Flinders University
Australian Industrial Transformation Institute

Setting it straight

Human factors, technology, and pipe alignment in shipbuilding

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October 2021

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www.flinders.edu.au/aiti

ISBN: 978-0-6488941-9-3

URL:http://www.flinders.edu.au/aiti/

CAT: AITI202112

Suggested citation:

O'Keeffe, V., Rajagopalan, A., Manning, K., Howard, S., Hordacre, A-L. & Spoehr, J. 2021. *Setting it straight. Human factors, technology, and pipe alignment in shipbuilding*. Adelaide: Australian Industrial Transformation Institute, Flinders University of South Australia.

This report is supported by a supplementary document:

O'Keeffe, V., Rajagopalan, A., Manning, K., Howard, S., Hordacre, A-L. & Spoehr, J. 2021. *Setting it straight. Human factors, technology, and pipe alignment in shipbuilding*: *Supplement*. Adelaide: Australian Industrial Transformation Institute, Flinders University of South Australia.

This supplement contains detailed descriptions of the procedures involved in trial task activities undertaken by participants and the interview questions posed to participants during individual interviews and focus groups.

This report is based on work funded by the Department of Industry, Science Energy and Resources (Innovative Manufacturing CRC) in collaboration with BAE Systems Maritime Australia.

Preamble

Australian manufacturing contributes to the economy through skills, knowledge and goods, representing AUD$100 billion to GDP annually (Australian Government Department of Industry Science Energy and Resources, 2020). While the sector has faced considerable competitive pressure over the last decade, substantial investment in the Australian shipbuilding sector has stimulated rapid growth in low volume, high-value manufacturing. BAE Systems Maritime Australia (BAESMA) is at the centre of this revival through the Hunter Class Frigate program.

This report is one outcome of a major research partnership between BAESMA, Flinders University and the Innovative Manufacturing Cooperative Research Centre (IMCRC) - a not-for-profit initiative of the Commonwealth of Australia. The IMCRC has partnered with Flinders University and BAESMA to conduct research into accelerating the uptake and diffusion of Industry 4.0 (I4.0) in shipbuilding and the Australian manufacturing industry. This multi-year collaboration involves applying human factors and ergonomics (HFE) thinking to the adoption of advanced technologies.

Successful adoption depends largely on technology acceptance by a variety of end-users (including the workforce, business owners and the supply chain). The ease of use of the human-system interface is a critical component in acceptance of I4.0 technologies. HFE significantly contributes to successful uptake and diffusion through people-centred design and evaluation to ensure technology is fit for purpose. I4.0 technologies possess inherent flexibility, facilitating their application in low volume and high mix manufacturing settings like shipbuilding, which requires extensive manufacture of piping systems. The manufacture of pipe spools involves handling, alignment and welding heavy and high precision components, constituting demanding, dirty and dangerous work. Smart technologies provide a key opportunity to minimise effort and increase accuracy using digital optical measurement systems and fixtures, incorporated into smart work cells. Harnessing these technologies has the potential to transform work processes to improve productivity, job design and safety in harsh work environments.

This report presents findings of a research trial comparing a traditional manual pipe alignment technique with a digitally enabled smart process. It utilises a combination of evaluation methods that draw on perceptions of technology and human performance outcomes that might be readily applied in assessing the impact of new technologies in a range of manufacturing contexts.

The outcomes of this trial are expected to provide practical HFE (and some technical) insights to those enterprises currently requiring precision manufacturing measurement, and to those considering the potential adoption or extension of this technology.

We extend our thanks to all those who participated in the trial.

Professor John Spoehr,

Director,
Australian Industrial Transformation Institute

Our lead industry partners, BAESMA, involved in the implementation of this project include Sharon Wilson (Continuous Naval Shipbuilding Strategy Director), Evangelos Lambrinos (Exports and Innovation Manager), Andrew Sysouphat (Principal Technologist - Hunter Class), Ivor Richardson (Project Manager – Strategic) and Derek Morton (Project Manager – Industry 4.0 Trials). Tom Pearce (Flinders University Research Associate) provided quantitative data analysis of the live trial outcomes. Collectively we thank the Board of the IMCRC and David Chuter, CEO for their support for this project. We share their vision for growth of advanced manufacturing in Australia.

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Abstract

Like the circulatory system in the human body, piping transports energy and wastes throughout ships ensuring their safe and efficient operation. Pipework fabrication is a major process in shipbuilding due to its high volume and complexity. The integrity of pipes is critical, needing to withstand high pressures, temperatures and chemical contact, as well as harsh environmental conditions. To weld accurately and ensure integrity, all pipe sections must be aligned correctly in accordance with stringent specifications. Alignment is a skilful task requiring hand-eye coordination and manual dexterity.

Human factors trials aim to assess the impacts of technology on human performance. This project involved a total of 25 participants who participated in either a live or virtual (via video-conferencing) trial. Participants in the live trial undertook two tasks:

a) *Pipe alignment task*: comparing a manual alignment method (using jigs, clamps, screws and pins to secure components and a spirit level to judge accuracy of orientation) to a smart-assisted version involving a digital optical measuring system with graphic user interface and smart jig.

b) *Smart projector task*: editing a digital technical drawing of the pipe assembly.

Virtual trials were developed for the pipe alignment task for those who could not attend in person. These participants took part in an interview or focus group examining their perceptions of the usability and applicability of the manual and smart configurations of the pipe alignment task.

The low number of participants in the live trials precluded statistical analysis. Five themes were identified for the pipe alignment task: *impact on skills, reliability, speed and accuracy, impact on work design and workflow, cost benefit,* and *technology acceptance.* Three themes were identified for the smart projector task: *appealing features, impact on work performance,* and *design improvements.*

Our trials present implications for the implementation of smart cell technology in relation to work practices, skills development, policy and research. The introduction of technology has significant impact on job design, requiring tailored human resources management and change management strategies. Indicative results suggest the smart-assisted version has the potential to reduce alignment time, though small sample sizes mean results were inconclusive and further research is warranted. There is opportunity for government policy to support technology adoption through fostering the teaching of STEM at all levels of the education system, providing initiatives to support enterprises in their business and infrastructure planning, and provide programs to facilitate industry-research-supplier relationships, particularly in collaborative test facilities or through the development of learning factory programs.

1 Background

1.1 The human factors approach

Human factors and ergonomics (HFE) explores the interaction between humans, their work, the environment in which it happens, and broader social and economic systems. Human work involves the use of tools, equipment, and increasingly, new technologies. New technologies must be both easy to use and useful (Davis, 1989) if adoption is to be sustainable. HFE views the human as the centre of a system of work, which ideally supports them to achieve their goals (Stanton et al., 2017). Thus, the purpose of HFE is to optimise productivity, quality, safety and satisfaction, and ensure sustainable performance for individuals and enterprises through fitting tasks (including technologies) to the capacities and limitations of people (O'Keeffe, Moretti, Howard, Hordacre, & Spoehr, 2020).

1.2 The role of piping in ships

Piping transports energy and wastes throughout ships ensuring their safe and efficient operation. Pipes on ships must be built and installed adhering to stringent standards due to the nature of the various fluids contained, ranging from fuel, coolants and gases, to drinking and waste water essential for the functioning of the ship and its crew (Prior & Spadoni, 2021). Pipe work is a major undertaking in shipbuilding because of the relatively large sizes of ships, each containing up to 40,000 metres of pipe (Fraga-Lamas, Noceda-Davila, Fernández-Caramés, Díaz-Bouza, & Vilar-Montesinos, 2016) and millions of other components (Gourdon & Steidl, 2019). The integrity of pipes is critical, needing to withstand internally-generated high pressures, temperatures and chemical contact, as well as harsh environmental conditions, including exposure to salt water and extreme temperatures (Murdoch, 2012).

Long and convoluted sections of pipe running through the ship are built by welding together smaller sections involving precise and time-consuming preparation, requiring high quality human performance (Turan, Kocal, & Ünlugencoclu, 2011). To weld these sections accurately and ensure their integrity, all pipe sections must be aligned correctly in accordance with precise specifications.

1.3 Purpose of research

Precise alignment and welding of pipes to flanges are physically and mentally demanding tasks, involving the manipulation of awkward objects (S. D. Choi, Yuan, & Borchardt, 2016; Rosecrance, Cook, & Zimmermann, 1996), precise placement, working under time pressure, and frequently checking the relative positions of different components. The consequences of errors and faults are significant in terms of time, reputation, safety, health and environmental impacts (Nahangi, 2015). Smart work cells also enable access to digital work orders, drawings and associated documentation to facilitate electronic management of objective quality evidence (OQE) (Niedersteiner, Pohlt, & Schlegl, 2015). The trial was conducted in accordance with ethical standards[1], and aimed to:

- Establish the impact of using a smart cell (including the OptiTrack optical measuring system, Demmeler work bench and smart Fit Rite jig) on pipe alignment performance (accuracy, quality and efficiency)

[1] The trial procedures were approved by the Flinders University Human Research Ethics Committee, approval number 4378.

- Understand user perceptions of smart cell usability and acceptance across a variety of end users
- Understand the physical and mental demands on users and their problem-solving strategies when fitting and aligning pipes and associated smart technologies such as a digital projector system, and
- Inform potential future applications for smart cell technologies in shipbuilding and manufacturing settings.

2 The smart cell trials

Research involving in-person trials is highly vulnerable to mobility restrictions imposed to minimise COVID-19 community transmission. The smart cell trials were designed to assess performance of physically present participants. The implementation of the trials was impacted by the influx of the Delta variant resulting in a brief lockdown (and slow re-open) in South Australia. To enable the research to proceed despite COVID-19 restrictions, methods were adapted to add a fully online ('virtual') presentation of the manual and smart-assisted pipe alignment techniques, followed by a combination of interviews and focus groups to capture participants' perceptions. A live trial was also undertaken to assess usability of a smart projector.

2.1 Equipment

The live trial was undertaken at the Pilot Factory of the Future at the Tonsley Innovation District[2]. Participants were required to wear work gloves, safety shoes, full sleeved shirts, long pants, and high visibility vest while completing the tasks. The smart production cell consisted of a work bench equipped with a range of smart-assistive technologies. A list of equipment used in completing the pipe alignment task is itemised in Table 1 and shown in Figure 1. This table was used for the smart projector task, with additional equipment listed in Table 2.

Table 1: Equipment used in pipe alignment and smart projector tasks

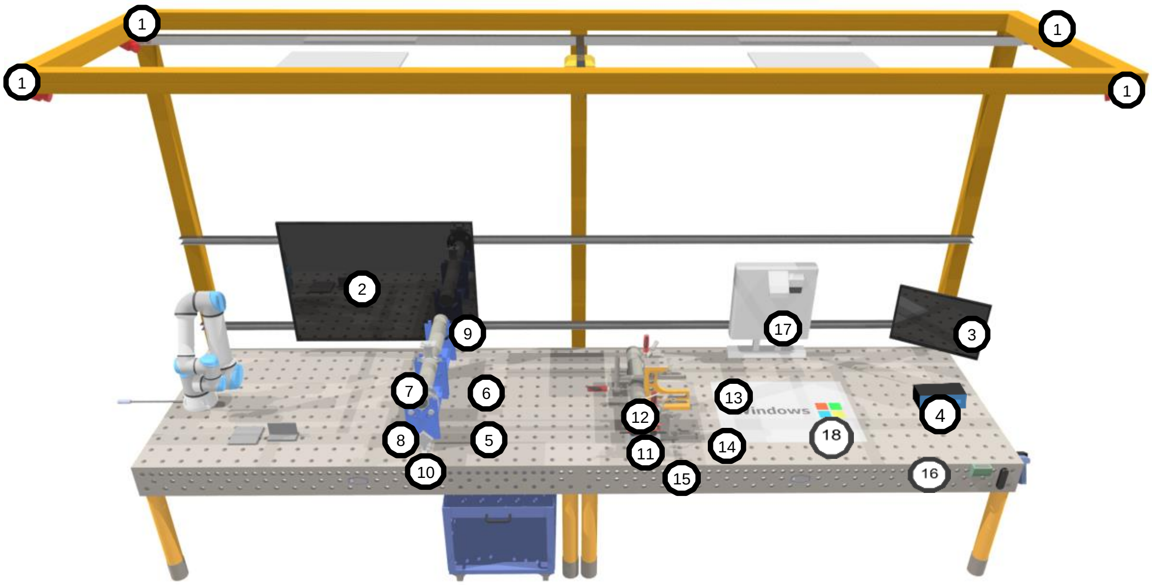
Equipment label	Summary Description
1	IR cameras which detect reflections from markers on rigid-bodies (digital spirit levels)
2	Large television screen which shows the operator dimensional control graphic user interface
3	Small television screen serving as secondary display to support interactive projector trial.
4	Small form factor PC hosting OptiTrack software displayed on screens.
5	Fit Rite pipe-fitting jig.
6	Digital spirit level that uses OptiTrack to track spirit level orientation in x, y and z.
7	Bolts used to mount Class 150 flange onto Fit Rite system to align to pipe.
8	Class 150 flange.
9	Representative carbon steel pipe used in the flange to pipe alignment task (DN80, Schedule 40).
10	Speed rail hosting Fit Rite jig cradle.
11	Flange pins used to support spirit levels on flange.
12	EZ pipe clamp used to align flange to the pipe.
13	Demmeler clamping system components for securing pipe on bench
14	Traditional spirit level
15	Class 150 flange
16	Demmeler workbench
17	Epson 1485fi Ultra-short-throw interactive projector
18	Interactive projector projection

Table 2: Additional equipment list for smart projector trial

Equipment label	Summary Description
1	Epson Brightlink 1485fi Ultra-short throw projector supporting multi-touch interaction using fingers and stylus
2	Projection displayed by projector.
3	Acrylic plate for operator to make digital annotations smoothly without experiencing workbench surface that is full of holes.
4	Secondary monitor used to show operator instructions to perform the trial.
5	Demmeler workbench
6	Epson V12H773010 Interactive Pen Stylus

[2] The Line Zero Pilot Factory of the Future is a testbed for new technologies established by Flinders University and BAESMA.

Figure 1: Depiction of smart production cell & equipment



An interactive ultra-short throw Epson Brightlink 1485fi ‘smart projector’ was used to project a drawing onto the workbench allowing participants to use a smart stylus to edit details. The projector was equipped with whiteboard software and a digital palette enabling selection of colours, line thicknesses, shapes and eraser functions. Equipment is itemised in Table 2. The live trial used a within-subjects (repeated measures) design where the same participant completed each pipe alignment method (manual and smart-assisted). Typically, the total time investment for each participant was one hour and 30 minutes, including familiarisation and completion of all three tasks and associated surveys.

2.1.1 Pipe alignment task

Welding of pipes requires the alignment of the spool components before they can be joined. Alignment is a skilful task requiring significant manual dexterity and eye-hand coordination, using equipment that is often heavy and cumbersome. Traditional alignment methods involve a range of tools including jigs, clamps, and screws in combination with pins to secure components, and spirit levels to judge the accuracy of component orientation. Joints in piping are areas of vulnerability that can make pipes prone to failure. The goal of alignment is to ensure the correct positioning of flanges, fittings and pipes prior to welding to ensure long-term integrity (Y. H. Choi & Choi, 2009) (see Figure 2). Pipe alignment requires experienced practitioners with skill developed through practice, hence pipe-fitters are needed to fulfill this role in shipbuilding (Ingalls Shipbuilding, 2019).

Figure 2: Pipe alignment application when joining pipes

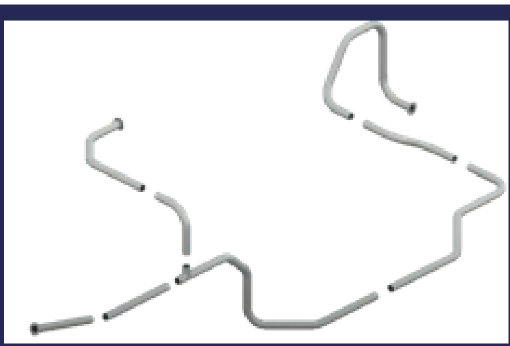
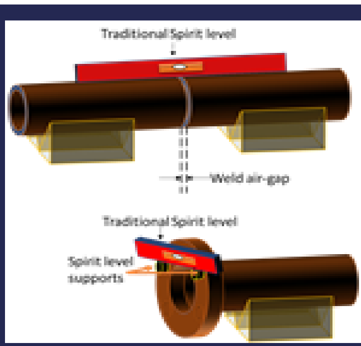


Figure 2.a: Long section of pipe broken into smaller pipe-spools



2.b: Depiction of pipe with flange aligned

Manual alignment technique

Pipe alignment involves assembly of different pipe spool components that can be joined in various configurations. Specific requirements are derived from the work order and technical drawing (traditionally in paper format). The traditional manual method has versatility in catering for a variety of pipe diameters and requires simple tooling. The skill in the traditional flange-to-pipe alignment task involves using hand-eye coordination and manual dexterity while handling the flange and clamp fastenings to achieve precision alignment while monitoring the spirit level. The pipe fitter manipulates the clamp assembly to align the flange to the end of the pipe according to specifications, which are then checked and recorded. These manipulations require significant manual handling of componentry with high levels of fine adjustment and concentration to achieve timely and accurate completion. The traditional method also typically requires manually recording the OQE for traceability. Images of the traditional manual flange-to-pipe alignment method are provided in Figure 3.

Figure 3: Traditional manual flange-to-pipe alignment technique

Figure 3.a: Front view of traditional flange-to-pipe alignment showing traditional pipe-clamp and traditional spirit level being used.

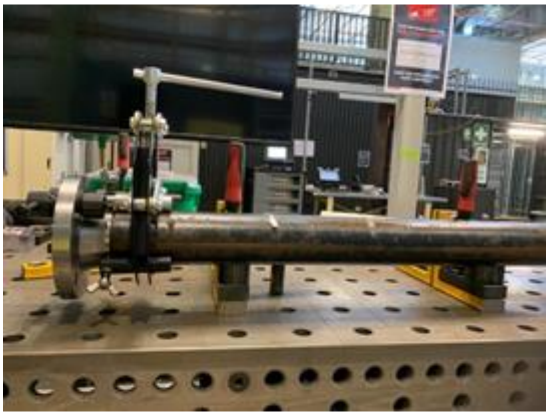


Figure 3.b: Side view of the flange-to-pipe alignment task with EZ-pipe-clamp holding flange to end of the pipe.

Figure 3.c: The alignment of the flange-to-pipe with metal rule inserted at junction to represent weld air gap. The wingnuts on the clamp hold the flange in place.

Figure 3.d: Manoeuvring the wing nuts allows adjustment of the flange position and orientation to the clamped pipe.

Smart-assisted alignment technique

'Smart' is an acronym used to refer to *self-monitoring, analysis and reporting technology* (Farlex, 2021), meaning the technology is electronic, able to connect, share and interact with its user and other smart devices. Smart alignment techniques introduce technologies that support precise measurement through using motion capture systems combined with advanced design smart jigs and work benches to improve alignment performance. Smart benches include a range of connected technologies, constituting a smart work cell. The Demmeler smart bench (used for this task) enables precision alignment to the floor, vibration isolation in the legs, and configuration and integration of other smart technologies, reducing errors in all components of the work system.

The smart pipe alignment technique substitutes the traditional spirit level with a 3D printed 'digital' spirit level incorporating passive retroreflective ball markers, allowing tracking in three dimensions. The OptiTrack optical motion capture system (rather than the human operator), measures the orientation of the digital spirit level to provide a reading. Tracking data is transferred to a graphical user interface (GUI) enabling the operator to monitor and record output into a digital workflow, providing traceability. The pipe clamp and jig used in the manual technique were also replaced with a smart alignment jig (the Fit Rite system), aiming to provide secure, convenient, and precise fastening, minimising human error. The smart alignment technologies are presented in Figure 4.

Figure 4: Smart technologies used in smart pipe alignment

Figure 4.a: Performing flange-to-pipe alignment using digital spirit level in place of traditional spirit level.

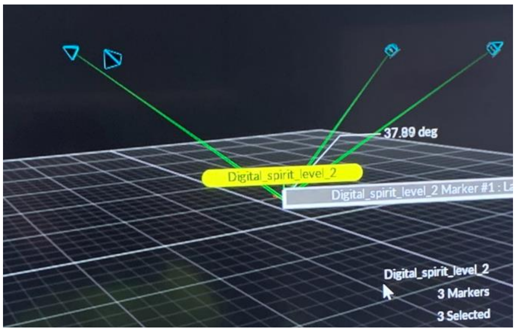


Figure 4.b: Visualisation of Digital spirit level being tracked by OptiTrack IR cameras shown in the OptiTrack Motive software tool.

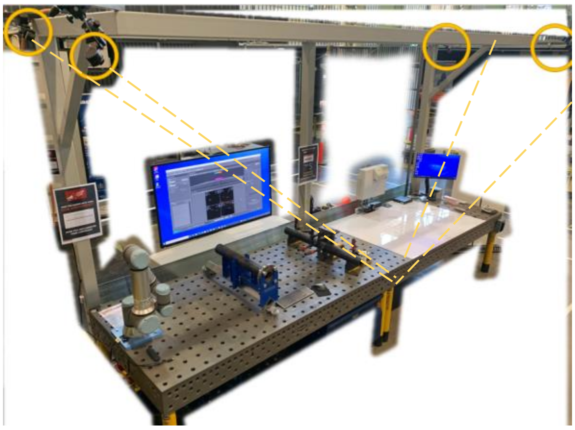


Figure 4.c: Physical workbench with OptiTrack IR cameras mounted above bench with 'virtual' lines within Field of View of each camera tracking digital sprit level in x, y and z orientations. Motive software shown on television screen.

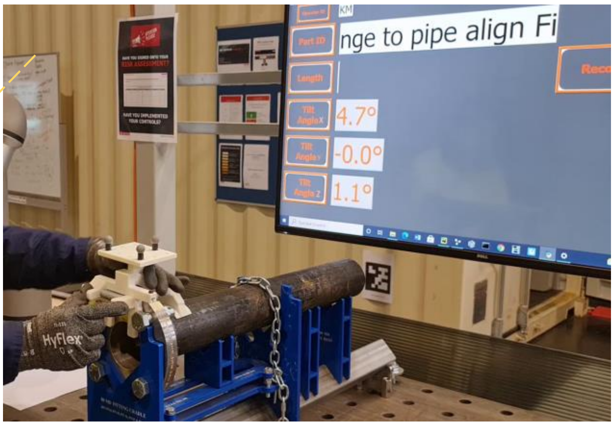


Figure 4.d: (i) Fit Rite pipe-fitting jig used for flange-to-pipe alignment; (ii) Harnessing digital spirit level for checking flange to pipe alignment. Digital spirit level angle data displayed on custom dimensional control GUI for OQE capture

Smart cells often include technology to enable interaction with a digital work order (e.g. smart phone, tablet, or augmented reality devices). Interactive digital projectors allow editing and approval of design changes to technical drawings in real time, improving traceability and efficiency and enhancing workflows (Niedersteiner et al., 2015). A digital work order is a key component of a smart work system, documenting work requirements in easy to access formats that link associated data, making it available at workers' fingertips. Integrated information sources increase the transparency of work requirements, minimise errors and data loss, and improve work performance and quality outcomes (Pimminger, Neumayr, Panholzer, Augstein, & Kurschl, 2020). Working with drawings has been found to be one of the more challenging usability tasks in implementing digital work orders (O'Keeffe, Jang, Howard, Hordacre, & Spoehr, 2021), requiring further research. Digital projectors may provide an additional option for enhancing management of drawings and improve the acceptance of digital work management processes.

2.1.2 Smart projector task

Smart work cells are highly flexible with the capacity to incorporate multiple technologies. Participants in the live trial also assessed the usability of a smart projector. Pipe-to-flange alignment must meet strict standards which are conveyed to the pipefitter in a technical drawing. Using an interactive projector mounted on the smart cell workbench, participants undertook a short usability trial to annotate a projected drawing in accordance with an updated specification.

A simple technical drawing of the pipe assembly was projected onto the workbench (see Figure 5.a). Images of the equipment used, and layout are presented in Figure 5.b and 7.c).

Figure 5: Pipe assembly drawing and projector tools used in editing task

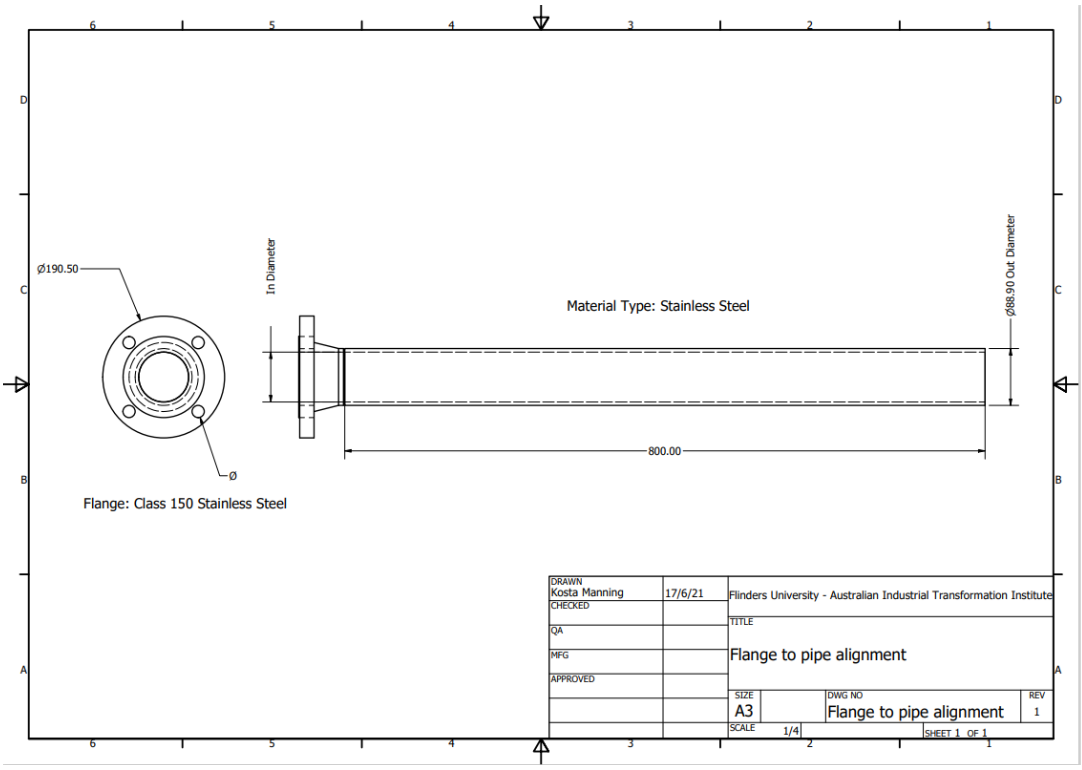


Figure 5.a: Screenshot of the simplified engineering drawing used for the trial

Figure 5.b: Making digital annotations on the projection of the simplified pipe-spool engineering drawing using the stylus

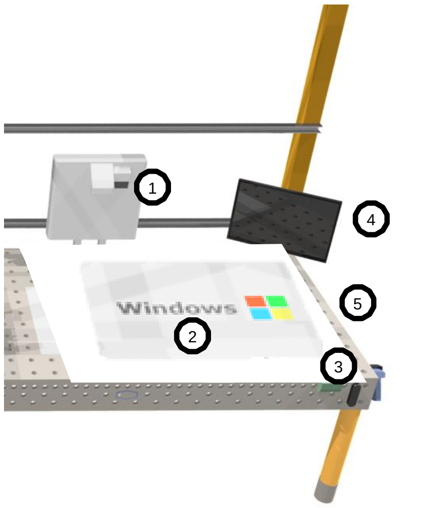


Figure 5.c: Visualisation depicting interactive projector along with projection on workbench

2.2 Recruitment and participants

The pipe alignment trial sought approximately 20 participants. We targeted engineering or trade-experienced personnel from the shipyard, SMEs specialising in pipe and/or metal fabrication, and apprentices from TAFE SA or equivalent vocational training organisations. Information about the trial was distributed by email to potential participants including those from the BAESMA shipyard who had visited the site and pipe-fabrication stakeholders from training organisations such as TAFE (boiler making and metal fabrication branch) and ATEC (metal fabrication branch).

Seven males with an average age of 40.6 years (ranging from 30-59) participated in the live pipe alignment trial. All had experience in manufacturing (average 9.3 years, range 0.5 – 19), three of whom were engineers. All had completed education beyond secondary school. Six participants indicated they were right-handed with one nominating as ambidextrous. Only one participant currently worked in an SME. Six of the seven live pipe alignment trial participants completed the smart projector trial. One of the seven participants did not complete the trial due to time limitations.

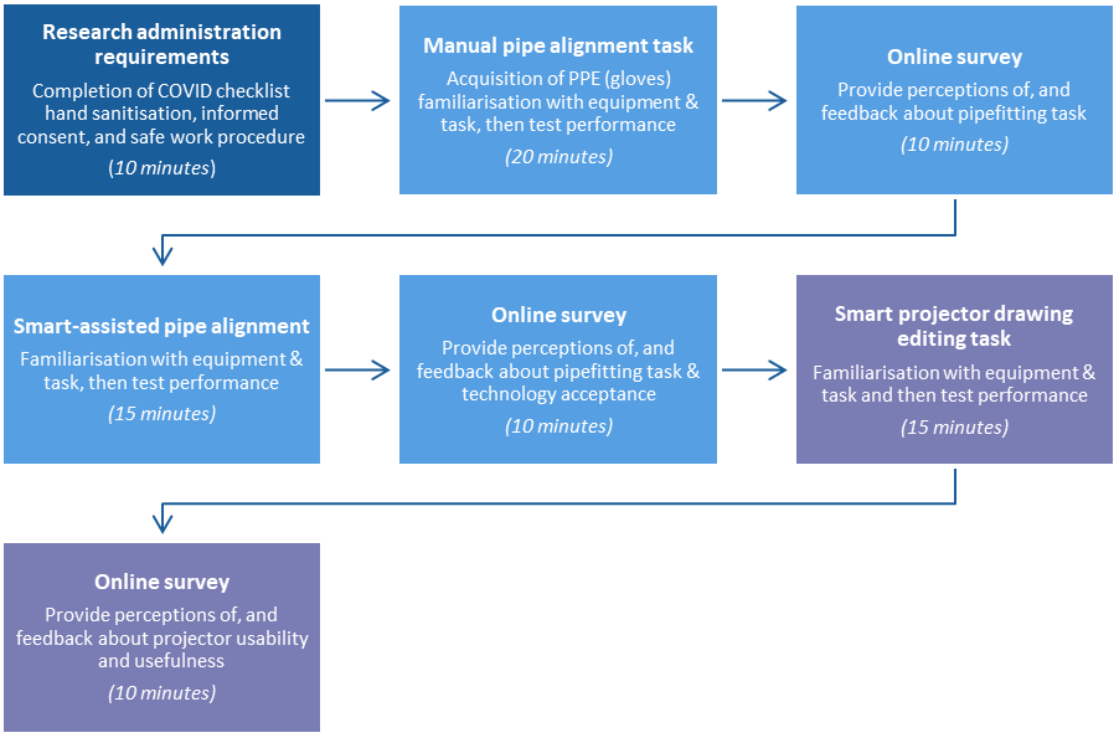
An additional 18 participants took part in the virtual trial, 11 of whom provided demographic information when requested via personal email. Virtual participants were briefed on the purpose of the trial and the procedure and provided verbal consent. High-definition pre-recorded videos of both pipe alignment tasks were uploaded to YouTube available to participants sequentially via time-limited links during the video conference. Interviews were audio recorded and canvassed similar issues to the survey questions answered by those completing the live trial. Questions explored ease of use, support needed to implement, impact on business, barriers to implementation and other possible applications for the technology (see the Supplement to this report for further information).

Virtual participants came from two SMEs (n=7), two shipbuilding organisations (n=7) and one training organisation (n=4). Participants of the virtual trial were male and tended to be in their 40s. With a mix of apprentices and experienced shipbuilders, half had been in their current job more than 3.5 years. Virtual delivery had the benefit of enabling an individual and group of five from regional South Australia to participate, for whom travel would have otherwise been a barrier.

2.3 Procedure

The trial process and duration are presented in Figure 6.

Figure 6: Live trial process



Pipe alignment

Pipe alignment live trial participants were briefed on task requirements, viewed an instructional video, and had the opportunity to familiarise with the equipment prior to task commencement. The manual and smart-assisted pipe alignment tasks were presented randomly to participants to account for learning effects and reduce bias. Three of the seven live trial participants completed the manual task first. Detailed instructions provided to participants on each task are included in the *Supplement* to this report.

Participants completed an online survey on their experience after each task. For each pipe alignment task, participants completed a subjective evaluation of task demands using the NASA Task Load Index (NASA-TLX) (Hart & Staveland, 1988). The NASA-TLX is a six-item tool allowing participants to rate perceptions of physical and mental demand, pace of task, overall performance success, and level of frustration experienced. Scores are summed and averaged to provide an overall estimate of workload. Participants also rated their evaluation of technology acceptance using measures based on the Technology Acceptance Model (Davis, 1989) and adapted from the Unified Theory of Acceptance and Use of Technology (UTAUT) model survey (Venkatesh, Morris, Davis, & Davis, 2003).

Smart projector

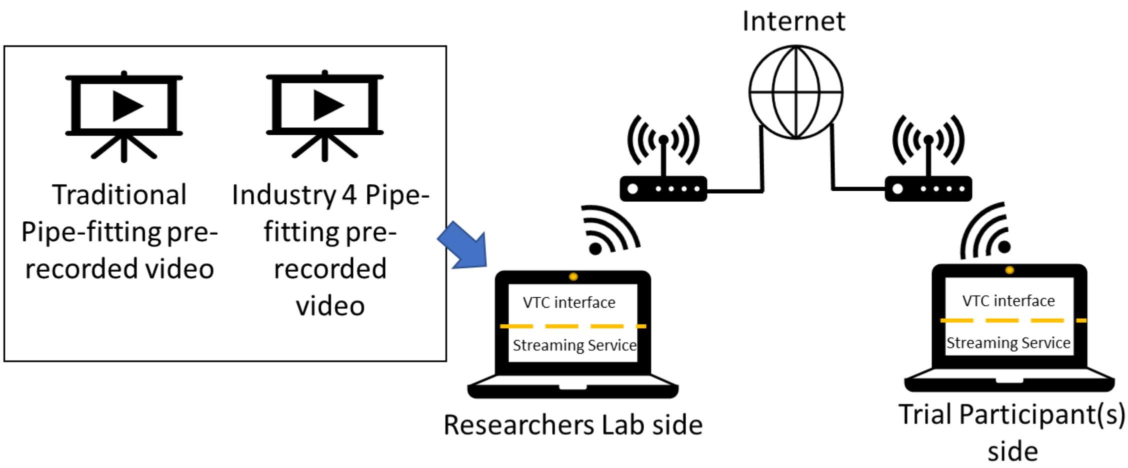
Participants were provided with a scenario requiring edits to the drawing. A list of required edits was provided involving various functions of the projector (e.g. changing colours, writing text, repositioning the palette, inserting shapes, enlarging detail, entering text and saving the file as a PDF (detailed information is provided in the Supplement to this report).

On finishing the interactive projector task, participants completed an online survey assessing perceived usability measured on the System Usability Scale (SUS), a ten-item scale assessing dimensions of perceived technology usability (Brooke, 1996). The SUS scale has become an industry standard for assessing usability (Grier et al., 2012). It consists of two sub-scales - usability (8 items) and learnability (2 items). However these sub-scales should be used with caution and may be more useful when system users have more experience with the system (Lewis & Sauro, 2017). A score of 68 reflects an average outcome while scores of over 80 indicate a 'good' outcome. The SUS grading scale ranges from A+ (84.1-100) to F (0-51.6). Free-text comments were also sought from participants on their perceptions of usability and usefulness.

Virtual trial

The virtual trial was delivered by video conferencing. Participants viewed a pre-recorded video of each version of the pipe alignment tasks followed by an interview exploring their impressions of the task and technologies. Participants required access to broadband internet and a laptop with microphone and speakers (see Figure 7).

Figure 7: Virtual trial using pre-recorded video format



3 Findings

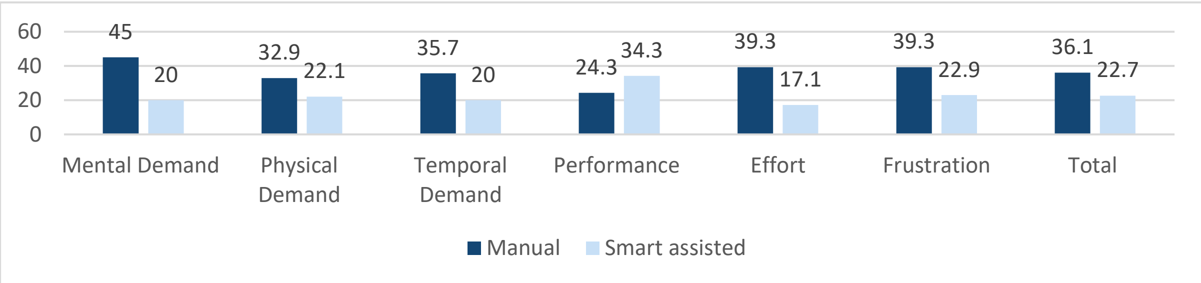
3.1 Comparing manual and smart-assisted alignment methods

The research assessed and compared user experience and perceptions of two methods of pipe alignment using a traditional manual technique and a smart technique supported by optical measurement technology. As discussed, methods of participation were modified due to COVID-19 restrictions, resulting in two delivery modes – live and virtual.

3.1.1 Demands

Participants of the live trial rated task demands on the NASA-TLX scale[3] following completion of each task. However, due to low numbers comparison between the techniques was not possible, although there was a trend towards rating the manual task as more demanding than the smart-assisted version. The smart-assisted task generally provided a narrower band of task demand ratings than the manual task with lower variability (standard deviations). A summary of mean scores by each dimension of the NASA-TLX subscales is presented in Figure 8. When possible, further trials to establish findings from a larger sample are required. Of particular interest, the mental demands (i.e. concentration, problem-solving and judgement), the effort and frustration of the manual task appeared to contribute most to perceptions of high workload.

Figure 8: Total NASA-TLX mean score and subscale means (n=7)



3.1.2 Strategies

Participant observations were conducted during each pipe alignment task to identify strategies used to facilitate successful performance. Strategies did not differ based on order of task completion apart from using more of the manual checks during the second task that had been missed while performing the first task (reflecting a learning effect).

For manual alignment, participants' frequent strategies included:

- Sliding the clamp along the pipe to achieve correct placement to support the flange
- Forcefully pushing or pulling the flange into position to achieve the alignment and reduce the weld gap
- Keeping the ruler between the pipe and flange throughout the task to maintain the weld gap
- Using the abdomen or torso to support the flange in position to enable hands to be free for manipulation of wing nuts.

[3] A task receiving an overall NASA-TLX score of 30 or below is considered to have low demands, with scores above 30 considered highly demanding (Bernard, Zare, Sagot, & Paquin, 2020).

For smart-assisted alignment, participants were observed to:

- Move the pipe forward on the Fit Rite jig to interface the flange
- More frequently become confused about correct orientation of the flange within the Fit Rite jig
- Struggle with securing the pipe with the chain, adopting sustained and awkward postures
- More frequently explore the relationship between the digital spirit level and movement of readings on the GUI
- Spend more time looking at the GUI with less reliance on manual checking.

3.1.3 Perceptions of the pipe alignment task

On completion of each task, participants provided feedback in an online survey containing free-text fields enabling them to provide commentary. Table 3 provides insight to user experience during physical performance of each task.

Table 3: Perceptions of the pipe alignment task

Theme	Manual	Smart-assisted
Task demands (mental and physical demands)	*Being unfamiliar with the equipment and process added a layer of cognitive load* *The task was quite awkward trying to support a weight while adjusting the clamps*	*Comfort level was high, and I felt confident undertaking this task* *It was comfortable but the chain caused some discomfort with leaning over to position it*
Task aids (instructions, information sources, tools and equipment	*It was not evident that I was using the fitment correctly. I was doubting myself during the process* *The digital spirit level was really easy to use and captured measurements without paperwork*	*You can't really see the display as you are assembling the gauge to the flange* *The jig was a useful aid, but the chain clamp element was a poor design and difficult to use*
Task difficulty (perceived difficulty, complexity and frustration)	*It was fiddly, iterative, not straightforward. Mess with this, fiddle with that, this affects that* *Multiple attempts were required to get the positioning right for all tools*	*The task was fairly simple with less adjustability in the system* *The digital gauge is not complete, there is some variation about how it sits on the fixture. I feel like I am required to trust that it is horizontal.*
Strategies (steps to problem-solve and achieve goals)	*There was a risk of dropping the flange, so I had to use my torso to hold the assembly in place* *The task needed three hands, so I had to rest tools against my body to support them*	
Quality (impacts on quality of product or process)		*Task was completed to specification without any significant user input* *Task achieved the required accuracy with minimal effort or variance – less rework needed*

Participants found the manual version of the task more physically and mentally demanding and felt it was more prone to error. While the smart version was preferred by all (see Figure 9) for its comfort and relative ease of use, there remained opportunities to enhance usability with implications for uptake (see Section 4).

Participants identified the following potential barriers to adoption of the smart fixtures:

> *Heavy industries would struggle to adopt this in wider processes due to limited working set up*
>
> *It would appear to lack robustness for industrial environments*
>
> *It would be hard to get buy-in from users and have the supporting IT/OT infrastructure*

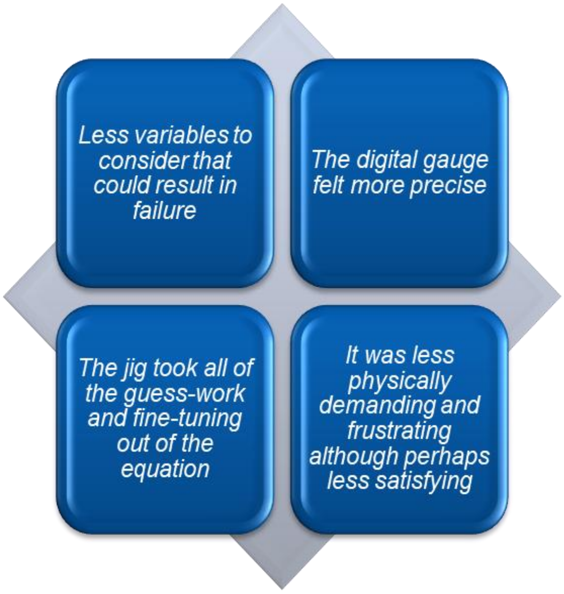


Figure 9: Smart assisted alignment benefits

Other possible applications identified for this smart technology included repetitive high-volume manufacturing and general assembly tasks. Tasks involved in the repair and modification of existing piping installed in ships could also benefit, for example measuring flanges to make a new spool to fit and complete a connection.

All participants indicated:

- willingness to use the technology
- expectations that the technology would be easy to learn and use
- confidence that a smart workstation would be good for business, and
- confidence that using a smart workstation would increase individual productivity.

Most agreed they would like to use the 'smart' technology and it was likely to improve the quality of their work and job satisfaction. However, there was some concern that it may not be compatible with existing technology.
The virtual trial provided the opportunity for participants to view the two techniques remotely and contribute perceptions and comments through focus groups and interviews. Five broad themes were identified:

Impact on skills: participants felt that many of the traditional skills would continue to be required, particularly while the older workers were still practising their trade. There was also some concern about skills that might be required in the future becoming depleted through technology adoption:

> *You need to have the underpinning knowledge of alignment for pipe fitting, it's a critical element. It needs to be taught and learned. Manual will be around forever and a day*
>
> *It will be harder to teach those older tradesmen but when you get the new workers in, that's when you'd want to teach them the new ways*
>
> *There's the regular skill set involved in the smart one, purely manufacturing. Very, very minimal skillset. Like '50s making car parts. Pull the lever, move it out, stamp, lever, move it out…. There's no adjustment. It's whatever the computer says and that's not very satisfying.*

Reliability, speed and accuracy were expected to improve, although some concern was expressed about the impact of harsh environments on the smart device:

> *It seems like it needs a very clean environment. Many work areas are dirty, dusty, greasy – it would probably damage the system*

> *For new people you can take out the likelihood of error*

> *It's good technology – it's practical, not time consuming. You can wind something up, get it square and away you go. I reckon it would cut down on fabrication time*

Impact on work design and workflow examined perceived impacts on the system of work, job design and workflow. It is noted that those undertaking the virtual trial were more expansive on broader system impacts, whereas those engaged in the live trial tended to focus on their experiences in achieving the task objectives and performance standard:

> *It's well and good setting it up in a nice open area. In a functioning workshop, let alone a shipbuilding scenario, would bring a lot of problems aligning the cameras, battling with tight spaces, tight time slots…. if there's a permanent set up there could be some value*

> *You could take kids straight out of school and get them doing that [smart version], get them qualified, then get them doing meaningful work for the rest of their lives so they can progress*

> *You'd want to set up five bays with different sizes of Fit Rite and pump out a lot of pipe – fit it, weld it and change sizes periodically. That's where the system would be handy. We work in just-in-time production – you're all over the shop, and we're doing all sorts of sizes. You'd need storage to do mass production working ahead of time*

Comments about **costs** considered the expense of implementing new technologies as well as the business advantages:

> *If everything can be calibrated, set up in an hour or so, then you can whip out a heap of work. If it's going to be quicker, more efficient, obviously it will be more time and cost effective, viable really*

> *It will be interesting to see how long it takes to set up infrared cameras. The cynic in me says that the cost of that system would far outweigh that of a spirit level*

> *The maintenance of the firmware, software. You're going to need another organisation to do all this work – people who know stuff. The cost factor would be an issue*

Technology acceptance is a key factor in the successful uptake of technology and includes the concepts of ease of use and perceived usefulness (Davis, 1989). Younger workers were expected to engage more quickly, with higher levels of acceptance because of the potential benefits:

> *I think it will go down well with newer people and less well with the old souls, they may have zero interest in using something like that, or struggle to….*

> *Potentially it has value in reducing errors and designing them out, increasing repeatability and consistency.*

> *Technology has been encroaching for a while now in manufacturing. I suppose you need to get the trust of people once they can see the benefits*

In summary, virtual participants raised broader issues about technology acceptance and integration into existing systems of work and production processes. Discussion points highlighted the necessity for effective training and support on the job particularly to encourage adoption in 'older' workers or those with less familiarity with technology. Participants recognised the introduction of technology had the potential to significantly transform associated work processes, tasks and occupations.

Participants showed significant interest in the opportunities and challenges for implementing the smart technology in their businesses and recognised the roles of leaders in successful adoption. The role of leadership was highlighted by participants who acknowledged that leaders must lead the change management process, through:

- assessing the cost benefit,
- matching technology with applications, and
- assessing the impacts on quality, safety, efficiency and skill development.

Attention to each of these factors is critical in achieving successful technology adoption and sustainable use.

3.2 Smart projector usability

The median total SUS score for the interactive digital projector was 81.2 (a 'good' outcome), placing the system at an A grade rating, suggesting participants found the projector relatively easy to use.

Participants' descriptive feedback revealed three broad themes:

Appealing features: Participants found it easy to use the interactive projector, identifying the most appealing features to be the choice and ease of changing colours, the electronic capture and connectivity for sharing of information, and the intuitiveness of the user interface.

Impact on work performance: Participants liked the digital capability and immediacy of information management provided by the projector, one stating '*there is no hard copy to mess with'*. Others identified the potential for immediate editing and approvals to avoid bottlenecks in production and improve workflow through greater traceability. Participants also commented that it would be difficult to ensure sufficient space and cleanliness in a workshop setting, which would also hamper the projector's use in a workflow.

Design improvements: Participants identified several additional features or design improvements to enhance usability and technology application.

- auto-convert text would be useful although illegible handwriting could be a limitation.
- latency of the digital exchange had led to inaccuracies, errors and re-work in editing the technical drawing
- the stylus pen was uncomfortable to use and compromised accuracy due to its *'clunkiness'* - a finer pen or a pull up keyboard could assist with data entry.
- There was no clear preference for size, one participant felt that A3 size would be useful, and others identified a smaller projection field would reduce the need to bend over the drawing leading to back discomfort and blocking of the projection beam.

Other suggestions included a simpler zoom feature, better resolution, and the ability to change the size of the projection field.

4 Implications of smart cell technology

Preliminary results from our small sample suggest the smart-assisted technique combining the Fit Rite jig and OptiTrack optical measurement system has potential to reduce:

- Risk of awkward postures, high forces and musculoskeletal risks in pipe alignment tasks.
- Mental effort, pace of task and frustration levels.
- Performance time.

Perceptions of the impact of adopting the smart-assisted version on skill acquisition and maintenance, and job satisfaction were mixed. Compared with those undertaking the live trial, virtual trial participants were more likely to consider the technology's potential to diminish skills and job satisfaction for already skilled workers, and to fast-track skill development in newer workers. There were perceptions work layout and workflows would change, with smart technology deemed more suitable for workshop applications involving fabrication although less aligned to high mix, low volume just-in-time production, or installations in tight workspaces - both typical of shipbuilding.

Technology designers and providers have a key role in improving the durability and reliability of the system for use in harsh environments, particularly designing for portability and ease of camera installation in a variety of work locations. Cameras and tracking ball components on the digital spirit level also require ruggedised design. Successful adoption of technologies within smart work cells are reliant on compatibility with other technologies to ensure integration and ease of use, which may be a limitation of the existing system.

As with the introduction of any new technology or process, an effective change management strategy is the cornerstone of success (Bano & Vasantha, 2021). Success involves overcoming uncertainty by responding to feelings and perceptions and adopting a planned approach during which the vision is explained to the workforce. Workers must be empowered to act in fulfilling the vision, be engaged in determining short-term goals and establishing and embedding new ways of thinking and working (Wentworth, Behson, & Kelley, 2020). Key features of a successful change management process include:

- articulating the reasons and vision for change,
- frequently communicating key information,
- involving the workforce in the process, listening carefully and sensitively to concerns,
- providing training in technology and personal development skills,
- running trials or technology 'come and try' sessions to increase familiarity with and acceptance of technology, and
- seeking ongoing feedback to identify emerging issues and addressing these early (O'Keeffe et al., 2021).

4.1 Skills development

To achieve successful technology adoption, organisations must develop their workforces to support them in acquiring new skills. Required skills include technical (task and technology specific) and personal development skills (collaboration, communication and reflection) to cultivate a growth mindset (Guan & Frenkel, 2019; Schallock, Rybski, Jochem, & Kohl, 2018). Participants in this trial identified the need for specific training programs and resources, including tailored training packages for delivery through vocational training providers. Such training resources are ideally standardised short courses, using a combination of hands-on skill application and technology-focused training (e.g. computer and programming skills), that provide consistent, transferable and transportable skills recognised nationally.

Participants were universally of the view that the manual pipe alignment technique would remain as essential training, since it provides the underlying skills and knowledge of the fundamental task process, and a foundation for problem-solving. Accordingly, the smart-assisted technique may provide an entry-level skill pathway for apprentices enabling faster skill acquisition. Training on technology transfer would be required for instructors (Anderson, 2020) and the workforce, to ensure successful adoption and accelerate industry uptake. Supporting resources will be essential to facilitate formal and on-the-job training, including the need for online resources like an interactive piping handbook that includes standards and images.

Successful technology adoption extends beyond a need for technical skills. Other critical skills include transformation skills (i.e. understanding the transformation of the production system and applying these principles to planning and task execution) and social skills, including team work, knowledge transfer and collaboration (Schallock et al., 2018). New technology has the potential to invoke fear and uncertainty about the future (West, 2015). Participants in this trial identified the potential for the smart-assisted technique to diminish the manual skill acquired through traditional practices, with associated anxiety about technology taking jobs. To minimise adverse impacts, organisations must consider job design and opportunities to grow skill bases through incorporation of greater planning, monitoring and coordination activities within discrete jobs. Human resources strategies must be developed that support skill acquisition and job satisfaction in technology-rich work environments (Guan & Frenkel, 2019). One strategy helpful for minimising fear and increasing technology familiarity and acceptance is to provide programs that allow the workforce to interact with technologies in ‘come and try’ sessions or workplace trials.

4.2 Policy implications

Underpinning implications for skills development, governments globally have highlighted the urgent need for policy that supports accelerated STEM training in future workforces through programs at primary and secondary school, vocational training and university (Freeman, 2013). STEM knowledge and skills fuel innovation, enhance capacity to solve complex and global problems, and boost competitive edge (Anderson, 2020). To achieve this end, Australia has adopted a national STEM school education strategy aimed at increasing student STEM ability and engagement, and supporting the teaching ecosystem to increase its STEM capacity (Australian Government Department of Education Skills and Employment, 2016). Given STEM is associated with 75% of the fastest growing occupations, the demand for highly skilled labour is expected to double by 2026 (Hajkowicz et al., 2016). Therefore, governments must support education and training providers to embed STEM skill development as a life skill by promoting technology-specific separate subjects and infusing technology competencies throughout curricula. Interdisciplinary project work, particularly in the form of work placements using authentic problem-solving opportunities, is also recommended to consolidate practical skill application (Tytler, 2020).

Extending opportunities for on-the-job training, the learning factory concept pioneered in Germany highlights that Industry 4.0 adoption involves more than just technology and that human resource management is a critical foundation (Schallock et al., 2018). Learning factories provide opportunities to achieve hands-on qualification of participants, including employees and students by using an alternating sequence of observation, theory and practice. Expanding beyond existing training models of group training, opportunities exist for government to initiate learning factory programs within the Australian context.

To enable enterprises to harness the benefits of a growing technology-literate entry level workforce, industry support programs are needed to develop business models that can capitalise on technology uptake, particularly in SMEs. Specific initiatives should include access to business and infrastructure planning support (e.g. to establish rigorous management systems capable of addressing exacting specifications), technology skills development, and guidance on implementing effective change management and workforce selection and recruitment strategies. Working in synergy with business planning, programs that provide businesses the opportunity to trial technology in collaborative test spaces like Flinders University's Pilot Factory of the Future and on location in their businesses will enable curious experimentation with capacity to learn and fail safely.

Aligned to such test spaces, policy can also support technology adoption through establishing ecosystems of providers and integrators to provide technical support during implementation. Financial incentives to innovate production processes integrating technological solutions and provision of subsidies to assist in training key personnel in certifiable skills would further stimulate and accelerate technology uptake.

4.3 Research and future directions

There is a need for further research and development to increase the robustness and reliability of optical measuring systems and smart jig technologies in harsh manufacturing environments where dust, oil, grease, high temperatures and vibration are common. Further research is also required to assess human-technology performance in such work conditions, given this trial was conducted in a relatively clean, stable simulated workspace.

Given the variety of methods employed in this trial, actual performance metrics (performance time and usability ratings) were only available for a small sample. Further research is required to test any potential performance advantage in the smart-assisted method compared to the traditional manual method. The viability of the Optitrack and Fit Rite smart-assisted pipe assembly technique also requires real work trials over longer periods of time and with a variety of pipe configurations to assess cost-benefit analysis. Viability would also be increased through research that is able to identify and verify broader applications and use cases in a variety of manufacturing and construction industry contexts.

5 Conclusions

This research aimed to establish the impact of using smart technologies to augment human performance in the intricate practice of pipe alignment. Two modes of trial delivery were offered – live participation, and virtual observation followed by interview or focus group. Participants completed a manual and a smart-assisted version of pipe-to-flange alignment, with the latter version assisted by the Optitrack digital optical measurement system and the Fit Rite jig. Participants responded positively to the smart technology, perceiving it to be more comfortable, more accurate and faster to use.

Participants from the virtual trial raised broader issues on the impact of the smart-assisted task including technology acceptance, integration into systems of work and production processes, skills acquisition, job design and career trajectory. Perceptions of the impacts on skills were mixed, with a spectrum of views suggesting smart-assistance could be de-skilling and unsatisfying, to having capacity to fast-track skill acquisition. The reliability and configurability of the systems in harsh environments and in the high mix, low volume manufacturing context characteristic of shipbuilding was of general concern. Further research is required to examine these issues in greater depth with larger sample sizes, and in higher fidelity workplace contexts.

As part of the smart cell configuration, participants used an interactive projector to complete annotation of design changes on a technical drawing. Usability of the system was rated as 'good' (median score of 81.2 in a scale ranging 0-100), with several appealing features (colour choices, ease of changing function, connectivity for sharing information) and suggested potential for design improvements (auto-convert handwriting to text, better ergonomics of the stylus). In addition, the interactive projector could assist flexibility through supporting digital work orders.

Performance on tasks was related to the design features of the hardware and software, task, working environment and individual characteristics. These interactions illustrate the value of addressing human factors and ergonomics as instrumental aspects of technology assessment and adoption. The implications for adoption include the need for organisations to identify specific use cases matched to business operations and goals, and the necessity for integrating technology to optimise workflows and cost benefit. Businesses' technology adoption can be accelerated by policy responses to cultivate STEM capabilities in the education system and manufacturing workforce. Key to success is providing opportunities for curious experimentation, and business planning support, including human resources and management systems development. Funding subsidies to support infrastructure development and initiatives like workplace trials, and collaborative learning ventures between industry, education providers, researchers, and technology providers would catalyse uptake. Ventures like collaborative spaces and learning factories can provide the ecosystem to foster sustainable and successful technology adoption.

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