Physical Ergonomics and Human Factors, Vol. 63, 2022, 108–116
https://doi.org/10.54941/ahfe1002603

Physical, Psychophysical and Demographic Changes Require Automated & Autonomous Machines & Equipment (AAM&E) in Construction

Sang D. Choi[1,2] and James G. Borchardt[3]

[1]University of Wisconsin – Whitewater, Whitewater, WI 53190, USA
[2]The George Washington University, Washington, DC 20052, USA
[3]Construction Ergonomics LLC, Bettendorf, IA 52722, USA

ABSTRACT

Construction is one of the most dangerous occupations with high prevalence of work-related fatalities and injuries among the high-risk industrial sectors. Concurrently, the construction industry is experiencing workforce demographic changes and shortages of skilled trade/construction workers. This paper provides an overview of the shifting construction workforce and the benefits & exposures from the evolving automated and autonomous machines & equipment (AAM&E) under development for the construction industry. Specifically, this paper describes a synopsis of design methodology and principles of AAM&E associated with human-related factors (e.g., self-efficacy, mental/cognitive workload, situation awareness). Also, this paper discusses potential practical applications and insights on the human-machine interaction/collaboration and key factors for building trust in human-robot teamwork (e.g., rule-based framework, transparency/feedback, observation, predictability). This paper can assist human factors & ergonomics (HFE) practitioners and safety professionals who may not be current with this evolving AAM&E technology to pre-plan and design control methods into industrial and construction projects.

Keywords: Physical, Psychophysical, Demographic changes, Human-machines interaction, Trust, Automated, Autonomous, Construction

INTRODUCTION

The U.S. Bureau of Labor Statistics [BLS] reported the U.S. construction sector employed approximately 7.6 million workers and unfortunately, experienced 4,764 fatalities and 174,100 non-fatal injuries (BLS, 2021). Moreover, the U.S. population and its workforce have experienced significant physical, psychophysical and demographic changes (e.g., age, gender, disability) during past decades which contributed to the current and projected nationwide skilled labor shortages in the construction industry (Graf, 2021). Robotic or automated systems can reduce occupational injuries and free workers from performing dangerous job tasks. According to Construction Industry Institute™ (2022), non-construction industries have been applying digital technologies for decades but these technologies have only recently been applied to construction machines and equipment to improve the cost, schedule, quality, safety, and production.

Shifting Characteristics – U.S. Population and Workforce

In the past 60+ years, the U.S. population and its workforce have undergone significant changes in many areas which have resulted in the need and opportunity for all industrial sectors to adapt to the changing characteristics. Cutler et al. (2003) reported in the 40 years from early 1960 to 2000, the average U.S. American male and female weight shifted from 168 lbs and 142 lbs to 180 lbs and 152 lbs respectively. The Centers for Disease Control and Prevention [CDC] (2021) reported the average weight of males and females has continued to increase i.e. 200 lbs and 171 lbs respectively. In the 1960's, researchers began to use the psychophysics of weights, forces and frequencies with the objective to develop guidelines for manual handling tasks. This became known as the psychophysical approach to analyzing and designing manual handling tasks. Between 1970s – 1990, the Snook Tables were developed and published by Liberty Mutual Research Institute for Safety (Snook et al., 1970, 1978, Snook & Ciriello, 1991). In 1994, NIOSH Revised Lifting Equation (NRLE) emerged as one of several ergonomic assessment tools of lifting/lowering tasks with a Load Constant of 51 lbs (Waters et al. 1994). NRLE was further refined by the Variable Lifting Equation (Waters et al. 2009). In 2001 when studying lowering tasks of various size boxes, Ciriello "observed" a potential shift in the workers' "willingness" to handle heavier boxes so Ciriello et al. 2008 "repeated" the Snook Tables studies and found a significant shift to 69% of Maximum Acceptable Weight (MAW) for male workers performing lifting/lower/carrying tasks and 82% of Maximum Average Force (MAF) in pushing/pulling tasks. If additional studies verify that the various changes to the U.S. population and its workforce during the past 60+ years have lowered workers' capacity to perform manual tasks such as lifting/lower, pushing/pulling and carrying, then the Load Constant (LC) of the NRLE and other assessment tools will need to be lowered accordingly i.e. about 35 lbs. Another significantly change which has occurred in the past 60+ years is the participation rate of the labor force by gender. Szafran (2002) reported the 1960 U.S. workforce participation rate was 83.3% of males and 37.7% of females. By 2000, the U.S. workforce participation rate shifted to 75% of males and 61.9% of females. As the "baby boomers" who were born in the 1940's, entered the workforce in the 1960's and began to retire in 2000, BLS (2021) reported the "total" workforce participation of adults began to decline i.e. 67.1% in 2000, 64.7% in 2010 and 61.7% in 2020 and the participation rate "by gender" also declined i.e. 74.8% of male & 59.9% of females in 2000; 71.2% & 58.6% in 2010 and 67.7% & 56.2% in 2020.

AUTONOMOUS AND AUTOMATED MACHINES AND EQUIPMENT (AAM&E) BENEFITS

International Organization for Standardization (ISO) 17757 (2019) defines that autonomous operation as "the mode of operation in which a mobile machine performs all machine safety-critical and earth-moving or mining functions related to its defined operations without operator interaction. The operator could provide destination or navigation input, but is not needed to assert control during the defined operation." ISO 17757 (2019) also defines autonomous machine as "a mobile machine that is intended to operate in autonomous mode during its normal operating cycle" (ISO 17757, 2019; Tiusanen et al., 2020). Automated/autonomous machines and equipment can provide substantial improvement in safety, cost savings, and efficiency. Robots, automated/autonomous equipment, and other workplace technologies are inevitable since younger workers have grown up using smart-phones, tablets and expect technology to be provided to help them perform their jobs (Jones, 2020). AAM&E solutions and technology may also help ease the shortages of skilled construction operators, and provide valued-added employment opportunities for workers with physical disabilities such as wounded veterans (Jurgens, 2021). AAM&E use less fuel, move more efficiently reducing their maintenance, preventing unnecessary wear/tear thus prolonging their operating life and increasing productivity and cost effectiveness. Automating some tasks provides skilled workers the opportunity to perform more complex tasks requiring human skills. AAM&E also can perform parallel tasks more quickly and allow jobsites to run beyond normal operating hours or in adverse conditions (e.g. at night or inclement weather). Automated or autonomous machines can be smaller which improves the economics of machine design. Eliminating the overhead of drivers or operators is the basis of the "swarm" concept. There is a large productivity gap between large/high-power vehicles and small robots. For example, an average increase in construction/mine productivity of 30% with autonomous vehicles results from longer production hours, reduced load and unit cost of 15%, improved tire life of 40% from optimized controls reducing sudden acceleration and abrupt steering (Jurgens, 2021). Most large autonomous machines are operated in restricted facilities where proximity to the automated equipment is controlled and extremely limited. Sensor technology and processing capabilities need to advance further to be able to identify many of the potential obstacles that must be avoided. Safety of autonomous systems is of utmost importance, and robotic/autonomous systems can reduce occupational injuries by conducting dangerous tasks that conventional construction methods have reached their limits. Automation and robotics technologies have also the potential to address the productivity challenges of the construction industry (Delgado et al. 2019).

BARRIERS AND CHALLENGES OF AAM&E

The construction industry is a major economic driver of the U.S. economy, but has numerous inefficiencies and low productivity. While robotics and automated systems have the potential to address these shortcomings, the adoption of these technologies in the construction industry is low. The construction factors which limit the adoption of automation in construction included contractor-side economics, client-side economics, technical/work-culture, and weak business case (Delgado et al. 2019). Contractor-side economic factors encompass all the factors related to the costs construction companies need to incur to adopt robotics or automation in construction including high initial capital investments and weak business case to improve productivity. Client-side economic factors categorize the cost the client should incur for adopting robotics or automation with decreased public/government infra-structure spending. Technical and work cultural category includes the practical factors that limit the implementation of robotics or automation concerned with the unproven effectiveness and immature technology. In a weak business environment, it is unclear what value construction companies obtain from return on investment by adapting to robotics/automated systems in construction so a thorough cost-benefit analysis is needed (Delgado et al. 2019). Examples of unique challenges in construction include safety/damage, dynamic worksites, dust/dirt, challenging environments, struck-by incidents, costs vs profits, and conservative industry (Morrison, 2020).

PROSPECTIVE DESIGN METHODOLOGY AND PRINCIPLES OF AAM&E

ISO 18497 (2018) provides documentation to assist in communicating the safety requirements, means of verification and usage information to ensure an appropriate level of safety for self-propelled machines and equipment with highly automated operations. Design of autonomous machines in construction focuses on the sensing, processing and actuation capabilities of the machine platform using existing machines as a basis for automation or robotization (Schmidt, 2016). Designing autonomous systems for deployment in dynamic and ever-changing work environments on construction sites can be considered a new direction in engineering design. The main interactions between humans and machines are about to change with the introduction of fully autonomous machines. Not only are the needs of the users, operators and bystanders to be considered, but the emerging needs of autonomous machines need to be documented and further analyzed to define requirements. The definition of these very specific and new requirements demands a novel approach in finding an effective engineering design. Useful design and development of autonomous machines can be generated by early experience prototyping via virtual reality (VR) combined with scaled-down versions of existing machinery (Ruvald et al. 2018). Ensuring a safe, productive and efficient cooperation between humans and automated systems should also be incorporated in the AAM&E design and development (Frank et al. 2019). To make appropriate decisions during *early design* and development phases of an autonomous machine, the vast majority of requirements can be taken from traditional machine developments to define the mechanical properties of the machine. Construction automated/autonomous machines require an effective and intuitive interface to their environment and workers in a simple or sophisticated system to facilitate interaction and collaboration (Frank et al. 2019). The notion of "trust" and "trust development" needs to be considered in the *early design* of autonomous or automated machines. Trust as a design requirement is a new item in the requirement list and needs to be described more thoroughly. Human-robot interaction in construction needs to create an intuitive interface development found in other fields like computer science and engineering design. In addition to traditional engineering tasks, psychology (e.g., self-efficacy) has to be included in the research and design work (McAlister et al. 2008) for the aspects of interaction/trust can be considered as a fundamental basis for the design of automated or autonomous machines (Lynas and Horberry, 2011). Observations and interviews at construction sites support the understanding and development of trust among human teams. Non-verbal communication, experience, the stable formation of the team and a comprehensive understanding of the work task support the inter-team trust development and its maintenance (Frank et al., 2019). In addition, a *rule-based framework*, applied at all sites, serves as an entry point into the trust development because new team members can rely on the "dos and don'ts" and that everyone follows the same company-wide rules. Similar to the development of trust between humans, the trust development between a human and an autonomous machine or robot can be facilitated. Transparency, constant feedback, reliability, and durability exposed by the autonomous system support the development of trust on the human side (Frank et al., 2019). For instance, "communication" is a key aspect of workers' situational awareness and safety performance on the job (Sorensen and Stanton, 2016).

Table 1 below provides a summary of the benefits, barriers/challenges, and design related principles of automated and autonomous machines & equipment in construction.

Example Insights of Human-Machine Interaction/Collaboration

Most of the research focused on automated equipment or systems require a human operator to function as intended (Lynas and Horberry, 2011). Associated issues such as implementation are acceptability of automation to operators, loss of situation awareness, deskilling, and operator behavioral changes based on different levels of automation. It is suggested a user-centered design approach (Haas, 2018) could overcome the issues with a parallel focus on system automation rather than component automation (Frank, 2019). Robots require human assistance to perform various tasks, especially those involving high dexterity and nuanced human judgment (Liu et el. 2021). Vaussard et al. (2014) conducted a study to investigate the human-robot interface of domestic robotic vacuum cleaners. During their study, they were able to split the direct and indirect interaction between humans and robots into three main parts, which are similar to the intended construction applications of the research: (1) how users operate and give commands to robots; (2) how the systems give feedback to users, and (3) indirect interaction with users and robots shared environment. It has been stated users wish to understand how the robot is working, which could be described as transparency. The study also revealed inadequate information sharing is decreasing the long-term acceptance of robotic systems, which was also stated in Lynas and Horberry (2011). Breazeal et al. (2013) and Jung et al. (2013) highlighted the importance of the human-robot interface, and its design, as a key success factor for the *human-robot teamwork*. Trust between teammates is a crucial success factor of collaboration and ultimately of the successful task

Table 1. Summary of AAME perspectives in the construction industry.

Benefits	Barriers/challenges	Design Methodology and/or Principles
Improve cost savings, efficiency and safety (e.g. reduce occupational injuries)	Low adoption of technologies	Focuses on sensing, processing and actuation capabilities of the machine platform
Ease the shortage of skilled construction workers	High initial capital investments	Provides a new direction in engineering design in a dynamic and ever-changing work environment
Provide valued-added employment opportunities for worker with physical disability (e.g., wounded veterans)	Limitation of implementation of robotics or automation concerns with the unproven effectiveness and immature technology	Early design and development phases provide: • early experience prototyping via virtual reality (VR) combined with scaled-down versions of existing machinery • "Trust and Trust Development" needs to be considered in the early design
Use less fuel, reduce maintenance, prevent unnecessary wear/tear, prolong operating life, run beyond normal operating hour and in adverse conditions	Unclear on return on investment (ROI) or cost-benefit analysis (CBA)	Human-robot interaction in construction needs to create an intuitive interface found in multi-disciplinary fields: • computer science and engineering design • psychology (e.g., self-efficacy) • observations and interviews at construction sites • non-verbal communication, experience, the stable formation of the team and a comprehensive understanding of the work, task support of the inter-team trust development and its maintenance
Improve the economics of machine design (e.g., smaller sized robots)	Safety/damage, dynamic worksites, dust/dirt, challenging environments, struck-by incidents, costs vs profits, and conservative industry	Rule-based framework: • "dos and don'ts" and that everyone follows the same company-wide rules • transparency, constant feedback, reliability, and durability • "communication" is a key aspect of workers' situational awareness and safety performance on the job

execution (You et al. 2018). Jung et al. (2013) found when robots used back-channeling, the team functioning improved and robots were seen as more engaged. On the other hand, the research also revealed robots using back-channeling were perceived to be less competent than those that did not use it. Breazeal et al. (2013) and Jung et al. (2013) performed their study by means of a collaborative game (in this case, Urban Search and Rescue), including participants, confederates and robots. In their study about resilient autonomous systems, Matthews et al. (2016) highlighted the challenges for the teaming between human operators and autonomous systems associated with the cognitive demands, trust, and operator self-regulation (Frank, 2019).

CONCLUSION

Automated and Autonomous Machines & Equipment (AAM&E) can help address safety/health issues, skilled labor shortages, and low productivity in the construction sector. The applications of robotics, automated and autonomous machines would result in human-machine interaction/collaboration due to the complexity of the task and due to the necessity of a human observer involved in the process. The collaboration between humans and machines has high relevance for the design of the machine and, even further, the design of an effective interface. While making conclusions from only human teams, trust between teammates is a crucial success factor of collaboration and ultimately of the successful task execution. Autonomous technology and robotics are rapidly becoming much more sophisticated, and this trend is only expected to accelerate, even though there remain significant challenges for companies that want to adopt automated/autonomous technology in the construction industry.

REFERENCES

Breazeal, C., DePalma, N., Orkin, J., Chernova, S., Jung, M. (2013). Crowdsourcing human-robot interaction. *Journal of Human-Robot Interaction*, 2(1), 82–111.

Bureau of Labor Statistics [BLS] (2021) "Employment Projections: Civilian labor force participation rate by age, sex, race, and ethnicity." Table 3.3.

Centers for Disease Control and Prevention [CDC] (2021) "National Center for Health Statistics, Anthropometric Reference Data for Children and Adults: United States, 2015–2018", Series 3, Volume 46.

Ciriello, V.M. (2001). "The Effects of Box Size, Vertical Distance and Height on Lowering Task." Int. J. Ind. Ergo. 28, 61–67.

Ciriello, V.M., Dempsey, P.G., Maikala, R.V., O'Brien, N.V. (2008). "Secular changes in psychophysically determined maximum acceptable weights and forces over twenty years for male industrial workers." Ergonomics, 51(5), 593–601.

Construction Industry Institute™ (2022). Construction Technology. Website: https://www.construction-institute.org/resources/knowledgebase/knowledge-areas/construction-technology.

Cutler, D.M., Glaeser, E. L., Shapiro, J. M. (2003). Why Have Americans Become More Obese? National Bureau of Economic Research – Working Paper 9446.

Delgado, J. M. D., Oyedele, L., Ajayi, A., Akanbi, L., Akindade, O., Bilal, M., Owolabi, H. (2019). Robotics and automated systems in construction. *Journal of Building Engineering, 26,* 100868.

Frank, M., Ruvald, R., Johansson, C., Larsson, T., Larsson, A. (2019). Towards autonomous construction equipment. *Int. Journal of Product Development, 23*(4), 292–308.

Graf, C. (2021). Building trade: Skilled trade labor shortages continue as boomers retire, replacements aren't there. *Glens Falls Business Journal.* June 17, 2021.

Haas, E. J. (2018). Applying the precaution adoption process model to the acceptance of mine safety & health technologies. *Occupational Health Science, 2,* 43–66.

ISO 17757 (2019) "Earth-moving machinery and mining – Autonomous and semi-autonomous machine system safety." https://www.iso.org/standard/76126.html

ISO 18497 (2018) "Safety of Highly Automated Agricultural Machines - Principles for Design." https://www.iso.org/standard/62659.html.

Jones, Kendall (April 16, 2020). Construction Technology Is Reshaping The Industry. Website: https://www.constructconnect.com/blog/technology-reshaping-construction-industry.

Jung, M. F., Lee, J. J., DePalma, N., Adalgeirsson, S. O., Hinds, P. J., Breazeal, C. (2013). Engaging robots: Easing complex human-robot teamwork using backchanneling. *Computer-Supported Cooperative Work, 92,* 1555–1566.

Jurgens, Jeff (March 15, 2021). Autonomous Equipment: Examining the Path Toward a Driver Less Tomorrow. Website: https://www.aem.org/news/autonomous-equipment-examining-the-path-toward-a-driverless-tomorrow.

Liu, Y., Habibnezhad, M., Jebelli, H. (2021). Brainwave-driven hymn-robot collaboration in construction. *Automation in Construction, 124,* 103556.

Lynas, D., Horberry, T. (2011). Human factor issues with automated mining equipment. *Ergonomics Open Journal*, 4, 74–80.

Matthews, G., Barber, D. J., Teo, G., Wohleber, R. W., Lin, J. (2016). Resilient autonomous systems: Challenges and solutions, *Resilience Week,* 208–213.

McAlister, A. L., Perry, C. L., Parcel, G. S. (2008). How individuals, environments, and health behaviors interact: Social cognitive theory. In K. Glanz, B. K. Rimer, & K. Viswanath (Eds.), pp. 169–188.

Morrison, Ross (December 17, 2020). Autonomous Construction Solutions Advance As Industry Specific Challenges Addressed. Website: https://www.roboticsbusinessreview.com/construction/autonomous-construction-solutions-advance-as-industry-specific-challenges-addressed/

Ruvald, R., Frank, M., Johansson, C., Larsson, T. (2018). Data Mining through Early Experience Prototyping -A step towards Data Driven Product Service System Design. IFAC-PapersOnLine, 51(11).

Schmidt, D. (2016) "Shaping the Future - A Control Architecture for Autonomous Landscaping with an Excavator." Technische Universität Kaiserslautern, 2016.

Snook, S.H., Irvine, C.H., Bass, S.F., (1970). "Maximum Weights and Work Load Acceptable to Male Industrial Workers." AIHA Journal, 31(5), 579-586.

Snook, S.H. (1978). "The design of manual handling tasks." Ergonomics, 21(12), 963–985.

Snook, S.H. and Ciriello, V.M. (1991). "The Design of Manual Handling Tasks: Revised Tables of Maximum Acceptable Weights and Forces." Ergonomics, 34.9, 1197–1213.

Sorensen, L. J., Stanton, N. A. (2016). Inter-rater reliability and content validity of network analysis as a method for measuring distributed situation awareness. *Theoretical Issues in Ergonomics Science, 17*(1), 42–63.

Szafran, R. F. (2002) "Age-Adjusted Labor Force Pacticipation Rates, 1960-2045", Monthly Labor Review, 125(9), 25–38.

Tiusanen, R., Malm, T. Ronkainen, A. (2020). An overview of current safety requirements for autonomous machines – review of standards: Open Engineering, 10(1), 665–673.
Vaussard, F., Fink, J., Bauwens, V., Retornaz, P., Hamel, D., Dillenbourg, P., Mondada, F. (2014). Lessons learned from robotic vacuum cleaners entering the home ecosystem. *Robotics and Autonomous Systems*, 62(3), 376–391.
Waters, T.R., Putz-Anderson, V., Garg, A. (1994). "Applications Manual for Revised NIOSH Lifting Equation." DHHS/NIOSH Publication No. 94–110.
Waters, T.R., Occhipinti, E., Columbini, D., Alvarez, E., Hernandez, A. (2009). "The Variable Lifting Index (VLI): A New Method for Evaluating Variable Lifting Tasks Using the Revised NIOSH Lifting Equation." NIOSH- Cincinnati, Ohio, USA.
You, S., Kim, J. H., Lee, S., Kamat, V., Robert, L. P. (2018). Enhancing perceived safety in human-robot collaborative construction using immersive virtual environments. *Automation in Construction, 96,* 161-170.