg	8-12 kg
1.0	0.75	0.25	0
Shape and symmetry			
Two fingers gripper required	3 fingers gripper required	4 fingers gripper required	Human hand required
1.0	0.75	0.25	0
Stability			
Stable	Deformation at low force	Deformation at high force	Shapeless
1.0	0.75	0.25	0
Sensitivity			
Robust	Damage at low force	Damage at high force	Sensitive
1.0	0.75	0.25	0

posturing. The precise sensing and grasping abilities make this task straightforward for humans but for robots it is quite challenging. The process of presenting the parts to the robot and making robot aware of the location and pose of parts is referred to as parts feeding and this needs to be flexible to the dynamics of part's design, shape, location, orientation and production volumes.

Feeding can be described as a set of two tasks i.e. part structuring and part presentation. Singulating individual part from a bulk and arranging it to have a known orientation is parts-structuring, while part-presentation refers to transferring a structured part to the point of application or assembly. The conventional automation devices for parts feeding are part-

dependent mechanical devices e.g. vibratory bowl feeders which are inflexible toward part variety. Besides several methods discussed in theory and praxis for parts feeding (Krüger *et al.*, 2009) the general criterion is that the more disorientated the parts are the more investment it will require to automate the feeding process. Further, the process would become more complex and less flexible. For this reason, for known position and orientation of parts, a robot is easy to use, while for disorganized parts it becomes cumbersome. The scores for various feeding possibilities are given in Table II with their rated complexity.

The HRC potential for feeding can be calculated by:

$$P_{\text{feed}} = \frac{\sum_{j=1}^{J_f} \text{feed}}{J_f} \times 100 \quad (4)$$

where P_{feed} is a potential score for part feeding attributes and J_f denotes to number of feeding related attributes.

4.3 Mounting and insertion

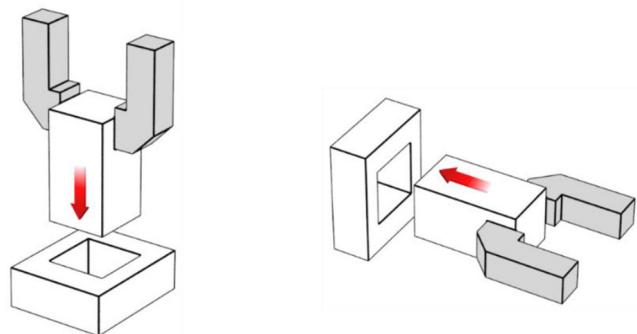
Mounting and insertion is the process of adding the picked parts to the sub-assembly forming a complete product. It is affected by the direction of placement of components and accuracy requirement.

4.3.1 Insertion direction

A z -axis (vertical to the ground) assembly in layer fashion with top down approach is preferable both for manual and automated operations (Boothroyd *et al.*, 2001; Eskilander, 2001). This simplifies the placing and mounting of components assisted by gravity (Figure 7). For robots, this can avoid any additional movement to secure the component that might be needed in a horizontal to ground assembly.

Table II Feeding attributes for HRC assembly

Known position and pose of components	Feeding	
	Parts presentation	Disorganized in a box or on plane
1.0	0.75	0.25
Parts Refilling		
1 × per shift	3-4 times per shift	For each cycle
1.0	0.75	0.25

Figure 7 Assembly direction and effect of gravitation force for ease of assembly

4.3.2 Holding down required

Holding down the components is defined as a task to maintain the position or orientation of an already assembled component (by a robot) before or during subsequent operations (Boothroyd *et al.*, 2001). If a task is performed by a robot and needs the component to be held down before mounting the next component which will eventually secure the component in place. A single arm robot (without the aid of any additional fixture) wouldn't be able to perform such tasks and either the human-robot or a robot-robot cooperation would be needed for the task execution. This implies that, in most cases, that a human would be the right choice.

4.3.3 Insertion resistance

The resistance to insertion is caused by the degree of tightness between two mating components that is defined in terms of tolerance limits. Too tight tolerances would need the robot to acquire precise sensing mechanism increasing automation cost and complexity. While humans are good in having sensor-motoric skills and adapting to the operation's requirements.

The scores for various mounting characteristics are given in [Table III](#) with their rated complexity.

The HRC potential for mounting can be calculated by:

$$P_{\text{mount}} = \frac{\sum_{j=1}^{J_m} \text{mount}}{J_m} \times 100 \quad (5)$$

where P_{mount} is a potential score for part mounting attributes and J_m denotes to number of mounting related attributes.

4.4 Fastening

Operation that are about fastening. It may be screwing, gluing or riveting. Screwing is the most occurring fastening method is assembly and suitable for automation. The reason is that screwing is done at a well-defined location with predefined torque and automated fed screws. Automating a screwing process is the easiest among fastening methods. While gluing requires careful programming of the robot making it less flexible to changes. Bending and riveting would require the robot to have force sensing capabilities [Table IV](#).

The HRC potential for safety can be calculated by:

$$P_{\text{join}} = \frac{\sum_{j=1}^{J_j} \text{safe}}{J_j} \times 100 \quad (6)$$

Table III Mounting attributes for HRC assembly

		Assembling/mounting	
		Insertion direction	
Vertical from above (gravitational support)		Horizontal (no-gravitational support)	
1.0		0.5	
<i>Holding down after assembly</i>			
Not required		Required	
1.0		0	
<i>Insertion resistance in mating parts</i>			
No force required	Medium force	Light force	Need to be pressed with force
1.0	0.75	0.25	0

Table IV Fastening attributes for HRC assembly

Joining			
Screwing	Gluing	Bending	Riveting
1.0	0.75	0.5	0.25

where P_{join} is a potential score for part joining attributes and J_j denotes to number of joining related attributes [Figure 8](#).

4.5 Safety considerations

Humans' safety is an important factor in HRC assembly planning (Pedrocchi *et al.*, 2013). In practice, it is observed that risks are mainly because of the use of custom designed handling devices (grippers) and handling of sharp-edged parts. Although cobots are designed for workspace where a collision between human and robot is likely to happen, however it tends to reduce the productivity. It must be tried to identify the robot's placement location and define its trajectories to have minimum collisions with the fellow human.

Because the use of custom designed grippers and handling of sharp-edged components may increase safety risks, a detailed safety assessment is mandatory before any new HRC strategy is executed. The below method highlights an early stage safety risk assessment for a robotic task for a potential safety hazard. If it appears to be not safe (and risk is unavoidable) then the task must not be assigned to the robot [Table V](#).

The scores for various safety related aspects are given below.

The HRC potential for safety can be calculated by:

$$P_{\text{safe}} = \frac{\sum_{j=1}^{J_s} \text{safe}}{J_s} \times 100 \quad (7)$$

Figure 8 Joining methods by robot

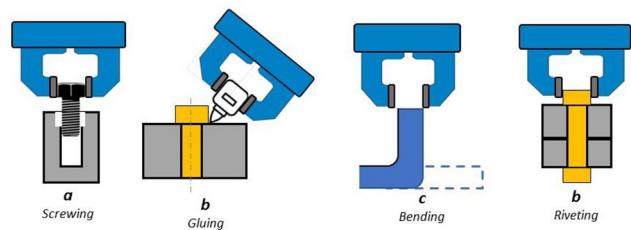


Table V Safety attributes for HRC assembly

HRC would increase safety	Safety considerations	
	Risk of collision	Frequent collisions
1.0	0.75	0.25
<i>Risk of cutting/ crushing with sharp tools</i>		
HRC would increase safety	Risk would be eliminated with safety devices	Possibility of injury
1.0	0.75	0

where P_{safe} is a potential score for part safety attributes and \mathcal{J}_s denotes to number of safety related attributes considered.

5. Use case for human–robot collaboration tasks distribution

An industrial case study of assembling an electronic linear actuator is demonstrated for evaluation and validation. The parts and operational sequence of the assembly are shown in [Figure 9](#). The subject product is a mechatronic device that converts electrical energy into straight line motion and is used to automate various machine tools and industrial machinery. The current method of production is manual assembly cell by high variability of assembly tasks. The operator receives sub-assembly on a conveyer and mounts; gear wheel #1, metal bush #2, ball bearing #3, M9 nut #4, back fixture #5, shell #6, gasket#7, lid #8, M27 nut#9 and lid screws #9, after which the subassembly is moved to the subsequent station.

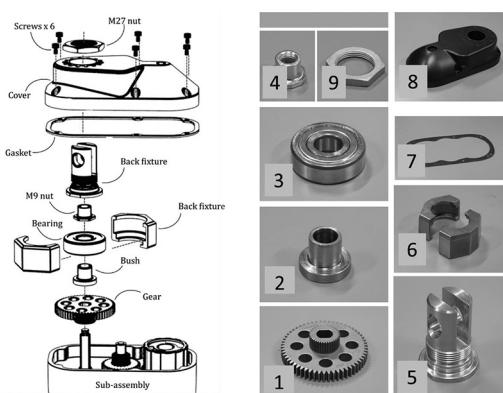
The task of assembling a Gear Wheel is evaluated for all the attributes as discussed in chapter 4. It is a metal part with a stable shape and enough surface area for picking the parts by a gripper. The parts are supplied in trays where the robot can easily grasp it from the known location. It is a top-down assembly therefore robot would just need to place the component at required location, release it and the part will fall under the force of gravity. The robot is aimed to be placed next to the operator and ISO-15066 is implemented before process execution, therefore the workspace is safe for the fellow human

[Table VI](#) and [Figure 10](#).

Similarly, the final score is achieved for all the tasks as shown in [Table VII](#).

The final scores helped to develop the assembly process plan. The proposed human–robot collaborative assembly cell is shown in [Figure 11](#). The robot is implemented with the objective to increase productivity by automating a portion of the assembly tasks by a robot. Operator and robot, in the proposed work cell, are sharing the workspace and are working simultaneously. The robot used is UR-10 collaborative robot by Universal Robots. The robot used has a payload capacity of 10 kg and a reach of 1,000 mm.

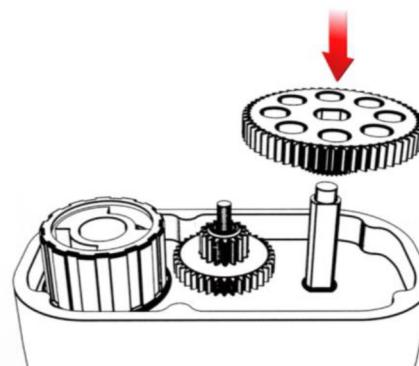
[Figure 9](#) Assembly use case



[Table VI](#) Assessment of HRC automation for gear wheel

		Task 1: Mounting of gear wheel	
Attribute	Analysis	Score	Automation potential for each attribute
Part			100%
Size	No special handling device needed	1.0	
Weight	<1 kg	1.0	
Shape	A two-finger gripper required	1.0	
Stability	Stable	1.0	
Sensitivity	Robust	1.0	
Feeding			75%
Parts structuring	Organized but pose identification required	0.75	
Parts refilling	Two-three times per shift	0.75	
Process			100%
Insertion direction	Vertical from above	1.0	
Holding down after assembly	No	1.0	
Insertion resistance	No	1.0	
Joining			100%
If any	No	1.0	
Safety			100%
Frequent collisions	No	1.0	
Risk of injury	No	1.0	
Aggregate automation potential			95%
Resource			Robot

[Figure 10](#) An assembly task in the use-case

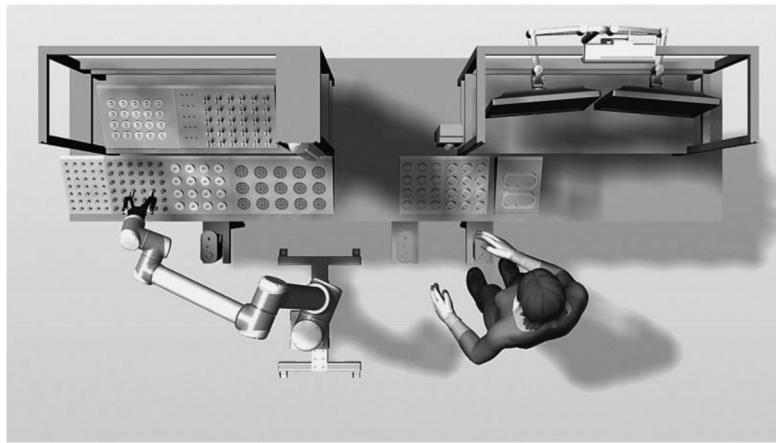


6. Discussion

The results show that above 70 per cent of the total assembly tasks have a potential for cobot automation that correspond to 80 per cent of the total time of manual assembly. But all the tasks with robot potential are not necessarily need to be automated. The final task assignment must consider the working time and availability of each resource at any instance of time.

Table VII Assessment of HRC automation for case assembly

Sr no.	Part name	Manual task time	Precedent	Automation score (%)	Suggested resource	Robot working time	Task assignment
1	Gear wheel	6 s	0	95	Robot	12 s	Robot
2	Bush	5 s	1	77	Robot	12 s	Human
3	Ball bearing	5 s	2	71	Robot	14 s	Robot
4	M9 nut	17.6 s	3	63	Robot	—	Human
5	Back fixture	5 s	4	81	Robot	15 s	Robot
6	Back fixture shell	4 s	5	48	Human	—	Human
7	Gasket	5 s	0	44	Human	—	Human
8	Lid	7 s	7	62	Human	—	Human
9	M27 nut	8 s	8	75	Robot	10 s	Human
10	Lid screws	22 s	9	75	Robot	26 s	Robot

Figure 11 Planned HRC workspace

The tasks with low automation potential are largely because of the components' shape and feeding complexity. It can be argued that for achieving a higher degree of automation, the critical factors are to have flexible gripping devices and flexibility in parts feeding methods. Research in vision-based feeders is an emerging trend for having feeding flexibility in automated assembly. An example is the flexible feeder (Rosati *et al.*, 2013) combining a vibratory bulk (for singularizing) and vision (for location and pose identification). Nevertheless, feeding flexibility is a challenging and non-value adding (but important) assembly activity. Future robotic solutions must be directed toward solving aforementioned challenges to tap the full potential of HRC.

The field of new product design and development must also take care of the HRC based assembly work. This opens another area of scientific exploration i.e. product design for HRC assembly. Several studies have documented product design techniques for manual assembly, robotic assembly and automated assembly, however the product design for HRC assembly has not been explored yet.

7. Simplified user interface for industrial application

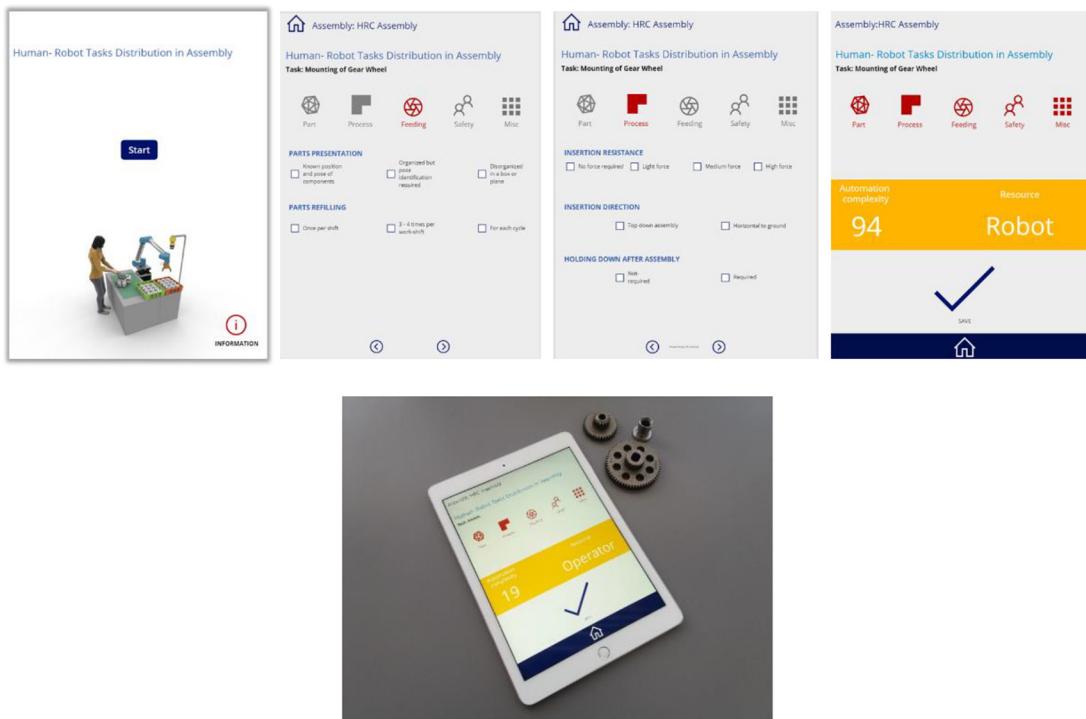
This chapter describes how the usability of the above presented task distribution method is further simplified for industrial practitioners. With the objective to have a fast and simplified

way for tasks distribution based on task complexity, a tablet-application is developed with easy user interface (see Figure 12). Microsoft PowerApps is used to develop the application. The app is touch-enabled with text and graphics-based interface. All the mathematical calculations are embedded into the app but are not visible to the user. Tasks assignment logic (see Figure 4) is incorporated into the app. It is expected that a person with ability to use a smart phone and understanding of the assembly process can use the app.

Upon start, the user enters project title, and starts the task evaluation by entering a unique name for each task. For each assembly attribute (i.e. part, process, feeding, fastening and safety) a separate page is presented to the user (see Chapter 3) where user check-marks the best attribute corresponding to the given task (see Chapter 4). The user navigates between the pages by hitting the “next” button available on the screen. Upon selecting all the corresponding attributes for a given task, a final score is calculated. The task assignment is achieved as presented in Chapter 5. Once all the tasks in an assembly process is evaluated, a spreadsheet is generated for detailed process plan.

8. Conclusion

The presented method for complexity evaluation of an assembly operation and subsequent distribution of tasks between human and robot forms a structured way of forming

Figure 12 Application for simplified use of the presented method

skills based human–robot work teams. In addition to geometrical and physical properties of assembly components, the method also combines the facets of safety in human–robot assembly, and dynamics of HRC environment such as part presentation and feeding. The method constitutes on the basis that no change in the product design is being suggested and only the existing product-design is investigated for HRC automation. It is also assumed that all the parts are designed with DFA techniques and are efficient enough for manual assembly. However, the usefulness of a collaborative robot for assembly can vary depending on its adaptability to various grasping tools and supporting devices.

Tasks allocation in human–robot assembly is not a onetime activity. With ever decreasing product life cycles, this is going to be a frequent activity at the shop floor gradually moving from the hands of experts to employees with low level of robotic knowledge. The usability of cobots can be increased by simplifying the user interfaces through software. Future research can explore developing user-friendly computer-based application to complete the task assessment and linking it up-to-simplified ways of robot programming with each changing scenario. With advancement in artificial intelligence, the assessment system can self-learn for assembly scores and generating robot programs.

The development in cobots should not be aimed to take humans out of the job rather providing humans the opportunity to contribute their efforts to value-added tasks. Owing to the complexity of certain assembly tasks, humans have to take all the non-interesting tasks together with the tasks where they are really needed. With HRC, the opportunities have arisen to make the manual industrial work more interesting for human

operators. This is equally important for attracting new workforce toward manufacturing sector.

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