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ICHORD: Integrating the Cognitions of Human Operators in digital Robot Design

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Executive Summary

The manufacturing industry is currently pursuing greater human-robot collaboration (HRC) on the shop floor to perform production tasks, including with the larger systems that have traditionally been too dangerous for close proximity. Although these close interactions with heavy robots will bring new psychological experiences for operators, current design methods that are used for predicting system performance are not equipped to evaluate any human behavioural responses in the system. Computer aided design (CAD) tools for digital human modelling (DHM) simply do not offer cognitive data analysis. Thus, industry does not yet have the ability to optimise the design of HRC systems to avoid any negative impacts on performance and safety caused by cognitive responses. The 'Integrating the Cognitions of Human Operators in digital Robot Design' (ICHORD) project was devised by the Cranfield University Industrial Psychology and Human Factors (IPHF) group to address this gap in current design knowledge and capability. The project aim to: *test the feasibility of 'Integrating the Cognitions of Human Operators in digital Robot Design' (ICHORD) using CAD modelling* was addressed via a set of four key objectives, each with respective work activities that produced developmental results:

Objective 1: Establish a human 'cognitive rule' for HRC – to generate data that predicts typical human responses to HRC.

- laboratory trials were conducted to establish the most suitable rule between levels of speed and operator trust
- an optimal speed-trust rule was established: >25 (on the Cranfield Trust Scale) when the robot is running at approximately 550mm/s

Objective 2: Define a current manual industrial use case suitable for HRC – to construct a real HRC demonstrator for testing the predictive accuracy of a new CAD model using the cognitive rule.

- single aisle slat installation was selected as an ideal industrial use case for HRC as it will improve both production efficiency and worker well-being in Airbus and was suitable for the testing environment / robot

Objective 3: Apply the cognitive rule in a new HRC model of the use case – to transfer the industrial use case into a HRC system demonstrator.

- the current manual Airbus slat installation process was redesigned into a HRC system using a CAD program and integrating the new speed-trust rule to predict performance
- the model predicted Trust scores of around 41.56 for robot speeds of 600mm/s

Objective 4: Create demonstrator to test accuracy of the CAD model – to test the fit between participant responses and those predicted by the new CAD HRC model.

- the new CAD HRC design was used to create a representative laboratory system to test the accuracy of the CAD model's predicted speed-trust rule performance
- the participants' Trust scores averaged 41.45 (SD: 1.07) at the robot speed of 550mm/s

Together these results show a good degree of congruence between data collected with two different industrial robots and tasks, across different participants, and between the real world and CAD simulations that have integrated human cognitive data. Thus, this project has been successful in demonstrating the feasibility of integrating cognitive response data within CAD / DHM models for enhanced prediction of human responses / behaviours and the potential for improving the design of future human-automation manufacturing systems.

1. Research challenge and Approach

Advances in control techniques and sensor technologies offer additional layers of monitoring and safety protection to a sociotechnical system that now make it possible for people to work safely with 'traditional' large and high-payload industrial robots [1]. Although much research to date on industrial human-robot collaboration (HRC) has focused on smaller scale robots (or 'cobots'), combining human skills with larger robots is desirable in the manufacturing industry as a solution for operators to perform assembly tasks involving large / heavy components [2]. Large scale HRC has the potential to greatly enhance production efficiency and augment human skills, but workers are not used to working directly with large scale robots as they have previously been too dangerous for close proximity and have been kept segregated from the workforce. Thus, new closer human-robot interactions are highly likely to invoke new human cognitive responses that could influence behaviour and affect well-being and performance. Given the "tremendous, accelerating rise in demand for industrial robots worldwide" [3] it is critical that industry is equipped to predict and minimise any negative impacts.

Computer aided design (CAD) is a typical method for designing new industrial systems and minimising negative outcomes by modelling known or expected values of key performance variables. However, CAD models are currently restricted to visualisation and prediction of functional safety or performance. Existing digital human modelling (DHM) tools offer a degree of postural ergonomic analysis but none are equipped for prediction of cognitive or behavioural responses [4]. This means industry currently does not have the capability to design HRC systems that predict and minimise any negative human responses that affect performance and safety. If it is possible to develop a tool for accurate prediction of human cognitive responses in robot interactions to enhance HRC design and implementation, industry would benefit significantly. Moreover, if this concept is possible, there are clearly much wider applications for CAD tools with integrated cognitive-based data to better predict human behaviour / performance in the design of interactive systems beyond the industrial HRC context.

This report describes a study that tested the feasibility of this concept. 'Integrating the Cognitions of Human Operators in digital Robot Design' (ICHORD), was developed by the Cranfield University Industrial Psychology and Human Factors (IPHF) group based on two key previous research findings:

1. limitations in the DHM capabilities of currently available CAD tools prevent accurate prediction of true human behaviour / performance [4, 5]

2. tendencies in people's cognitive responses to HRC system characteristics can be identified applied to improve system design [6,7]

Putting these two key findings together suggested that there was both a need, and potential for, improving CAD / DHM capabilities for the design of new HRC systems with integration of more realistic human cognitive-based data. However, in various reviews of the literature in this area and exposure to CAD modelling in industrial projects, the IPHF group had not found any evidence of other research being conducted to integrate cognitive data in CAD models to predict human behaviour. Therefore, a feasibility study was developed to explore the ICHORD concept with a series of key sequential steps:

- Identify an example of a typical human cognitive response (a 'rule') to HRC

- Apply data for this 'rule' into a CAD model of a new HRC system to predict typical response

- Build an industrial HRC demonstrator based on the new CAD model

- Conduct participant studies using the demonstrator to test whether real human responses accord with those that were predicted by the model using the cognitive rule

Together, these steps would demonstrate the feasibility, and perhaps effectiveness, of applying cognitive data in CAD models to enhance prediction of human responses. To achieve these steps the IPHF group and colleagues at Cranfield University were joined by engineers from the Advanced Manufacturing Research Centre

(AMRC) for expertise in industrial CAD modelling, and ergonomics specialists from Airbus for assistance with selection and supply of the industrial use case.

1.1. Aim

The aim of this project is to some extent represented by its title, to: *test the feasibility of 'Integrating the Cognitions of Human Operators in digital Robot Design' (ICHORD) using CAD modelling.*

1.2. Objectives

To meet the research aim, this feasibility study was designed to follow the sequential steps outlined above: to generate a cognitive response rule, to integrate it in a CAD model of a new HRC system, to build a real HRC demonstrator based on the new CAD model, and to test whether human responses were accurately predicted. Thus, the four principal objectives for this study follow this sequence:

1. **Establish a human 'cognitive rule' for HRC:**
   - to generate data that predicts typical human responses to HRC.

2. **Define a current manual industrial use case suitable for HRC:**
   - to construct a real HRC demonstrator for testing the predictive accuracy of a new CAD model using the cognitive rule.

3. **Apply the cognitive rule in a new HRC model of the use case**
   - to transfer the industrial use case into a HRC system demonstrator.

4. **Create demonstrator to test accuracy of the CAD model:**
   - to test the fit between participant responses and those predicted by the new CAD HRC model.

1.3. Schedule

ICHORD was designed to be a one year project, beginning 27th March 2018 but, due to contractual and technical delays at the start, completion was extended to June 2019, as shown in Table 1 below.

Implementation of the ICHORD project involved a range of activities to meet the four principal objectives; these are described in turn in the following sections

2. Implementation of Objective 1 Establish a human cognitive/behavioural rule for HRC

The ICHORD concept is that predictive capabilities of CAD DHM can be greatly improved if cognitive response data is integrated. To generate that data an initial study was designed to measure the relationship between *Trust* and robot *Speed* that was found in previous IPHF work [6].

2.1. Method

2.1.1. Research design

A repeated measures experimental design was used to allow measurement of the dependent variable (Trust level cognitive responses) across different conditions involving changes to the independent variable (robot speed). The experiment was conducted in the closed Intelligent Automation (IA) laboratory at Cranfield University as this allowed controls over environmental variables and privacy

2.1.2. Key variable selection

As described, two key variables were selected based on the results of previous work. Robot speed was the independent variable (IV) as this was the HRC system characteristic that would be

Table 1. ICHORD project schedule

ACTIVITY	LEAD	Apr-18	May-18	Jun-18	Jul-18	Aug-18	Sep-18	Oct-18	Nov-18	Dec-18	Jan-19	Feb-19	Mar-19	Apr-19	May-19	Jun-19
Define use case / task analysis	Airbus	Planned	Planned	Planned		Actual	Actual	Actual								
Identify rule via experimental tests	Cranfield	Planned	Planned	Planned				Actual	Actual							
Function allocation for HRC design	All			Planned					Actual	Actual						
CAD modelling to create HRC design	AMRC				Planned	Planned	Planned				Actual	Actual				
Development of demonstrator	Cranfield					Planned	Planned	Planned				Actual				
Participant testing and analysis	Cranfield								Planned	Planned	Planned	Planned	Actual	Actual	Actual	
Completion and report	Cranfield												Planned		Actual	Actual

Planned schedule Actual schedule

changed in different conditions. Trust in the HRC system was the dependent variable (DV) as this was the cognitive response that would be measured to analyse effects of robot speed.

2.1.4 Experimental task

To ensure that effects of the IV were captured without any confounding interference due to effects of task complexity, a simple task was required for all five conditions. A simple pipe fitting task (applied in previous IPHF robot Trust studies) was used. This involved the following steps:

1. The robot (initiated by technician) picks up a pipe from its left side and brings it to the participant and stops, presenting one end for assembly (robot in 'active mode')
2. The participant then attaches four fittings (robot in 'safe mode')
3. The robot (initiated by technician) then moves away again with the assembled pipe and places it in a box before returning to its start point (robot in 'active mode')

2.1.5 Materials and equipment

2.1.5.1 Robot cell

A Comau NM45 industrial robot was used for this experiment because of its availability in the IA laboratory and its suitability for a repeated measures study of this kind, having been used with this particular task in previous studies. **Figure** shows this robot within the surrounding layout of this experiment, indicating the pipe's start and end positions at either side of the robot, the 'participant marker' where participants were asked to stand when the robot was in 'active mode' and moving, and the 'fittings'.

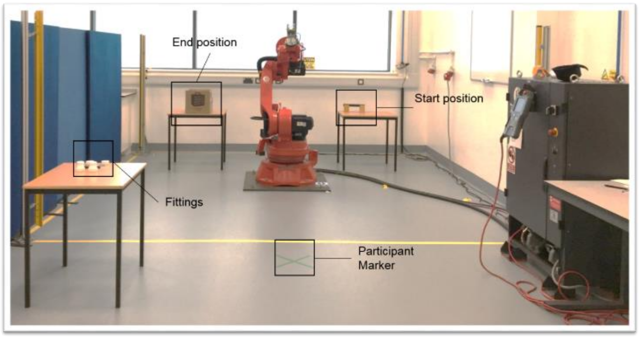

Figure 1. Experiment robot and layout

As the Comau NM45 industrial robot has no integral collaborative safety functions, a safety light curtain was installed to ensure protection of the participant during the robot's 'active modes'. The light curtain is the yellow vertical apparatus that can be seen on the left of the image in Figure 1, and its perimeter is indicated by the yellow line across the floor. When the robot is in motion and the device is operational it would initiate an immediate robot stop should there be any object / human incursion across the perimeter. The participant marker was used to prevent participants from changing proximity to the robot which could affect their perception of the robot speed.

2.1.5.2 Independent variable measurement

As robot speed was the IV that would be adapted, the different speeds that would be tested needed to fit within a predefined range which was determined by both regulatory and experimental criteria. At the upper threshold of this range it was necessary to comply with current safety standards for HRC (ISO TS 15066) and this dictated that the highest speed at which the robot could be run safely in collaborative mode was at 50% of its overall potential speed (= 1250mm/s). At the lower threshold it was considered that the experiment would be confounded if robot speed was so slow that it severely increased task time and prolonged task performance. Therefore, it was decided that the lowest speed at which the robot could run should be at just 5% of its overall potential speed (=125mm/s).

Having defined the maximum and minimum thresholds of robot speed it was decided that five speeds in this range would be sufficient for comparison: any fewer would be unlikely to offer enough discrimination but any more would likely be unnecessary and may have negatively impacted on participants, for example by inducing (fatigue and monotony). Table 2 below sets out both the exact speed values and what percentage of the robot's overall potential speed this represents across all five IV conditions within the specified range.

Table 2. Independent variable conditions: robot speeds

Condition programme	Actual Speed mm/s	Potential Speed %
Prog. 1	125mm/s	5% Speed:
Prog. 2	400mm/s	16% Speed:
Prog. 3	550mm/s	22% Speed:
Prog. 4	850mm/s	34% Speed:
Prog. 5	1250mm/s	50% Speed:

2.1.5.3 Dependent variable measurement

To evaluate the impact of different robot speeds on Trust, as the DV, participants completed a paper-based psychometric questionnaire after each trial. The *Cranfield Trust in Industrial Human-Robot Collaboration Scale* is a short questionnaire which requires participants to subjectively report their perceived levels of Trust in a robot system across three robotic dimensions (factors): motion and pick-up speed, safe co-operation, and robot and gripper reliability. The 'Cranfield Trust Scale' uses a five-point Likert scale ranging from strongly disagree to strongly agree in response to ten items measuring those dimensions (Table 3).

Table 3. The Cranfield Trust in Industrial HumanRobot Collaboration Scale

Dimensions	Item
Robot motion & pick-up speed	The way the robot moved made me uncomfortable
	The speed at which the gripper picked up and released the components made me uneasy
Safe co-operation	I trusted that the robot was safe to cooperate with
	I was comfortable the robot would not hurt me
	The size of the robot did not intimidate me
	I felt safe interacting with the robot
Robot and gripper reliability	I knew the gripper would not drop the components
	The robot gripper did not look reliable
	The gripper seemed like it could be trusted
	I felt I could rely on the robot to do what it was supposed to do

The Cranfield Trust scale psychometric tool was developed in previous IPHF work specifically to measure people's trust with large-scale industrial robots and HRC [6] because no other reliable measure of this specific type had been found. Other available scales measuring trust were either generic or designed for other contexts which would mean they would not measure the appropriate dimensions / factors that specific to industrial robots. In the process of its development, this particular type of Trust was found to consist of three principal dimensions, as shown in Table 3: perceived robot and gripper reliability, perceived safe co-operation, and perceived robot motion and pick-up speed. As applications of this tool in previous studies has demonstrated good validity and reliability, including one that used the same pipe fitting task and robot that was used in this ICHORD study, this scale was considered most appropriate.

2.1.6 Procedure

Participants took part in the experiment individually. Upon arrival they were given a standardised verbal briefing, then asked to read the written brief, before being asked to sign to confirm informed consent. They then provided age and gender details on a separate form (to be stored separately from the surveys to ensure anonymity).

Participants were then provided with personal protective equipment (bump cap and safety glasses), and given a demonstration of the task, so that they were prepared for the task sequence and which task steps the robot would perform versus those that they would themselves be required to perform. The demonstration involved a full run-through of the experimental task procedure, as described in section 2.1.1.4. with the robot running at Speed 2 to ensure enough time for the experimenter to explain everything but also to not overwhelm or influence participants with the faster speeds at their first introduction to the robot. Participants were reminded that after each condition they would need to complete the Cranfield Trust Scale questionnaire.

During the task briefing, three key points were highlighted to the participants:

1. The robot's stopping point in front of the participant for the assembly task was explicitly shown to participants to minimise any confusion during the trials about when and where the fittings should be attached to the pipe.
2. In previous IPHF studies the sound of a pneumatic gripper has been found to negatively affect Trust in a robot. Therefore, the normal pneumatic sound of the gripper was pointed out to the participants and explained so that they were prepared.
3. Participants were asked to stand on the participant marker and not cross the yellow line while the robot was in motion but advised that they could do so when the robot stops for the task as crossing the yellow line while the robot is in motion would activate the safety light curtain and the robot would be stopped, which would require a delaying re-start.

After the demonstration and task briefing, the five robot speed trials were conducted, each lasting two minutes. Counter balancing to re-order the IV conditions was undertaken to mitigate order and familiarity effects. After the experiment participants were fully debriefed.

2.1.7 Research Ethics

To ensure informed consent, participants were advised on the nature of the study and procedure, right to withdraw from the study, confidentiality and privacy, data management (including limitations on withdrawal of submitted data due to anonymisation procedures), dissemination of results, and researcher contact information for any subsequent enquiries.

This study was approved by the Cranfield University Research Ethics Committee, and conducted in accordance with the Cranfield Research Integrity Policy, the British Psychological Society's Code of Human Research Ethics, and the General Data Protection Regulation 2018.

2.2 Results

Table 4 presents the means and standard deviations for all participants' responses to each section of the Cranfield Trust Scale. A score greater than 25 indicates a 'good' level of Trust in a robot, which should signify good operational effectiveness and efficiency (although very close to 50 might signify dangers of over-complacency) [6]. Therefore, the Trust scores across the five speeds were, overall, in the best range. Although the results indicate that the participants trusted the robot at all speeds, they trusted the robot less at the higher speeds and had the greatest Trust for speed 2.

In statistical analysis to identify whether scores between the different speeds were significantly different, a Shapiro-Wilk test identified that the data was normally distributed; this meant a repeated measures Analysis of Variance (ANOVA) could be performed. The ANOVA, with a Greenhouse-Geisser correction, confirmed that the overall mean scores for Trust were significantly different across the five speeds ($F(2.864, 60.135) = 13.356$, $p < 0.05$). Post hoc tests using the Bonferroni correction procedure showed speed 5 to be significantly different from speeds 1 to 4 ($p<0.05$). There was a minimal change in the mean Trust scores between speeds 1 to 4, and none were statistically significant ($p>0.05$). These results are also shown in Table 4.

As no significant difference was found between the overall mean Trust scores across speeds 1 to 4, the individual scores required a closer analysis to identify the most suitable speed for use in the

Table 4. Means and Standard Deviations for Trust in Human-Robot Collaboration across dimensions

	D1: Robots motion and pick-up speed			D2: Safe co-operation					D3: Robot and gripper reliability					
Speeds	The way the robot moved made me uncomfortable	The speed at which the gripper picked up and released the components made me uneasy	D1	I felt safe interacting with the robot	The size of the robot did not intimidate me	I was comfortable the robot would not hurt me	I trusted that the robot was safe to cooperate with	D2	I felt I could rely on the robot to do what it was supposed to do	I know the gripper would not drop the components	The robot gripper did not look reliable	The gripper seemed like it could be trusted	D3	Total Trust score
1	3.7 (1.3)	3.6 (1.3)	7.3 (2.3)	4.5 (0.7)	3.9 (1.2)	4.4 (0.8)	4.5 (0.7)	17.2 (2.8)	4.4 (0.5)	4.5 (0.6)	4.3 (1.0)	4.4 (0.6)	17.6 (1.8)	42.1 (4.1)
2	4.3 (1.1)	4.5 (0.8)	8.8 (1.5)	4.4 (0.5)	3.8 (1.2)	4.2 (0.7)	4.4 (0.5)	16.7 (2.1)	4.4 (0.5)	4.3 (0.6)	4.3 (0.8)	4.3 (0.5)	17.3 (1.7)	42.8 (3.4)
3	3.7 (1.2)	4.2 (0.8)	7.9 (1.6)	4.1 (0.8)	4.2 (0.9)	4.4 (0.7)	4.3 (0.7)	17.0 (2.6)	4.4 (0.6)	4.4 (0.6)	4.2 (1.2)	4.3 (1.0)	17.2 (2.2)	42.1 (5.3)
4	3.5 (1.1)	4.0 (0.9)	7.5 (1.8)	4.0 (0.9)	3.6 (1.2)	4.0 (0.9)	4.1 (0.8)	15.7 (3.4)	4.0 (0.6)	4.4 (0.9)	4.5 (0.5)	4.4 (0.6)	17.2 (1.7)	40.4 (5.7)
5	2.6 (1.1)	3.2 (1.2)	5.8 (2.1)	3.4 (0.7)	3.5 (1.1)	3.5 (0.8)	3.7 (0.7)	14.1 (2.8)	3.5 (0.8)	4.3 (0.7)	4.0 (0.8)	3.9 (0.8)	15.7 (2.3)	35.5 (5.9)

validation test. To gain a clearer understanding of the trend of the data, a graph of the overall trust scores, as seen in Figure 3, was reviewed. As can be seen in the graph, in Speed 4 a downward trend in Trust levels begins, while in Speed 3 the horizontal trend of the previous speed continues, with a value higher than Speed 1's value. Whilst the primary goal of this project is to examine the feasibility of integrating cognitive data into CAD / DHM human analysis, a secondary intention for Airbus was to assess the feasibility of introducing a robot to the shop floor in Airbus for the slat installation process. For this reason, production needs were also considered so, for improved time efficiencies, the fastest speed with the highest overall trust scores – Speed 3 – has been chosen as most suitable for the Trust cognitive rule to be take forward for the design of the demonstrator.

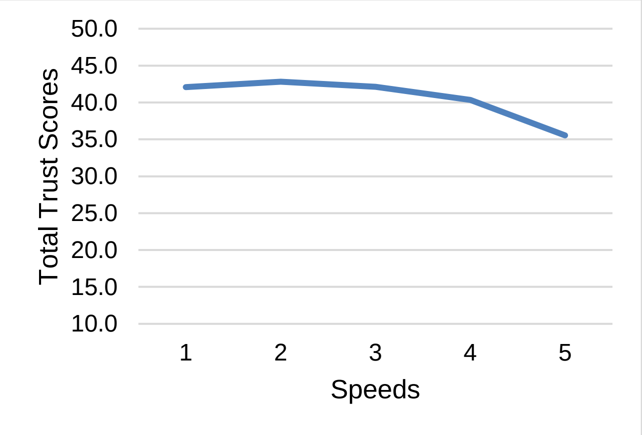

Figure 2: Total trust scores across robot speeds

2.3 Objective 1: conclusions

The repeated measures study undertaken for Objective 1 has, through a sequence of analyses, led to preliminary identification of the most suitable cognitive rule between Trust and Speed, whereby 'ideal' Trust scores (above 25) are best achieved when the robot is running at around Speed 3 (550mm/s).

3. Implementation of Objective 2: Define a current manual industrial use case suitable for HRC

The demonstrator that would test the predictions of human response (*Trust*) to HRC characteristic (*Speed*) needed to be based on a real manual industrial process that could be redesigned to a human-robot process. An existing Airbus manual process was considered an ideal use case because aerospace assembly is where large-scale industrial robots would be particularly advantageous for improving both worker health and task performance in tasks that involve large / heavy components.

3.1 Method

The method for defining an industrial use case suitable for HRC was devolved into three main tasks:

- Use case selection: down-select a manual process that would be apt for adaptation to HRC (i.e. where some human skill must be retained but unskilled input that would be better automated)
- Task analysis: deconstruct the selected use case section into discrete task steps in preparation for function allocation (needed for the new HRC design in subsequent CAD modelling)
- Task section identification: identify task steps that would be suitable for the demonstrator to simulate (i.e. a confined part of the overall manual assembly process)

3.1.1 Use case selection

Investigators at Airbus (Broughton) reviewed a number of candidate processes from the A320 and A350 wing production systems, based on suitability for transfer to HRC (e.g. complexity, components, cycle time), suitability for the Fanuc CR-35iA robot that was intended to be used as a demonstrator (because of its 'collaborative' design), and anticipated advantage if made a human-robot task:

- Access and spatial layout – current workstation layout / space would allow implementation of a robot of similar size / dimensions to the Fanuc CR-35iA
- Human physical performance – transfer of task steps to a robot would reduce manual handling demands, decrease task repetition and frequency, and improve required body postures
- Logistics – the implementation of a robot would not impede logistical requirements, e.g. transportation and positioning of large components

- Payload restrictions – the process would not require the robot to handle a maximum payload exceeding 35 kg

After assessing each individual case, the Airbus single aisle aircraft slat installation process was selected as the ICHORD use case for reasons of technical suitability for the experiment but also for potential longer-term benefit for the company. Technically, the angle of placement of the slat component was considered most appropriate for the FANUC CR-35iA and the slats were thought to be within the robot's payload limits. For Airbus, transferring this manual process to HRC was anticipated to bring productivity, cycle time and ergonomic / health and safety improvements.

3.1.2. Task analysis

It was originally intended that a full Human Factors methodology hierarchical task analysis (HTA) and task decomposition (TD) examination would be conducted to deconstruct the manual slat installation process to a level of detail for distinction of each individual physical and cognitive step. This would assist function allocation for the new CAD model by identifying whether steps should be retained, designed out, or reallocated to the robot. However, due to constraints of project scope and available resources it was not possible to employ this in-depth Human Factors methodology. Instead, the task was deconstructed using an engineering approach that produced a more technical task breakdown of physical / technical steps. For commercial reasons the full HTA of the Airbus slat installation process cannot be included in this report but a brief description of the general process is as follows.

Slat installation process overview

Slats are aerodynamic surfaces on the leading edge of aircraft wings which, when deployed, allow the wing to operate at a higher angle and increase the lift of the aircraft. Deploying slats enables an aircraft to fly at slower speeds, or take off and land in shorter distances. They are retracted in normal flight (cruise condition) to minimise drag. An Airbus Single Aisle aircraft has 5 slats in each wing and installation of each type requires similar steps or tasks, with some differences due to weight, manoeuvring and access. Thus, although Slat 1 would not be a suitable task for the demonstrator because the payload is over 35kg, thereby exceeding the maximum for the FANUC CR-35iA, the following generic description of slat installation is a representative overview:

- After reviewing standard operating instructions and conducting some wing preparation activities, two operators lift a slat from its trolley and carry it to the wing area for installation.
- The two operators position the slat to the wing and continue to hold it in place so that a third operator then moves in underneath to secure it in place with bolts.
- After the slat is secured only a single operator is needed for further fitting of bolts and nuts and application of sealant.

The slat is then retracted for rigging to fulfil gapping requirements: an eccentric bush is adjusted to align the slat leading edge whilst a slip gauge is used to check the gap at each track position.

3.1.3. Task section identification

After a review of the process via observation on the shop floor and development of the task analysis technical breakdown, the pick-up and placement of the slat onto the wing was identified as the most suitable aspect of the slat installation process for the Fanuc CR-35iA robot to complete as a demonstrator. This selection was based on consideration of the potential benefits for Airbus of trialling a HRC system for this process, which are likely to bring improvements to efficiency and health and safety. If a robot could be employed to handle the slat components this would reduce the time currently needed for finding two available operators who can lift and move the component into place, and it would also reduce the risk of musculoskeletal damage to operators as they would no longer be required to manually lift the slats and hold them in place while they are secured onto the wing.

3.2 Results

Outcomes have been described within the Method section above.

3.3 Objective 2: conclusions

The three tasks used to meet Objective 2 successfully defined a suitable industrial use case, generated a breakdown of the task for analysis of individual steps, and identified a specific section of the use case process for creation of the HRC model and demonstrator. Although not the full HTA that included cognitive analysis as had been planned, the output was sufficient for describing the slat installation process for the subsequent CAD modelling in Objective 3.

4. Implementation of Objective 3: Apply the cognitive rule in a new HRC model of the use case

This objective was designed to apply the new cognitive rule data in a new model which would transfer the current wholly manual use case into a HRC process. For this expertise, the work was assigned to the AMRC engineers who set out to develop a CAD model of a demonstrator which would represent a simplified version of the technical task breakdown provided by the work at Airbus in Objective 2. There were two intended goals for this model:

1. To provide a CAD cell design, to be built and tested at Cranfield University, that is simple enough for rapid build and testing, but close enough to the Airbus process to be representative.

2. To be able to run as a simulation with varying robot parameters and provide (using rules generated from previous Cranfield University HRC lab results) a predicted Trust score for a given set of robot parameters.

4.1 Method

The method needed to meet this objective was broken down into a series of six discrete tasks:

- Review the Airbus use case process
  - to trim the overall task down to key steps

- Review Cranfield facilities
  - to design a suitable cell in CAD that would accord with the IA laboratory

- Review software
  - to identify most suitable package for carrying out the modelling required

- Model cell
  - to simulate behaviour and movements with variable speed parameters

- Generate rule-set
  - to identify the required cognitive rule from the Objective 1 participant study data

- Combine model and rule-set
  - to compare results of the model to the final participant test results

The activities undertaken to complete these tasks are now described in turn.

4.1.1 Review Airbus use case process

The work conducted at Airbus as part of Objective 2, described in the previous section, had led to the selection of slat installation which would mean the robot replacing the undesirable task of two workers holding the slat in place while retaining bolts were entered by a third worker. Documents produced in the Objective 2 work (standard operating instructions, technical task breakdown, etc.) were reviewed at the AMRC to determine key steps where robots could be deployed. It was identified that the movement inwards of the slat part into position, and the holding of that part as retaining bolts were manually inserted from below, would be the steps most suitable for transfer to the robot. Once this had been identified, any extraneous activities in the standard operating instructions document (secondary bolting, measurement checks etc.) that would not require any interaction with the robot were removed. This down-selection of the robot role ensured that a) the demonstrator would be simple enough to avoid having other factors influence results outside of human-robot interaction, and b) would allow results (via survey after the test) to be gathered as close as possible in time to the actual robot interaction.

4.1.2 Review Cranfield facilities

Having defined the human-robot task steps, the AMRC then developed a basic design of a robotic cell for the Fanuc CR35iA robot that Cranfield University intended to use, including a rough specification for a jig to stand in for the wing, an example slat part, and a process of manual bolting to take place similar to the wing slat installation task selected. This was developed in unison with the Cranfield team to ensure it matched the resources they had available, and also to ensure that it would comply with the relevant safety standards for HRC.

4.1.3 Review Software

A software down-selection was also performed by the AMRC, to determine the best package for this assignment. After considering a range of available software packages, the AMRC selected a Visual Components ® package as it had a series of key features included that made it the most suitable:

- physical layout (CAD) and simulation in one package
- a fully functioning model of the Fanuc robot (that could output Fanuc code)
- physical object simulation in real-time (for part jig interaction etc.)
- customisable person and behaviour modelling
- creation of scripts and macros to run with the simulation (ideal for implementing behaviour rules)

4.1.4 Model cell

The cell was designed and programmed to carry out the process as outlined in Visual Component's 3D layout and simulation environment. As shown in Figure 10 below, the experimental set-up for the cell designed at the AMRC would involve a model of a slat (section), which is positioned in a holding frame (representing the main wing structure), the robot (which replaces the two operators currently required for manual handling) so only the third operator who is still needed to secure the attachment of the slat (as described in section 2.2.1.2.1) would be retained.

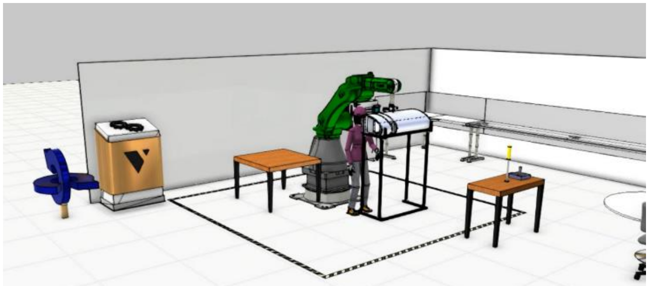

Figure 10. Visual Component Model in-process

4.1.5 Generate rule-set

Finally, the cognitive response rule had to be generated and added in to the model. This rule would be based on metric data generated in the participant study conducted at Cranfield as part of Objective 1 which reflected levels of human Trust in a given robot operating speed. This data was collected using the Cranfield Trust Scale which, as described previously in section 2.1.1.5.3, gathers ten different scores of values between 1 and 5 to measure three principal dimensions of this type of human trust. Thus, the Trust scores of 1-5 across the 10 factors give a total score between 10 and 50 per person. For the purposes of analysis and graphical representation for this work the overall scores per person have been divided back down from 10-50 to a 1-5 score for the entire operation. The accuracy of the new model generated from these could be determined by comparing the results gained in real world tests to those generated by the simulation.

Initially the AMRC intended to develop a live Trust output, which would change in the simulation as the person carried out the task. However, as all data from previous tests was derived from surveys which only represented a single point in time after the task was carried out, it was not suitable for developing a time-series relationship.

4.1.6 Combine model and rule-set

The combined data of all the tests ran previously was taken to attempt best fitting in order to identify an equation that matched the controlled IV (robot speed) to the output cognitive response DV (Trust score). This was added into a Python script in the Visual Components model that looked at the movement speeds of the robot during the simulation run, and output the calculated Trust score for that speed on the screen (along with other simulation output data such as process time).

4.2 Results

The series of fits – linear, exponential, logarithmic and polynomial – are shown in turn across Figures X to X below, where the data points are robot speed on one axis, and total Trust score on the other.

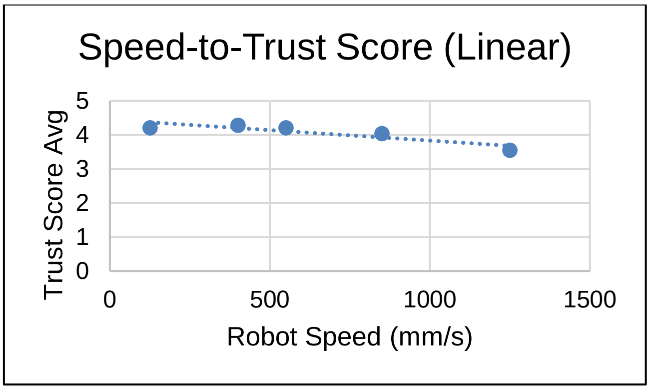

Figure 11. Equation 1: Linear Trend-line Equation: $y = -0.0006x + 4.4481$

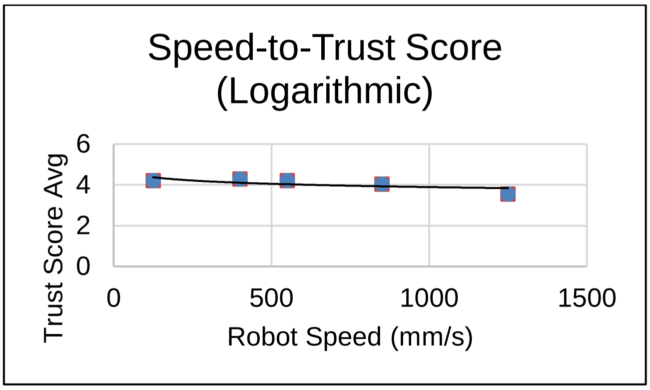

Figure 12. Equation 2: Logarithmic Trend-line Equation $y = -0.232ln(x) + 5.4994$

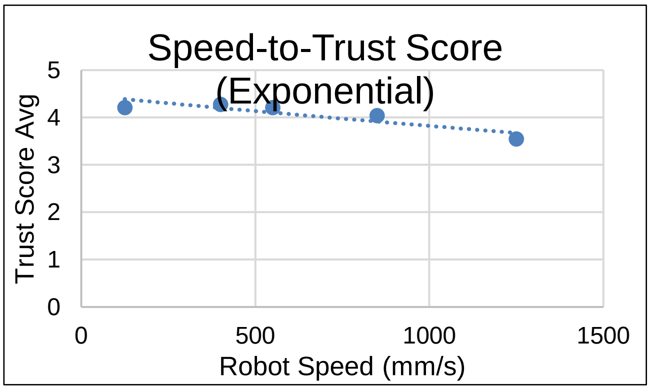

Figure 13. Equation 2: Exponential Trend-line Equation $y = 4.4745e - 2E - 04x$

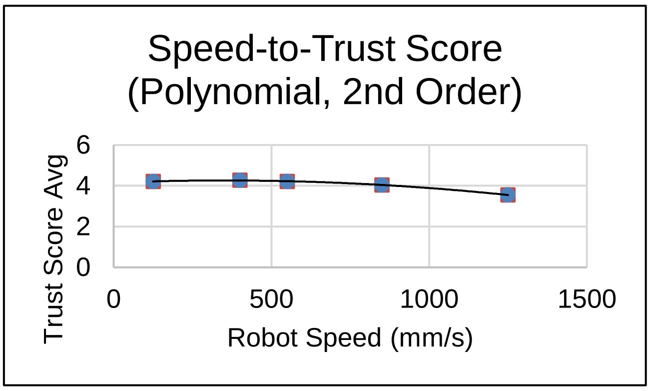

Figure 14. Equation 3: Polynomial (2nd Order) Trend-line Equation $y = -9E - 07x2 + 0.0006x + 4.1526$

As the charts show, the best fit was the Polynomial equation. However, it should be noted that the data was very heavily clustered in one "Trust" area (Y-axis) and all the responses are within a small (<20% of total) range window which suggests the IV speed range was too limited and subtle. Ideally, more varied and extreme speeds would be tested to generate a wider range of Trust responses, and likely a different type of relationship. However, this is limited by what can be safely tested with people, and also represented the speed range in which the slat installation demonstrator trials were running.

With this equation, it is possible to simply plug in any speed within a suitable range and get an output of predicted Trust. Although a series of speeds were originally planned for the participant testing that would follow to test the model as part of Objective 4, it was subsequently decided that only the speed that was associated with most suitable Trust levels was necessary for the demonstrator: 550mm/s. However, due to functional limitations of the Fanuc CR-35ia, this speed had to be increased by 2% to 600mm. When the robot was run at this speed in the simulation for this work, the expected human Trust score was given as **4.15672** (41.5672 when not divided back into 1-5 range), as shown in the output window at the bottom of Figure 2.

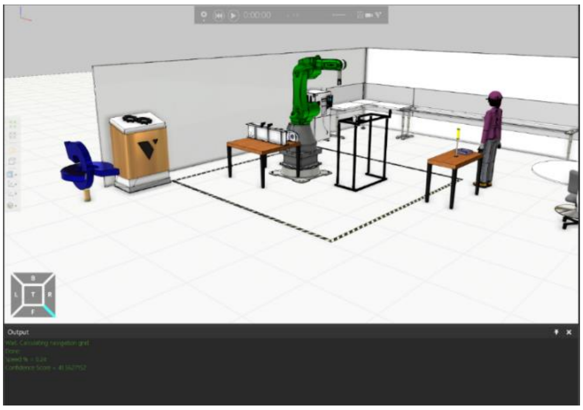

Figure 15: End output from simulation run

4.3 Objective 3: conclusions

Together, the six tasks undertaken to meet Objective 3 were effective as they led to the redesign of the wholly manual Airbus slat installation process to a new HRC process model, and a predictive cognitive rule: *in response to the most suitable robot speed of around 600mm/s the expected overall operator Trust score would be 41.5672 per person*.

5. Implementation of Objective 4
Create demonstrator to test accuracy of the CAD model

This final principal objective of this study was designed to measure how accurately the CAD model with the new integrated cognitive rule data had predicted real human responses. Having developed the new use case HRC model and the cognitive rule-set, development of a demonstrator was now required for a second round of participant trials to measure trust at different robot speeds as this would enable the model and rule-set accuracy to be evaluated. Therefore, the new trials would be run similarly to those that were conducted to develop the original cognitive response data, except now with a different experimental task – the new use case HRC design – and new robot cell for the Fanuc CR-35iA.

5.1 Method

5.1.1 Research design and key variables

As the preceding work had led to specification of the most suitable robot speed (section 2.1.2) and predicted overall trust score per person at (approximately) this single speed (section 2.3.2), it was not deemed necessary to replicate the repeated measures design of the previous participant studies which measured trust I response to multiple robot speeds. Instead, this study was designed to simply measure participant trust in response to the one identified 'most suitable' speed.

5.1.2 Participants

Thirty-seven participants volunteered in response to an internal Cranfield University advertisement: fifteen female and twenty-two male participants aged between 21 and 59 years old (mean: 30, SD: 8.17).

5.1.3 Experimental task

Whereas the experimental task used in the first participant trials was only a simple abstract assembly, this study required a task that represented the Airbus slat installation use case, as described in section 2.2.1.3. Thus, for this experimental task the robot performed the manual handling role for pick-up and placement and the participant would perform the role of the retained third operator who was needed to secure the slat (section 2.3.1.4):

- Participant sits under the frame
- Robot picks up the slat and moves it into place
- Participant secures slat with two bolts using an Allen key through the inside of the frame
- Participant comes out from under frame and completes the Cranfield Trust Scale questionnaire

This simplified version of the use case was designed to represent the shop floor process as much as possible. However, although in the real process operators install three in the same way but one at an angle (section 2.2.1.2.1), for this study equipment limitations (type of brackets available) meant this was not possible so only the comparable installation of slats 2, 3, and 5 was used.

5.1.4 Materials and Equipment

5.1.4.1 Robot Cell

The Fanuc CR-35iA industrial robot with a pneumatic gripper was used for this experiment because it is a system designed specifically for HRC with heavier payload (35kg). As such, the robot has integral safety features which allowed participants to work in close proximity without the need for additional measures, such as safety light curtains or physical guarding. The robot and experimental set-up is shown below in Figure 16.

A representative slat section was custom made for this study. Although the Fanuc CR-35iA robot can lift items of up to 35kg close to its base, when the arm and component is further away from its base less weight can be moved. Therefore, the slat section model was scaled down from its original size to 17kg to accommodate the distance needed for the robot to place the slat. The frame representing the main wing component was designed to precisely fit the slat but also to protect the participant if the slat was dropped.

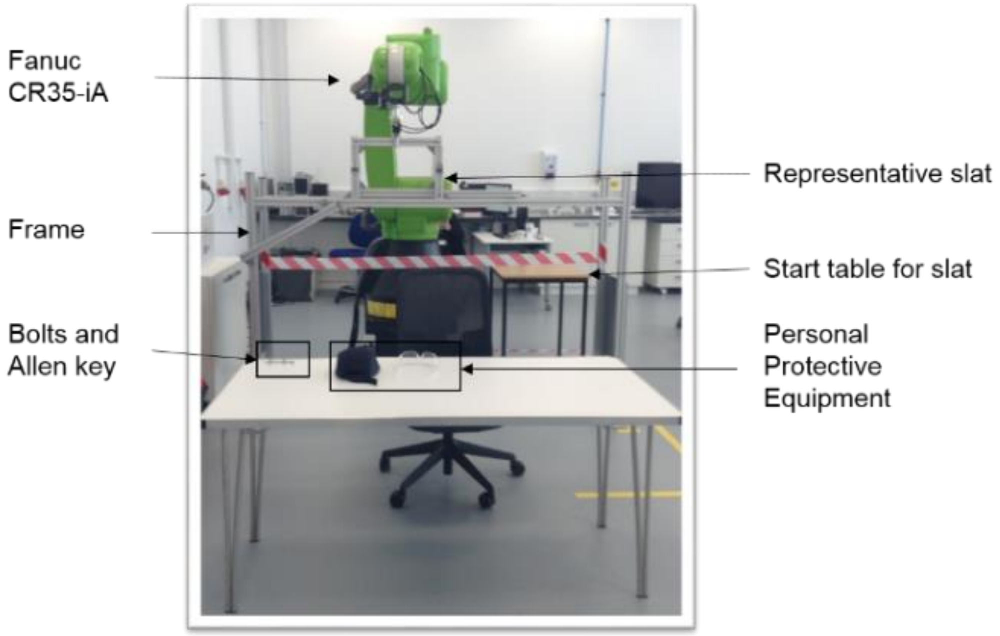

Figure 16. Experiment robot and layout

A chair with an adjustable back was provided for the participants so that they could lean backwards to fit under the frame and move into place. Although the height of the chair could be adjusted participants were asked not to make any changes as it was set at a height that reflected that of the benches used by the operators on the shop floor in Airbus.

A table was set up in front of the demonstrator cell, as shown in Figure 16 to house the personal protective equipment, bolts and Allen key. This is also where participants could complete the DV Trust questionnaire after task completion.

5.1.4.2 Trust measurement

Trust level response data was again collected using a paper-based questionnaire of the *Cranfield Trust in Industrial Human-Robot Collaboration Scale* [6] as previously described in section 2.1.1.5.3. On a separate sheet biographical data was collected including: age and gender.

5.1.5 Procedure

Participants took part in this study individually. Upon arrival, they received a verbal briefing, and were then asked to read the written Brief that covered: the nature of the study, ethical considerations and entitlements, and key components of the procedure. Participants were then asked to sign and confirm informed consent, and to provide some biographical data.

A demonstration of the entire experimental task was then given to participants, to familiarise them with the procedure as well as the robot's movement, speed, and the sound of the gripper. To begin the demonstration, participants were shown the personal protective equipment they needed to wear (a bump cap and safety glasses). Next, the researcher both demonstrated and described the full task procedure that participants would need to follow whereby they sit under the frame, the robot picks up the slat and moves it into place, and the participant secures it with two bolts using an Allen key, through the inside of the frame.

It was emphasised to participants that they should sit under the frame while the robot moves the slat into place, and fit the bolts overhead, as this resembled the real slat installation process. The start and finish positions of the experiment are shown in Figure17.

Figure 17: Experiment Layout with Representative Slat Start and Finish Positions

After the demonstration, the participant's trial began w the technician started the robot program, which simply involved the robot picking up the representative slat and moving it into place onto the frame. Upon completion of the task and the Cranfield Trust Scale the participants were fully debriefed regarding the nature of the project and reminded of their ethical entitlements. The researcher answered any questions the participant had regarding the study before thanking them for their participation.

5.1.6 Research Ethics

To ensure informed consent, participants were advised on the nature of the study and procedure, right to withdraw from the study, confidentiality and privacy, data management (including limitations on withdrawal of submitted data due to anonymisation procedures), dissemination of results, and researcher contact information for any subsequent enquiries.

This study was approved by the Cranfield University Research Ethics Committee, and conducted in accordance with the Cranfield Research Integrity Policy, the British Psychological Society's Code of Human Research Ethics, and the General Data Protection Regulation 2018.

5.1.7 Analysis

The results produced by the work towards Objective 1 revealed that Trust scores were highest when the robot ran at a speed of 550mm/s. For Objective 4, this experiment was initially designed to replicate this speed with an industrial scenario and a fully collaborative robot, in order to both validate the rule and test the accuracy of the CAD HRC model. Therefore, a comparison of the overall trust scores obtained in Objective 1 with the overall trust scores acquired from Objective 4 was required to show that the rule was valid. As ANOVAs do not provide evidence of an absence of effect within a population an alternative method was required.

Quertemont (2011) recommends using the confidence interval test to provide evidence of an absence of an effect in the population [8]. The confidence interval provides details about the highest difference likely to exist at the population level. Therefore, if the upper and lower bounds of the confidence interval of the trust scores obtained within this Objective fall within those from Objective 1 it is possible to conclude that any variation between the two data sets is a consequence of natural population variation rather than response to the variables. Therefore, the two data sets from both participant studies were analysed using descriptive analysis in SPSS to identify the 95% confidence interval for the means of the two data sets (trust scores for the speed 550mm/s from Objective 1 and the trust scores gained from the study detailed in Objective 4).

To further support these findings the minimum mean difference was identified for two samples of the same size along with standard deviation of the observed data, to identify significantly difference. The minimum mean difference was 2.927. Although the observed difference is below this threshold, it was necessary to ensure that it was significantly smaller and not likely to be generated by natural variance occurring within the population. Thus, to test for this a Monte Carlo simulation was conducted.

The Monte Carlo simulation involved two datasets being simulated, both having the same sample size and standard deviation to that of the real datasets but with their mean difference being set to 2.927. In effect, 37 values were randomly generated from a normal distribution (mean = 100; SD = 5.485) for the first dataset, while 22 values were randomly generated from another normal distribution (mean = 102.927; SD = 5.294), thus replicating the sample sizes of the original datasets. The mean difference between the two simulated samples was recorded. After 1000 iterations of this simulation, a normal distribution of expected mean differences was obtained, under the condition that the two populations had the minimum significant difference of 2.927 identified in the first step.

To compare the simulated and observed data, the simulated average and standard deviation were compared with the observed difference to ensure that, if the two populations were different, the observed difference was significantly smaller than the smallest possible significant difference. A one-sample t-test then compared the simulated mean difference and standard deviation with the observed mean difference.

5.2 Results

The one-sample t-test result revealed significance ($t(999)= 56.83$, $p.<0.05$) which further suggests that the observed difference between the two conditions was due to random variation and not due to actual difference between the two populations.

Confidence interval results presented in Table 5 below show how closely the Trust level data derived from the study in Objective 1 corresponds with the data collected in the second participant trials with the demonstrator.

Table 5: Descriptive Statistics and Confidence Interval Data

		Objective 1 Speed 3 Trust Score	Objective 4 Demonstrator Trust Score
	Mean	42.14 (1.13)	41.45 (1.07)
95% Confidence Interval for Mean	Lower Bound	39.7891	39.2199
	Upper Bound	44.4837	43.6892

The predictive cognitive rule generated and modelled by the AMRC indicated that operator Trust scores (using the Cranfield Trust Scale) would be around 41.56 in response to robot speeds of 600 mm/s.

5.3 Objective 4: conclusions

The study undertaken to meet this final objective involved further participant trials with the new HRC design demonstrator and a set of analytical procedures to establish the relationship between the two data sets. This was successful in establishing a strong indication of concurrence in the levels of Trust that are invoked in response to a robot speed of approximately 550-600mm/s. Moreover, results are relatively congruent with the CAD simulation predictive speed-trust rule developed in Objective 3.

6. Summary of Results

Overall, the results show a good degree of congruence between data collected with two different industrial robots and tasks, across different participants, and between the real world and CAD simulations that have integrated human cognitive data:

- Objective 1: a desirable level of human Trust in industrial robots (above 25 on the Cranfield Trust Scale) is induced when the robot is running at approximately 550mm/s.
- Objective 2: single aisle slat installation is a candidate industrial use case for HRC in Airbus, as it will improve production efficiency and worker well-being.
- Objective 3: a CAD model redesign of the current wholly manual Airbus slat installation process to a HRC process has generated a predictive cognitive rule that Trust scores of around 41.56 result when the industrial robot runs at 600mm/s.
- Objective 4: The predictive accuracy of the CAD model with an integrated cognitive rule for levels of Trust in response to robot speed for an HRC system is fairly accurate.

7. Conclusion: Future Plans and Wider Applications

7.1 Digital Human Modelling (DHM)

As ICHORD has demonstrated the potential for CAD DHM tools to be improved with richer data about human responses, that it does appear feasible to integrate human cognitive data to improve the fidelity and capability of computer based human analysis for system design, the work has satisfied the research aim. Consequently, future plans are yet to be discussed and structured, but there is every intention to build on this work and pursue this concept in greater detail in further research collaboration(s). The AMRC have already indicated interests in further work with Cranfield to develop:

- Operator data modelling
  As it has been shown that it is possible to develop data that reflects typical or normative responses /, more data about operators and operating conditions derived from real participant testing could be applied to develop more detailed and dependable behavioural rule models. For example, data that indicates how characteristics such as distance from the robot, experience with robots, equipment and PPE being used, etc, impacts on operator responses – physiological and cognitive – would lead to a wider range of factors to be modelled, and for more holistic models to be generated.

- Live trust data / simulation
  In addition to gathering data from more variables, it is possible to also gather data from the time-domain, i.e. from an operator during a process. This could be done either through a mid-process rapid survey (to give a series of time-separated responses), or via a sensor with which a relationship to Trust or Trust-related performance could be made through testing (i.e. heartrate monitor, accelerometer). With this data, a map of behaviour due to a wide range of robot variables (speed, distance, end-effector state) and human variables could be mapped over the whole course of the process in the time domain, allowing simulation of a factory to

model how work around robots would change in real-time during a process. This could lead to much more accurate, detailed, and useful models of human-robot interactions which, in turn, would promote more efficient collaborative processes and faster, more reliable production lines.

- Human modelling data and functions
  To achieve the above it will be necessary to develop more data that can be integrated in simulation tools for human analysis. The literature shows that much work is being produced but often it is not conducted using sound research and analysis methods and, therefore, is not reliable. Future work could provide more data and test it rigorously to enhance software / tools for human analysis.

7.2 Human Robot Collaboration (HRC)

The original concept for ICHORD was to improve the fidelity and capability of DHM tools. The industrial robot / HRC context provided a relevant framework for this venture because it represents a new and emerging sociotechnical problems for which enhanced, more sophisticated DHM functionality could provide a solution. However, as the project has progressed the discovery of a potential relationship between robot characteristics and human responses has become of equal interest and importance. By demonstrating that there are measurable human-robot interaction rules ICHORD has also shown potential for organisations to optimise the implementation of collaborative robotics and minimise disruption to production and workforce, via system design and integration but also wider protocols such as operator training. Airbus supported this work to explore the feasibility of HRC to enhance manual processes so further work will undoubtedly be of interest. The AMRC has also expressed interests in further research work:

- Probability range on results
  A larger data set would enable modelling of the error bands of the calculated relationship equation to offer a result with a confidence range attached, allowing for a more accurate and useful output, and to determine a degree of confidence in the simulation's results.

- Further robot variable modelling
  Modelling wider robot variables, such as gripper state, joints configurations, acceleration, safety technology etc., would produce more holistic models. This in turn would make any simulated layout of more use, as it could capture a more realistic range of issues and benefits at the modelling stage. This study found congruent results between the two different robot types but there could be attributes of other robots that may affect normative human responses.

- Further human data measures
  The psychometric measure used in ICHORD – the Cranfield Trust Scale – is just one example of a tool for human data capture and analysis that could be developed to deliver the data needed for further development of DHM and HRC. In further work, the rules of behaviour and cognitive response needed to develop reliable models will require more tools of this kind, and such tools could also be applied in other applications such as training interventions. Moreover, the Cranfield Trust Scale may need to be revised and adapted for other environments and types of robot.

The ICHORD project has accomplished a good degree of progress towards its original goal of enhancing DHM capabilities with richer human data, but it has also made a preliminary contribution to knowledge for the improvement of HRC system design and implementation. It is intended that at least one high quality publication is achieved to disseminate the results of this work and that the partners work together to pursue further work with consideration of the above suggestions and beyond.

8. References

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9. Feasibility study team members

The study was conducted by a team of researchers from Cranfield University, the Advanced Manufacturing Research Centre.

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