Transportation Consortium of South-Central States

Tran-SET

*Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation*

# Development of Robotics & Automation Roadmap for Construction/Maintenance Projects

**Project No. 21COLSU06**

**Lead University: Texas A&M University**

**Collaborative University: Louisiana State University**

**Final Report**

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<tr><td colspan="3">16. Abstract<br>Over the past few decades, there have been no significant improvements in the construction industry's productivity. Outside the construction industry, robots have proven to be beneficial in improving productivity, safety, and quality. There is a growing interest in adopting robots in the construction industry to address these issues. As robots get introduced to the project sites, human-robot interaction becomes an important consideration for wide-scale adoption. The success of deploying robots in the construction industry depends on how well humans collaborate with the robots. This project focused on investigating the perception of various construction industry stakeholders in adopting robots in their projects, and the level of control they feel can be delegated to robots. This project also investigated major factors that impact the decision to use a robot for a particular task. The research used a survey to collect relevant data from various construction industry stakeholders for 11 specific types of robots that were applicable to the construction industry. The main findings from this study are that there was a generally positive perception of different types of robots regarding their job relevance, ease of use, output quality, and usefulness. Furthermore, from a human-robot collaboration perspective, majority of respondents supported shared autonomy between human and robot in different scenarios. This highlights the need for developing more robots that share control with the human when executing construction tasks.</td></tr>
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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oF$ | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | $^oC$ |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oC$ | Celsius | 1.8C+32 | Fahrenheit | $^oF$ |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

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# EXECUTIVE SUMMARY

In recent years, there has been an increasing interest and use of robots in road construction/maintenance, and construction industry in general. However, the type of robot that is going to be beneficial for the project depends on several factors such as the type of robot, it's suitability for the task, its current maturity, and its ease of use etc. Furthermore, many projects do not reap expected benefits of robots due to several reasons such as need for human supervision, errors from robots, increased costs to adopt robots in the project etc. Since there are several types of robots that have been developed for different types of tasks, it is difficult for practitioners to understand if certain robots are suitable for their projects.

Several questions arise when making the decision to adopt a certain robot in a project. For instance, what factors should be considered in prioritizing tasks for robotic technologies applications? Once we select tasks for robotization, how can we implement the appropriate robotic solution for the specific task? Which aspects of the target task influence the perception associated with the robot adoption? With the introduction of construction robots, how would the current construction operation transform with the deployment of the robot? Currently, there is no guideline or tool to help practitioners decide on whether adopting robot is suitable for their project. This project aims to address this issue by developing a decision supporting framework that will help practitioners decide whether a certain robot is suitable for use in their project or not.

Although the demand for new technologies and innovation is growing, the civil infrastructure industry lacks a decision-making mechanism, and as a result, the actual implementation is still very limited. To address this gap in practice, the goal of this study is to develop a decision supporting framework to deploy robots with specific designs for a certain construction and maintenance work. While it is very difficult to conduct experimental case studies for many types of robots in many scenarios to draw generally applicable guidelines to create a decision-making framework, we can gain valuable insights from experience of other practitioners. The decision support framework in this project will be designed by understanding the perception of industry practitioners towards different types of robots and their perceived/ observed benefits and drawbacks based on their experience.

Technology Acceptance Model (TAM) is utilized to dig into the factors that influence the intention and behavior to use a new technology as a theoretical model to understand industry perception towards adoption of robots. This TAM is modified to be applicable to this research by including construction specific criteria related to human-robot collaboration, and potential/observed benefits and barriers for different types of robots in our decision support framework. The benefit of this project is that using the results from this project, practitioners can decide whether a certain type of robot is suitable for their project based on perception of other practitioners who have some familiarity with that robot. This will help practitioners avoid potential issues or understand if any changes are needed before deciding to adopt different types of robots.

The technical phase involved a survey study that aimed to understand perception of different types of robots in construction projects. The survey aimed to develop a conceptual understanding of robotics by using the Technology Acceptance Model. The technical phase of this project involved designing the survey, collecting the data, and analyzing the data to see how perception towards different types of robots varies based on the Technology Acceptance Model. The preliminary analysis of the survey results has been completed and a conceptual framework is developed that

describes industry perception towards different robots. The results from the survey and the conceptual framework are presented in this final report from the technical phase.

During the implementation phase, this research will investigate, the applicability of the decision-making framework by seeking feedback from industry practitioners. Since the project follows qualitative research and investigates a subjective phenomenon (perception towards robots), the way to assess the functionality/ applicability of the output will also be subjective. The expected outcome is that the decision-making framework developed in this research will provide some insights to practitioners regarding current state of construction robotics and how they can adopt robots in their projects/ companies.

# 1 INTRODUCTION

According to the McKinsey Global Institute report published in 2017 [1], construction-related spending accounted for 13% of the world's GDP. However, there has been only a 1% annual productivity increase over the past two decades. The construction sector in the United States is a significant contributor to the economy, valued at approximately $1.4 trillion. As per the US Bureau of Labor Statistics, Office of Productivity and Technology [2], labor productivity in the construction industry is inconsistent and has had marginal growth in productivity over the past two decades. On the contrary, sectors of manufacturing and agriculture have grown their productivity about 15 times in the past two decades [1]. Executing projects with poor productivity often leads to time and cost overruns, thus impacting the nation's economy.

In North America, in the 1980s, a skilled labor shortage in the construction industry began, which has continued over the last thirty years. This shortage makes it difficult to recruit and retain skilled labor, putting the financial success of projects at risk. The situation of trade workmen shortage began to temporarily reduce in 2008 during the great recession in the US over the period up to 2009. However, during the post-recession period, there was rapid economic recovery resulting in a skilled labor shortage in the industry [3]. Based on the annual workforce survey analysis conducted by the Associated General Contractors of America in partnership with Autodesk [4], it was found that 88% of the projects are running behind schedule, of which 61% of the projects cite a shortage of labor as their prime reason for the delay. The blow of shortage in the workforce was deepened by the covid-19 pandemic. The covid-19 pandemic has affected the construction industry seriously, from experiencing project delays, supply chain issues, terminations, layoffs, order cancellations, and work restrictions [5].

Over the years, numerous solutions for improving productivity and reducing the skilled labor shortage have been developed, including the use of automation and robotic technology in the construction industry. Robotic technology has demonstrated the potential benefits of improving quality, productivity, safety, and sustainability. Thus, extensive research and development have been conducted in the construction industry on using robots for a variety of construction activities [6]. Based on the research conducted by Jang et. al. [7], artificial intelligence (AI), neural networks (NN), deep learning (DL), smart materials, 3D printing, and robotics are the technologies that have the highest potential in the construction industry.

Some of the recently developed robotic technology integrates the use of building information modeling (BIM), artificial intelligence (AI) and machine learning (ML) in the construction industry. Over the years, attempts have been made to use robots to do repetitive and strenuous jobs on construction projects. For example, TyBot [8] is a rebar tying robot developed by Advanced Construction Robotics which is used in tying reinforcement in bridge decks. This robot has helped in solving the problem of human rebar fitters bending their backs throughout the day in tying rebar for long hours. The productivity achieved by TyBot is equivalent to the productivity of 4-6 human rebar fitters on a similar job. Examples of efforts made toward using robots in the construction industry include Canvas [9] which is a company that has developed a construction robot that uses sensors and AI to apply finishes to the drywall surface. An Israel-based startup Buildots [10], attaches 360-degree cameras to the project managers' hardhats and collects images of the construction sites. It produces progress updates by comparing them to the drawings and schedule using AI and DL algorithms. Dusty Robotics [11] uses the collaboration of robotics and BIM to print the construction layouts directly on the construction surface. Apart from the benefits of improved productivity, safety, quality, and reduction of skilled labor requirements, robots can be effectively used in the construction industry to allow remote work and achieve social distancing. Robots will help in eliminating the requirement of a human to physically be present at any hazardous sites and thus improve safety at the worksite.

Construction industry is adopting robotic technology to solve the current problems of declining productivity, skilled worker shortage, hazardous working conditions and dynamic work environments. In the future, most of the repetitive and strenuous work could be delegated to robots. Due to the complex and unstructured nature of construction projects, robotic technology is not developed to the extent that it can execute a project site autonomously [12]. This means that as robots are introduced to construction sites, humans and robots will interact with each other. Human acceptance of robot is one factor that predicts successful human-robot interaction. Thus, research should be done to identify what tasks on a construction project can be executed by robots and how the robotic technology can be integrated to form an effective human-robot team.

# 2 OBJECTIVES

Robotics and automation will play a significant role in improving labor productivity, safety, quality, skilled labor shortages, and work restrictions after the pandemic. Robots have been around for a long time, but there has been little implementation in the construction industry. One underlying reason for low adoption of robots in the construction industry is that the robot adoption and implementation involves multidisciplinary involvement of various stakeholders including the project execution team, leadership team, academia, and robot developers. Consequently, it is very important to know what the perceptions and expectations of all stakeholders are about robotic technology otherwise, the project may face resistance when it comes to adopting robotics. In the construction industry, there is no decision-making framework to guide the automation of specific construction tasks. Numerous factors influence the usefulness of technology, such as individual factors, organizational factors, and the nature of the project.

The objectives of this research project re as follows:

1. To review the state-of-the-art robotic technologies and their applications in the industry.
2. To investigate the perception of different stakeholders in the construction industry towards adopting robots in their projects.
3. To evaluate the factors that impact the decision to adopt a robot for different types of construction tasks.
4. To identify the level of comfort of various stakeholders for different human-robot interactions.
5. To develop a decision supportive framework for deploying robots in the construction industry.

# 3 LITERATURE REVIEW

## 3.1 History of robots in the construction industry

Looking back at the history of robots, the oldest robots in construction date back to the 1980s. These robots were teleoperated or remotely controlled machines developed in Japan as a solution to the labor shortage [13]. In the United States, the earliest remote-controlled machinery was developed for performing hazardous work such as unexploded ordnance removal or rapid runway repairs. In Europe, research on developing robots for bricklaying activities in building construction was conducted in this period. In recent years, with development in robotics, software, and technology, new developments and collaborations are happening between academia and the construction industry.

Manufacturing and automation industries have implemented digitization in their respective industries known as industry 4.0. Although, construction industry is not at top in adopting to this, efforts have been made in integrating digital technology in construction, known as construction 4.0 [14]. Numerous technologies have been identified to have significant impact on the digitization of the construction industry including BIM, AR, VR, robotics, 3D printing, AI, and drones [14].

Based on the market research [15] conducted by Straits Research Pvt. Ltd., a market intelligence company, growing urbanization and the safety of workers are the driving factors toward adopting robots in the construction industry. The global construction robotic market size is expected to grow to US $160 million in the next 8 years. The market size of construction robots was valued at the US $50 million in 2021. According to the report, the United States and Europe will be the leading markets for develop robot in the construction sites.

## 3.2 Benefits of using robots in the construction industry

Previous researchers have identified the benefits of adopting robots in the construction industry. These include reduced reliance on labor, enhanced productivity by automation, increased safety in construction by avoiding human involvement in hazardous environments, and increased quality control by reducing variability in construction [16]. Research also suggests that the short-term application of robots can be expensive. However, in the long term, companies can reap cost benefits, especially by reducing human errors and increasing productivity [17].

Several researchers have studied the applications of robots in different construction activities which can be classified into main tasks and assistive tasks. Examples of main tasks include using robots for earthmoving operations [18], and bricklaying operations [19]. Examples of assistive tasks include project progress monitoring using unmanned aerial vehicles [20], structural inspections for bridges [21], tunnel inspection robots for maintenance operations [22], assistive wearable robots to reduce fatigue while doing repetitive and strenuous tasks [23], and many more. Recent studies carried out in the construction industry in the United States [24] and Hong Kong [25] suggest that different stakeholders have a common viewpoint regarding the benefits offered by robots in enhancing the safety of the workforce. Apart from this, other benefits reported for using robots include cost benefits in terms of reduction of labor and strategic benefits like job opportunities in the construction industry.

## 3.3 Barriers to adopting robots in the construction industry

Despite the advantages offered by robots, not all construction companies have adopted robotic technologies. According to a survey conducted by KPMG in 2016, only 30% of construction companies use robotics and automated technologies in the United States [26]. In 2021, a market analysis conducted by ABB Robotics reported that only 55% of construction companies used robots on their project sites as compared to 84% companies in the automobile sector and 79% in manufacturing sector. [27].

Previous research has tried to study the barriers to the adoption of robotic technology. These barriers can be categorized into various levels like the construction industry level, company level, and project level. At the industry level, there are numerous barriers like economic constraints of contractor and client [16] [28], the industry's aversion to change [7], and lack of standardization in the construction industry [24] [28]. At the company level, there are several challenges like low research and development investment by the company towards automation and robotics [7], lack of technology culture in the company [24], lack of long-term vision and top management support for the adoption of robots [6] [29]. At the project level, there can be challenges like complex nature of the project , lack of skill in understanding the application of robotics [7], and technological barriers like accuracy of robots [24]. There are some safety concerns that arise due to lack of literacy in using robots, for example, it was observed that while flying drones on the project, some workers stopped doing their work to see drone on the work site [30]. Also, other factors that can challenge the adoption of robots in the construction industry include location factors, weather, availability of network and electricity, and site logistics [31].

## 3.4 Human-robot collaboration in the construction industry

The aim of using robots in a project is to reduce the workload of a human in performing repetitive tasks [32]. Due to the complex nature of the construction industry, it is currently difficult to eliminate humans from the project sites, instead humans and robots have to collaborate with each other to achieve maximum efficiency [12]. Human-Robot Collaboration is defined as the contact of humans and robots in an environment for performing specific tasks [33]. The amount of autonomy given to the robot for executing a particular task forms the basis of developing various levels of Human-Robot Collaboration. A study by Liang et. al. identified the evolution of construction robots in the past two decades and categorized different levels of Human-Robot Collaboration [34].

There are ten levels of human-robot collaboration with respect to robot involvement but when studied in the context of the construction industry these levels of human-robot interaction are confusing. This study by Liang et. al. [34] defined a new taxonomy for various levels of Human-Robot Collaboration. These include manual, preprogramming, adaptive manipulation, imitation learning, improvisatory control, and full autonomy. In preprogramming, the robot is programmed to do a set of repetitive tasks, and the decisions are taken by the human. When a robot adapts to the decisions taken by the human, the level of collaboration is known as adaptive manipulation [34]. In the case of imitation learning, the human plans the work, and the robot learns by observing humans. In Improvisatory control, the robot does most of the execution of the task, and the human acts as a supervisor. In full autonomy, the robot performs the task independently without any human intervention [34].

## 3.5 Trust in human robot interaction

A study [35] explored the level of trust humans have on human robot collaboration based on the level of human involvement in a shared environment i.e., Human in The Loop (HITL) and Human Out of The Loop (HOTL). The study concluded that humans showed increased level of trust when they were in the loop as compared to out of the loop. When a human experiences more control in a particular automated process which creates a trustworthy partnership with robots. When a human cannot predict the movements of a robot in a shared environment the level of trust in this human robot collaboration is less as compared to when a human is involved in the loop.

The level of Human-Robot Collaboration is also dependent on the level of comfort humans feel in sharing workspace with the robots. For example, now a days in the manufacturing industry and the medical sector, robots and humans share a common workspace [36]. However, this is not the case for the construction industry. Differing site conditions and uncontrolled environments limit the sharing of workspace between robots and humans. There is a safety fence that is generally installed between the robot and the human worker when both share a common workspace. An experiment was conducted to test the level of perceived safety in human workers when there is Human-Robot Collaboration [36]. This experiment was conducted in two virtual environments with varying levels of work separation between robots and humans. The results of this study indicate that perception of safety increased in human workers when the work areas between humans and robots were separated. Also, the study concluded that intention of the human to work with a robot increased with increased perceived safety.

Despite the numerous advantages offered by robots on project sites, there have been studies [37] that indicate that introducing robots and technology on site also introduces additional safety concerns. A literature review [37] was conducted to categorize the existing robotic technology in three categories which include wearable robots such as exoskeletons, remote operated robots which include drones, and on-site robot systems which include painting, and welding and brick laying robots. The safety hazards that are associated with each category of robot were summarized in this study using a survey followed by interview-based approach. Major safety concerns that were identified include unworkable combination of robot and PPE in case of wearable robots, mechanical part failure, and collisions in workplace for remote operated robots. Lack of trust, and unstable work platform/work area were major safety concerns identified for the case of autonomous robots. These safety risks also play an important role when selecting a suitable human-robot interaction. The study recommends doing future work in identifying different human-robot interaction types that will eliminate various safety risks.

## 3.6 Previous work on understanding the perception of construction industry

To ensure the success of adoption of robots in the construction industry, it is important to understand how humans and robots collaborate with each other in executing a particular task. A recent study by Kim et. al. examined perceptions of trade workers and managers working in the high rise residential construction in using construction robots performing qualitative content analysis [38]. This study compared the perceptions of stakeholders from structural engineering and architectural background towards adopting main task executing robots or assistive robots. According to the study, the group with architectural background was inclined towards adopting robots that were able to execute main tasks as compared to assistive tasks, and the group with structural background had the perception of adopting assistive robots. According to the study by Kim et. al., safety risk associated with using a robot influenced the desired level of autonomy of a robot [38]. Although the study findings offer significant insights, there were several limitations to it including the lack of actual experience of participants in the use of robots. Other than this, the participants were mainly from the residential construction industry, thus the findings of this study cannot be generalized to the construction industry. Also, this study focused on one human – one robot collaboration scenario and recommended future studies to compare perception based on other human robot collaboration scenarios.

A survey based study [39] was conducted to measure the willingness of adopting construction 4.0 technologies by the construction industry in South Africa. Construction 4.0, which is adopted from the concept of industry 4.0, includes adopting technology, smart construction, and virtualization in the construction projects. The results of this study indicate that the industry stakeholders have a willingness towards adoption of technologies. However, the possibility of integrating robotics in the construction industry was rated as not important by the stakeholders. The stakeholders gave importance to technologies that are already developed in the industry such as drones. Major barriers identified in adoption of construction 4.0 were high cost, industry's resistance to change and less knowledge of new technology. A major gap in this research was that it focused only on one specific province of South Africa and hence, the results cannot be generalized for the entire South African construction industry.

Another study [40] aimed to explore the perception of construction project managers in accepting robots as a teammate. The results of this study indicated that if a robot moved in a predictable way, looked durable and reliable, project managers were more likely to accept it as a teammate. This study utilized a survey-based approach and had 63 respondents. As a future scope, it was recommended to compare the perceptions of managers and field superintendents which will be covered in this study.

Based on the current literature available, there is a gap in understanding the perception of stakeholders of different segments of the US construction industry. This project aims to bridge the gap by exploring a survey-based approach to determine the perception of different stakeholders of the construction industry toward adopting robots in the project sites. The research of Human-Robot Collaboration is still in its embryonic stages in the construction industry [41]. The success of implementing human-robot collaborations in construction projects is highly dependent on how much trust various stakeholders have in the robots. The limitations of the experiment by You et al. [36] are that the participants did not have any construction experience and this experiment tested the level of comfort for one robot – one human level of collaboration. This research project aims to address these gaps by analyzing the perception of industry stakeholders in working with robots and understanding the level of comfort in different Human-Robot team scenarios.

# 4 METHODOLOGY

This research follows qualitative method of data collection by utilizing a questionnaire approach. A questionnaire was developed and circulated to various stakeholders of the construction industry. The initial part of the questionnaire collected information related to general awareness of participants about the use of robots in the construction projects and the type of tasks they would prefer a robot to perform in their project. In the next part of the questionnaire, participants were shown several types of robots that are currently being used in the construction industry and were asked to select the robots that they want to know more about. These robots were identified during the literature review phase of the research. The different robots and their applications are tabulated in the Table 1.

**Table 1: Summary of robots used in the construction industry**

| Sr. No. | Type of robot | Robot name and developer | Robot description |
|---|---|---|---|
| 1 | Excavator/Grader | Exosystem ™ - Built Robotics | The robot utilizes artificial intelligence technology to upgrade common construction excavation machinery into fully autonomous excavators that can be used to carry out tasks of excavation such as digging trenches, grading, laying underground utilities [42]. |
| 2 | Hauling Truck | HX2 autonomous - Volvo Construction Equipment | This autonomous hauling truck is still in its prototype stage. HX2 autonomous is a battery-operated robot that can be used for hauling the excavated earth in project sites and can help in reducing carbon emissions [43]. |
| 3 | Field Printer | Dusty - Dusty Robotics | This is a construction layout robot that uses Building Information Modelling (BIM) to print full-scale layouts on a construction surface autonomously and with precision [44]. |
| 4 | Block Laying Robot | Hadrian X® - FBR | This block laying robot can work autonomously in external environments with safety and accuracy. The robot uses a unique optimization software that minimizes the handling and waste of block products to improve the efficiency of blockwork [45]. |
| 5 | Painting Robot | PictoBot – Transforma | This is a semi-autonomous painting robot that can paint large sections of walls without significant human input. It uses a spray nozzle to paint quickly in the building interiors and at significant heights [46]. |
| 6 | Tunnel Investigation Robots | Robinspect – Robotnik | This robot is tele-operated and is used to inspect and evaluate the structural health of tunnels as well as ensures the safety of the operator [47] |
| 7 | Pipeline Investigation Robots | The PureRobotics® - Pure Technologies | This is a pipeline investigating robot which is a crawling robot with numerous sensors that help in checking any defects that exist inside the pipeline |

| Sr. No. | Type of robot | Robot name and developer | Robot description |
|---|---|---|---|
| | | | along with sending videos to the human operator [48]. |
| 8 | Grass Mowing Robots | Electric Sheep - Dexter Robot | This robot attaches to grass mowing machines and can mow autonomously. The robot uses light detection and ranging (LiDAR) to move across differing site conditions. The operator can monitor the robot from a remote location to ensure safety [49]. |
| 9 | Unmanned Aerial Vehicle | Phantom 4 RTK - DJI Enterprise | This is a tele-operated robot used for various purposes such as monitoring building progress, topographic mapping and analysis, soil analysis, surveying, digital mapping, inspections, physical construction, and 3D renderings [50]. |
| 10 | Exoskeleton | EXO-O1 - Hilti | This is an assistive robot used for reducing workplace injuries, decreasing medical fees, sick leave, and lawsuit costs; enhancing worker alertness, productivity, and quality of work; lowering worker fatigue; maintaining quality and skilled personnel in the workforce after they have reached their physical prime [51]. |
| 11 | Demolition Robots | Husqvarna DXR 140 - Husqvarna | This is a remote-controlled robot that is suitable for heavy demolition operations with a long reach as well as capable of maneuvering to different places [52]. |
| 12 | Rebar Tying Robots | TyBot - Advanced Construction Robotics | This is an autonomous reinforcement cage tying robot which is very useful in increasing the productivity of reinforcement tying activity as it can function in day and night [53]. |
| 13 | Project Progress Tracker | Doxel's lidar-equipped robot | This is a robot that can scan construction sites using LiDAR to monitor if everything that is installed is correct and as per the drawings [54]. |

## 4.1 Technology Acceptance Model

To ensure successful collaboration between humans and robots, it is important to analyze the factors that affect the perception of different stakeholders. This can be understood using a Technology Acceptance Model or TAM [55]. This model explains that the behavior to use a technology develops from the intention to use it. The intention to use is defined as a function of perceived usefulness and perceived ease of use of the technology. “Perceived usefulness” is defined as "the degree to which a person believes that using a particular system would enhance his or her job performance" whereas “perceived ease of use” is defined as "the degree to which a person believes that using a particular system would be free from effort” [55].

Historically, TAM was used to understand human – computer interaction. However, research by Bröhl et.al. [56] concluded that TAM can also be applied to human – robot collaboration with appropriate variations. This research aimed towards developing a Human Robot Collaboration Acceptance Model for the industrial/ manufacturing industry by following a survey-based approach. A total of 1,326 responses were taken from participants of four different countries – USA, China, Japan, and Germany. Correlation coefficients were calculated, and the technology acceptance model was generated. According to this study, perceived usefulness is strongly influenced by job relevance, perceived ease of use is influenced by anchor variables (perception of external control, self-efficacy) and adjustment variables (perceived safety, perceived enjoyment). The correlation coefficients between perceived usefulness, perceived ease of use, and behavioral intention to use reached medium to high levels showing the original TAM model is applicable to the domain of Human – Robot Collaboration. These similarities observed in this study between the results of TAM and the Human Robot Collaboration Acceptance Model imply that the basic assumption of TAM can be applied to topic of robotics in the manufacturing industry. This forms the basis of using TAM to develop an acceptance model for use of robots in the construction industry [56].

There have been studies that have proven the effectiveness of TAM in the construction industry; however, previous researchers have modified the existing TAM to better suit the construction robot adoption model as robots are significantly complicated as compared to other technologies [57]. These additions to the original TAM include "perceived job relevance" which can be defined as "the extent to which an individual believes the technology applies to his or her job" and "perceived output quality" which can be defined as "the extent to which an individual believes the technology will perform tasks well" [38]. Apart from the different TAM attributes that help in determining the development of intention to use a particular robot, the propensity to trust a new technology plays an equally important part in deciding whether the technology will be adopted or not. Lack of trust in robotics can lead to its failure in successful adoption in the construction industry [59]. Also, trust has a correlation with commitment, which is a significant predictor of the successful implementation of new technology [60].

## 4.2 Questionnaire

The questionnaire designed for this study can be divided into 4 parts. In the first part of the survey, details of the participant were collected such as the industry, position in the organization, scope of project. In the next part of the survey, general awareness of the participant related to robots in the construction industry was captured. In this part of the survey, the participant was given a prompt to select specific robot cases for which further questions will be asked in the third section.

For each robot case selected by the participant, different questions were asked related to understanding the perception of participants in terms of robot's usefulness, ease of use, relevance, and output quality. The next part of the questionnaire asked the level of human-robot collaboration the participant would prefer for a particular robot case. Based on the literature review, it was found that the classification available for human-robot collaborations is from the point of view of the robot. To understand the different levels of collaborations easily, a different scale of human-robot collaboration from the point of view of the human was developed and customized to be applicable for the construction industry. The different levels of human-robot collaboration are summarized in the Table 2.

**Table 2: Different levels of human-robot collaborations in the construction industry, modified from [34]**

| Sr. No | Level of human-robot collaboration | Description |
|---|---|---|
| 1 | Manual control | The human operates the machine, either directly or remotely with a controller. |
| 2 | Adaptive control | The robot adapts and executes the task as planned and assigned by the human based on site conditions. Human monitors and intervenes if needed. |
| 3 | Supervisory control | Human only supervises the task that is planned and executed by the robot. Human can intervene if needed, and robot learns from human intervention for future tasks. |
| 4 | Full autonomy | The robot plans and executes the task without any human involvement. |

Based on the level of human-robot collaboration selected by the participant, different factors influencing the decision were asked from the participant. From the literature review phase, top barriers and advantages offered by robots in construction were identified and are summarized in Table 3 and Table 4 respectively. In the questionnaire, the level of trust a participant has on the robot's ability to perform the task accurately based on the level of human-robot collaboration selected is determined by using a five-point Likert scale. At the end of the questionnaire, the participant's likelihood of using robots in the construction industry before and after covid-19 pandemic to mitigate shortage of workforce, working remotely, and maintaining social distance, is recorded.

**Table 3: Barriers to adoption of robotics in the construction industry**

| Sr. No | Description |
|---|---|
| 1 | Workforce is not skilled to work with robots as it is a complex technology |
| 2 | High Cost of implementation |
| 3 | Insufficient applicability due to uncertain site conditions |
| 4 | Job security of labor, workforce will be resistant to adopting the change |
| 5 | It is easy to work with labor as compared to robot |
| 6 | Robotic technology is still immature, not reliable and accurate, needs to develop further |
| 7 | Very few companies that manufacture robots |

**Table 4: Drivers for adoption of robotics in the construction industry**

| Sr. No | Description |
|---|---|
| 1 | Enhance worker's safety |
| 2 | Assist in monitoring and quality control |
| 3 | Save time by eliminating labor intensive procedures |
| 4 | Reduce costs and enhance profits |
| 5 | Improve accuracy of planning/design work, allow precise construction |
| 6 | Enable design freedom |

Approval for circulating the questionnaire to different stakeholders of the construction industry was taken from Texas A&M University's Institutional Review Board (IRB) as this research falls under human subject research.

## 4.3 Data Analysis Methodology

The collected data was analyzed to determine the key factors that influence adoption of robots in the construction industry. The most preferred cases of human-robot collaboration were determined based on different sectors of the construction industry. The perception differences of different stakeholders depending upon their role and position were analyzed. Metrics were developed to evaluate the effectiveness of adopting robots on a project depending upon the type of task to be executed. Finally, a decision-making framework that can be used by stakeholders in deciding tasks that should be executed by robots was developed.

Statistical measures of mean, median, and standard deviation were used to identify the preferred level of autonomy for each robot case, the factors that positively affect the adoption of robots, and the factors that are the current biggest barriers to robot adoption. For each robot case, the most preferred human robot collaboration environment, and the perceived level of comfort of the person and their team was compared. Further analysis was done to compare the perceptions of different stakeholders from different groups to identify differences based on age, years of experience, primary job role etc., if any.

# 5 ANALYSIS AND FINDINGS

## 5.1 Participant Description

The survey was distributed to more than 500 stakeholders in the construction industry. A total of 79 complete responses were recorded for the survey. 66% (52) of the participants are from the commercial industry, 23% (18) of participants are from industrial or transportation industry, 8% (6) belong to the residential industry, and 4% (3) belong to Academia.

31% (23) of participants are project engineers, 23% (17) are project managers/ assistant project managers, 13% (10) are the part of the top management which includes (VP, CEO, COO, CFO), 9% (7) of the participants are superintendents, 8% (6) are from the project controls background, 7% (5) of the participants are students/ interns, and 5% (4) of the participants are from the innovation/VDC (virtual design construction team.

## 5.2 General Awareness about Robots in the Construction Industry

In the case of commercial construction industry, the results indicate that 37% (19) are moderately aware about robots in the construction industry, whereas 21% (11) are very aware about the use of robots in the construction industry. In the case of industrial and transportation industry, 33% (6) are slightly aware, 50% (9) of the respondents are moderately aware, and 11% (2) are very aware about the use of robots in the industry.

Participants were asked to select the tasks that they would think will be executed by a robot on site. The tasks that received maximum response were layout (52), surveying (52), and loading and unloading of materials (52). Demolition activities received 45 responses and inspection activities received 45 responses. Excavation and Bricklaying received 39 and 38 responses respectively. The tasks that received lowest number of responses include painting (23), plastering (23), and welding (32). Apart from the given options, participants also suggested some other tasks that can be executed by robots. This includes glazing installation, framing layout, pre-pour checking, estimation, traffic control, and 3D Printing.

## 5.3 Developing a Decision-Making Framework for Adopting Robots

Based on the number of robot-specific cases selected by each stakeholder, it was found that the construction industry is most curious to know about drones (49 responses), construction layout robots (41 responses), and robotic excavators (40 responses). The robots that received the lowest response include mowing robots (25 responses), and painting robots (22 responses). The Likert scale of strongly agree to strongly disagree was converted into a 5-point scale with 1 corresponding to strongly agree and 5 corresponding to strongly disagree. The arithmetic mean was calculated to find the weighted average of perceived usefulness, perceived ease of use, perceived job relevance, and perceived output quality for each robot case. The results indicate that the layout robot is perceived to be the most useful robot (mean = 1.32) and the mowing robot is perceived to be the least useful robot (mean = 2.2) and is considered as least relevant on job sites (mean = 2.36). On the contrary, the construction industry considers mowing robots the easiest to use on a job site (mean = 2.24) and robotic excavators the most difficult to use on job sites (mean = 3.48). Drones are perceived to be the most relevant to be used on projects and the industry considers the output of using drones is of good quality (mean = 1.37). Robotic excavators are perceived by the industry to have the lowest output quality (mean = 2.33). Following sections discuss each robot case by case to understand the factors that impact the industry's perception in adopting robots on project sites.

### 5.3.1 Layout Robots

The total number of responses for layout robots was 41 as summarized in Table 5. A total of 98% stakeholders (40) consider layout robots to be useful on their project sites. Thus, the overall perceived usefulness of this robot is positive. 95% respondents (39) consider that layout robots are relevant to their projects and 90% (37) respondents consider that the robot will be able to perform the job with good output quality. Thus, the overall perceived job relevance and perceived output quality for this robot are positive.

However, only 54% of the stakeholders (22) consider that adopting layout robots on the projects will be free from effort. 32% (13) of stakeholders disagree that adopting this robot will be free of effort. Thus, the overall perceived ease of use for this robot is moderately positive. This means, to ensure a good adoption rate of layout robots, efforts need to be made in making this technology easier to use. Some of the major barriers identified in adopting layout robots are lack of skilled workforce in using complex technology and high cost of implementation (Table 7).

Table 6 summarizes the level of trust stakeholders have in adopting layout robots. 90% (37) of the stakeholders indicate that they trust the robot. Major factors contributing to this perception include robot assisting in monitoring and quality control, improve accuracy of planning/design work, and allow for precise construction (Table 7).

**Table 5 TAM Results Summary – Layout Robots**

| **TAM Question** | | **No. of Responses** | | | | |
|---|---|---|---|---|---|---|
| | | **Strongly agree** | **Somewhat agree** | **Neither agree nor disagree** | **Somewhat disagree** | **Strongly disagree** |
| Using this robot in my project will be useful in enhancing job performance | Perceived Usefulness | 29 | 11 | 1 | 0 | 0 |
| Using this robot in my project will be free of effort | Perceived Ease of Use | 6 | 16 | 6 | 8 | 5 |
| This robot is relevant to the job | Perceived Job Relevance | 28 | 11 | 1 | 1 | 0 |
| The robot will be able to perform the job well. | Perceived Output Quality | 22 | 15 | 4 | 0 | 0 |

**Table 6 Level of Trust - Layout Robots**

| Level of Trust | No. of Responses |
|---|---|
| I trust the robot completely; it will always execute the task accurately | 7 |
| I mostly trust the robot; it may make some errors while executing the task | 30 |
| I neither completely trust robots nor distrust them | 4 |
| I mostly distrust robots as robots may make considerable errors when they execute the task | 0 |
| I distrust robots as they make many errors when they execute the task | 0 |

**Table 7 Summary of Factors Affecting Technology Acceptance – Layout Robots**

| Positive | | Negative | |
|---|---|---|---|
| **Factor** | **No. of Responses** | **Factor** | **No. of Responses** |
| Assist in monitoring & quality control | 34 | Workforce is not skilled to work with robots as it is a complex technology | 1 |
| Improve accuracy of planning/design work | 32 | High Cost of implementation | 1 |
| Allow precise construction | 32 | | |
| Save time by eliminating labor intensive procedures | 31 | | |
| Reduce costs & enhance profits | 23 | | |
| Enhance worker's safety | 13 | | |
| Enable design freedom | 8 | | |
| Other | 1 | | |

### 5.3.2 Drones

The total number of responses for Drones is 49 as summarized in Table 8. 94% stakeholders (46) consider drones to be useful on their project sites. Thus, the overall perceived usefulness of this robot is positive. 98% of the respondents (48) consider that drones are relevant to their projects and 98% (48) of the respondents consider that the robot will be able to perform the job with good output quality. Thus, the overall perceived job relevance and perceived output quality for this robot are positive.

However, only 57% of the stakeholders (28) consider that adopting layout robots on the projects will be free from effort. 35% (17) of stakeholders disagree that adopting this robot will be free of effort. Thus, the overall perceived ease of use for this robot is moderately positive. This means, to ensure a good adoption rate of drones, efforts need to be made in making this technology easier to use. Some barriers identified in adopting the drones on project sites include high cost of implementation, limited applicability due to uncertain site conditions (Table 10). Some stakeholders also commented that “Need to work further with development and interaction, currently working on drone footage QC but not completely AI at this time”, “I work at an airport so we can only fly drones in specific places at specific times, thus drones would need to be human operated".

Table 9 summarizes the level of trust stakeholders have in adopting drones. 88% (43) of the stakeholders indicate that they trust the robot. Major factors contributing to this perception include robot assisting in monitoring and quality control, improve accuracy of planning/design work and allow for precise construction, and save time by eliminating labor intensive procedures (Table 10).

**Table 8 TAM Results Summary – Drones**

| **TAM Question** | | **No. of Responses** | | | | |
|---|---|---|---|---|---|---|
| | | **Strongly agree** | **Somewhat agree** | **Neither agree nor disagree** | **Somewhat disagree** | **Strongly disagree** |
| Using this robot in my project will be useful in enhancing job performance | Perceived Usefulness | 32 | 14 | 3 | 0 | 0 |
| Using this robot in my project will be free of effort | Perceived Ease of Use | 11 | 17 | 4 | 11 | 6 |
| This robot is relevant to the job | Perceived Job Relevance | 32 | 16 | 1 | 0 | 0 |
| The robot will be able to perform the job well. | Perceived Output Quality | 32 | 16 | 1 | 0 | 0 |

**Table 9 Level of Trust - Drones**

| **Level of Trust** | **No. of Responses** |
|---|---|
| I trust the robot completely; it will always execute the task accurately | 14 |
| I mostly trust the robot; it may make some errors while executing the task | 29 |
| I neither completely trust robots nor distrust them | 6 |
| I mostly distrust robots as robots may make considerable errors when they execute the task | 0 |
| I distrust robots as they make many errors when they execute the task | 0 |

**Table 10 Summary of Factors Affecting Technology Acceptance – Drones**

| **Positive** | | **Negative** | |
|---|---|---|---|
| **Factor** | **No. of Responses** | **Factor** | **No. of Responses** |
| Save time by eliminating labor intensive procedures | 25 | Workforce is not skilled to work with robots as it is a complex technology | 2 |
| Assist in monitoring & quality control | 37 | High Cost of implementation | 3 |
| Enhance worker's safety | 21 | Insufficient applicability due to uncertain site conditions | 3 |
| Reduce costs & enhance profits | 25 | Robotic technology is still immature, not reliable and accurate | 1 |
| Enable design freedom | 9 | Needs to develop further | 2 |
| Improve accuracy of planning/design work | 32 | Other | 4 |
| Allow precise construction | 32 | | |
| Other | 1 | | |

### 5.3.3 Painting Robots

The total number of responses for painting robots is 22 as summarized in Table 11. A total of 100% of stakeholders (22) consider painting robots to be useful on their project sites. Thus, the overall perceived usefulness of this robot is positive. 95% of the respondents (21) consider that painting robots are relevant to their projects and 82% (18) of the respondents consider that the robot will be able to perform the job with good output quality. Thus, the overall perceived job relevance and perceived output quality for this robot are positive.

However, only 55% of the stakeholders (12) consider that adopting painting robots on the projects will be free from effort. 27% (6) of stakeholders disagree that adopting this robot will be free of effort. Thus, the overall perceived ease of use for this robot is moderately positive. This means, to ensure a good adoption rate of painting robots, efforts need to be made in making this technology easier to use.

Table 12 summarizes the level of trust stakeholders have in adopting painting robots. 73% (6) of the stakeholders indicate that they trust the robot. 5% (1) of stakeholders do not trust the robots and believe that the robot will make errors while performing the task. Major factors contributing to this perception include robot assisting in monitoring and quality control, improve accuracy of planning/design work and allow for precise construction, and save time by eliminating labor intensive procedures (Table 13).

**Table 11 TAM Results Summary – Painting Robots**

| TAM Question | | No. of Responses | | | | |
|---|---|---|---|---|---|---|
| | | **Strongly agree** | **Somewhat agree** | **Neither agree nor disagree** | **Somewhat disagree** | **Strongly disagree** |
| Using this robot in my project will be useful in enhancing job performance | Perceived Usefulness | 12 | 10 | 0 | 0 | 0 |
| Using this robot in my project will be free of effort | Perceived Ease of Use | 5 | 7 | 4 | 4 | 2 |
| This robot is relevant to the job | Perceived Job Relevance | 14 | 7 | 0 | 1 | 0 |
| The robot will be able to perform the job well. | Perceived Output Quality | 9 | 9 | 4 | 0 | 0 |

**Table 12 Level of Trust – Painting Robots**

| Level of Trust | No. of Responses |
|---|---|
| I trust the robot completely; it will always execute the task accurately | 3 |
| I mostly trust the robot; it may make some errors while executing the task | 13 |
| I neither completely trust robots nor distrust them | 5 |
| I mostly distrust robots as robots may make considerable errors when they execute the task | 1 |
| I distrust robots as they make many errors when they execute the task | 0 |

**Table 13 Summary of Factors Affecting Technology Acceptance – Painting Robots**

| Positive | | Negative | |
|---|---|---|---|
| **Factor** | **No. of Responses** | **Factor** | **No. of Responses** |
| Save time by eliminating labor intensive procedures | 17 | Workforce is not skilled to work with robots as it is a complex technology | 0 |
| Assist in monitoring & quality control | 17 | High Cost of implementation | 0 |
| Enhance worker's safety | 12 | Insufficient applicability due to uncertain site conditions | 0 |
| Reduce costs & enhance profits | 13 | It is easy to work with labor as compared to robot | 0 |
| Enable design freedom | 4 | Very few companies that manufacture robots | 0 |
| Improve accuracy of planning/design work | 17 | Job security of labor | 0 |
| allow precise construction | 17 | Robotic technology is still immature | 0 |
| Other | 0 | Workforce will be resistant to adopting the change | 0 |

### *5.3.4* Demolition Robots

The total number of responses for demolition robots is 33 summarized in Table 14. A total of 85% of stakeholders (28) consider Demolition robots to be useful on their project sites. Thus, the overall perceived usefulness of this robot is positive. 79% of the respondents (26) consider that demolition robots are relevant to their projects and 82% (27) of the respondents consider that the robot will be able to perform the job with good output quality. Thus, the overall perceived job relevance and perceived output quality for this robot are positive.

However, only 52% of the stakeholders (17) consider that adopting Demolition robots on the projects will be free from effort. 21% (7) of stakeholders disagree that adopting this robot will be free of effort. Thus, the overall perceived ease of use for this robot is moderately positive. This means, to ensure a good adoption rate of demolition robots, efforts need to be made in making this technology easier to use. Some of the barriers identified in adopting the demolition robots on project sites include limited applicability due to uncertain site conditions, high cost of implementation etc. (Table 16). Some stakeholders also commented that “concerned with robot’s safety ability to adapt to changing conditions during demolition”, “the only issue is we have to use about 3 times more robots as many as we need because they break so frequently”, “don't see a way this robot could be autonomous without heavy human interface in the case of selective demolition”.

Table 15 summarizes the level of trust stakeholders have in adopting demolition robots. 58% (19) of the stakeholders indicate that they trust the robot. 9% (3) of stakeholders do not trust the robot and believe that the robot will make errors while performing the task. Major factors contributing to this perception include enhanced safety for workers, save time by eliminating labor intensive procedures, reduce costs & enhance profits (Table 16).

**Table 14 TAM Results Summary – Demolition Robots**

| **TAM Question** | | **No. of Responses** | | | | |
|---|---|---|---|---|---|---|
| | | **Strongly agree** | **Somewhat agree** | **Neither agree nor disagree** | **Somewhat disagree** | **Strongly disagree** |
| Using this robot in my project will be useful in enhancing job performance | Perceived Usefulness | 21 | 7 | 4 | 1 | 0 |
| Using this robot in my project will be free of effort | Perceived Ease of Use | 4 | 13 | 9 | 4 | 3 |
| This robot is relevant to the job | Perceived Job Relevance | 17 | 9 | 4 | 3 | 0 |
| The robot will be able to perform the job well. | Perceived Output Quality | 18 | 9 | 4 | 2 | 0 |

**Table 15 Level of Trust – Demolition Robots**

| **Level of Trust** | **No. of Responses** |
|---|---|
| I trust the robot completely; it will always execute the task accurately | 3 |
| I mostly trust the robot; it may make some errors while executing the task | 16 |
| I neither completely trust robots nor distrust them | 11 |
| I mostly distrust robots as robots may make considerable errors when they execute the task | 3 |
| I distrust robots as they make many errors when they execute the task | 0 |

**Table 16 Summary of Factors Affecting Technology Acceptance – Demolition Robots**

| **Positive** | | **Negative** | |
|---|---|---|---|
| **Factor** | **No. of Responses** | **Factor** | **No. of Responses** |
| Save time by eliminating labor intensive procedures | 21 | Workforce is not skilled to work with robots as it is a complex technology | 1 |
| Assist in monitoring & quality control | 10 | High Cost of implementation | 1 |
| Enhance worker's safety | 21 | Insufficient applicability due to uncertain site conditions | 5 |
| Reduce costs & enhance profits | 16 | It is easy to work with labor as compared to robot | 1 |
| Enable design freedom | 3 | Very few companies that manufacture robots | 1 |
| Improve accuracy of planning/design work | 12 | Job security of labor | 1 |
| allow precise construction | 12 | Not reliable and accurate, needs to develop further | 1 |
| Other | 1 | Other | 4 |

### 5.3.5 Rebar Tying Robots

The total number of responses for rebar-tying robots is 26 as summarized in Table 17. A total of 81% of stakeholders (21) consider rebar-tying robots to be useful on their project sites. Thus, the overall perceived usefulness of this robot is positive. 77% of the respondents (20) consider that rebar-tying robots are relevant to their projects and 85% (22) of the respondents consider that the robot will be able to perform the job with good output quality. Thus, the overall perceived job relevance and perceived output quality for this robot are positive.

However, only 62% of the stakeholders (16) consider that adopting rebar-tying robots on the projects will be free from effort. 23% (6) of stakeholders disagree that adopting this robot will be free of effort. Thus, the overall perceived ease of use for this robot is moderately positive. This means, to ensure a good adoption rate of rebar-tying robots, efforts need to be made in making this technology easier to use.

Table 18 summarizes the level of trust stakeholders have in adopting rebar tying robots. 81% (19) of the stakeholders indicate that they trust the robot. 4% (1) of stakeholders do not trust the robot and believe that the robot will make errors while performing the task. Major factors contributing to this perception include enhanced safety for workers, saves time by eliminating labor intensive procedures, and reduced costs & enhanced profits (Table 19).

**Table 17 TAM Results Summary – Rebar Tying Robots**

| TAM Question | | No. of Responses | | | | |
|---|---|---|---|---|---|---|
| | | **Strongly agree** | **Somewhat agree** | **Neither agree nor disagree** | **Somewhat disagree** | **Strongly disagree** |
| Using this robot in my project will be useful in enhancing job performance | Perceived Usefulness | 17 | 4 | 4 | 1 | 0 |
| Using this robot in my project will be free of effort | Perceived Ease of Use | 10 | 6 | 4 | 4 | 2 |
| This robot is relevant to the job | Perceived Job Relevance | 14 | 6 | 3 | 1 | 2 |
| The robot will be able to perform the job well. | Perceived Output Quality | 17 | 5 | 4 | 0 | 0 |

**Table 18 Level of Trust – Rebar Tying Robots**

| Level of Trust | No. of Responses |
|---|---|
| I trust the robot completely; it will always execute the task accurately | 10 |
| I mostly trust the robot; it may make some errors while executing the task | 12 |
| I neither completely trust robots nor distrust them | 4 |
| I mostly distrust robots as robots may make considerable errors when they execute the task | 1 |
| I distrust robots as they make many errors when they execute the task | 0 |

**Table 19 Summary of Factors Affecting Technology Acceptance – Rebar Tying Robots**

| Positive | | Negative | |
|---|---|---|---|
| **Factor** | **No. of Responses** | **Factor** | **No. of Responses** |
| Save time by eliminating labor intensive procedures | 26 | Workforce is not skilled to work with robots as it is a complex technology | 0 |
| Assist in monitoring & quality control | 18 | High Cost of implementation | 0 |
| Enhance worker's safety | 20 | Insufficient applicability due to uncertain site conditions | 0 |
| Reduce costs & enhance profits | 23 | It is easy to work with labor as compared to robot | 0 |
| Enable design freedom | 4 | Very few companies that manufacture robots | 0 |
| Improve accuracy of planning/design work | 17 | Job security of labor | 0 |
| allow precise construction | 17 | Robotic technology is still immature | 0 |
| Other | 0 | Workforce will be resistant to adopting the change | 0 |
| | | Not reliable and accurate | 0 |
| | | Needs to develop further | 0 |
| | | Other | 0 |

### 5.3.6 Block Laying Robots

The total number of responses for block-laying robots is 32 summarized in Table 20. A total of 88% of stakeholders (28) consider block-laying robots to be useful on their project sites. Thus, the overall perceived usefulness of this robot is positive. 88% of the respondents (28) consider that block-laying robots are relevant to their projects and 88% (28) of the respondents consider that the robot will be able to perform the job with good output quality. Thus, the overall perceived job relevance for this robot is positive.

However, only 34% of the stakeholders (11) consider that adopting block-laying robots on the projects will be free from effort. 47% (15) of stakeholders disagree that adopting this robot will be free of effort. Thus, the overall perceived ease of use for this robot is negative. This means, to ensure a good adoption rate of block-laying robots, efforts need to be made in making this technology easier to use. Some of the barriers identified in adopting the brick laying robots on project sites include limited applicability due to uncertain site conditions, and the robotic technology is still immature and needs to develop further (Table 22).

Table 21 summarizes the level of trust stakeholders have in adopting brick laying robots. 77% (24) of the stakeholders indicate that they trust the robot. Major factors contributing to this perception include saves time by eliminating labor intensive procedures, improvement in accuracy of planning/ design work, allows precise construction, and enhances workers safety (Table 21).

**Table 20 TAM Results Summary – Block Laying Robots**

| **TAM Question** | | **No. of Responses** | | | | |
|---|---|---|---|---|---|---|
| | | **Strongly agree** | **Somewhat agree** | **Neither agree nor disagree** | **Somewhat disagree** | **Strongly disagree** |
| Using this robot in my project will be useful in enhancing job performance | Perceived Usefulness | 11 | 17 | 3 | 0 | 1 |
| Using this robot in my project will be free of effort | Perceived Ease of Use | 2 | 9 | 6 | 11 | 4 |
| This robot is relevant to the job | Perceived Job Relevance | 11 | 17 | 2 | 1 | 1 |
| The robot will be able to perform the job well. | Perceived Output Quality | 18 | 10 | 4 | 0 | 0 |

**Table 21 Level of Trust – Block Laying Robots**

| **Level of Trust** | **No. of Responses** |
|---|---|
| I trust the robot completely; it will always execute the task accurately | 5 |
| I mostly trust the robot; it may make some errors while executing the task | 19 |
| I neither completely trust robots nor distrust them | 7 |
| I mostly distrust robots as robots may make considerable errors when they execute the task | 0 |
| I distrust robots as they make many errors when they execute the task | 0 |

**Table 22 Summary of Factors Affecting Technology Acceptance – Block Laying Robots**

| Positive | | Negative | |
|---|---|---|---|
| **Factor** | **No. of Responses** | **Factor** | **No. of Responses** |
| Save time by eliminating labor intensive procedures | 26 | High Cost of implementation | 1 |
| Assist in monitoring & quality control | 19 | Insufficient applicability due to uncertain site conditions | 2 |
| Enhance worker's safety | 19 | Robotic technology is still immature | 1 |
| Reduce costs & enhance profits | 19 | Not reliable and accurate | 1 |
| Enable design freedom | 6 | Needs to develop further | 2 |
| Improve accuracy of planning/design work | 23 | | |
| allow precise construction | 23 | | |

### 5.3.7 Monitoring Robots

The total number of responses for monitoring robots is 38 summarized in Table 23. A total of 84% of stakeholders (32) consider monitoring robots to be useful on their project sites and 14% (5) of them consider the opposite. Thus, the overall perceived usefulness of this robot is positive. 84% of the respondents (32) consider that monitoring robots are relevant to their projects and 82% (31) of the respondents consider that the robot will be able to perform the job with good output quality. Thus, the overall perceived job relevance and perceived output quality for this robot are positive.

However, only 58% of the stakeholders (22) consider that adopting monitoring robots on the projects will be free from effort. 37% (14) of stakeholders disagree that adopting this robot will be free of effort. Thus, the overall perceived ease of use for this robot is moderately positive. This means, to ensure a good adoption rate of monitoring robots, efforts need to be made in making this technology easier to use. Some of the barriers identified in adopting the monitoring robots on project sites include limited applicability due to uncertain site conditions, the robotic technology is still immature and needs to develop further, and workforce is not skilled to work with robots as it is a complex technology (Table 25).

Table 24 summarizes the level of trust stakeholders have in adopting monitoring robots. 84% (31) of the stakeholders indicate that they trust the robot. 8% (3) of stakeholders do not trust the robot and believe that the robot will make errors while performing the task. Major factors contributing to this perception include assisting in monitoring and quality control, saves time by eliminating labor intensive procedures, improvement in accuracy of planning/ design work, allows precise construction, and enhances workers safety (Table 25).

**Table 23 TAM Results Summary – Monitoring Robots**

| TAM Question | | No. of Responses | | | | |
|---|---|---|---|---|---|---|
| | | **Strongly agree** | **Somewhat agree** | **Neither agree nor disagree** | **Somewhat disagree** | **Strongly disagree** |
| Using this robot in my project will be useful in enhancing job performance | Perceived Usefulness | 16 | 16 | 1 | 4 | 1 |
| Using this robot in my project will be free of effort | Perceived Ease of Use | 8 | 14 | 2 | 11 | 3 |
| This robot is relevant to the job | Perceived Job Relevance | 20 | 12 | 1 | 4 | 1 |
| The robot will be able to perform the job well. | Perceived Output Quality | 21 | 10 | 5 | 1 | 1 |

**Table 24 Level of Trust – Monitoring Robots**

| Level of Trust | No. of Responses |
|---|---|
| I trust the robot completely; it will always execute the task accurately | 11 |
| I mostly trust the robot; it may make some errors while executing the task | 20 |
| I neither completely trust robots nor distrust them | 3 |
| I mostly distrust robots as robots may make considerable errors when they execute the task | 2 |
| I distrust robots as they make many errors when they execute the task | 1 |

**Table 25 Summary of Factors Affecting Technology Acceptance – Monitoring Robots**

| **Positive** | | **Negative** | |
|---|---|---|---|
| **Factor** | **No. of Responses** | **Factor** | No. of Responses |
| Save time by eliminating labor intensive procedures | 28 | Workforce is not skilled to work with robots as it is a complex technology | 1 |
| Assist in monitoring & quality control | 30 | High Cost of implementation | 1 |
| Enhance worker's safety | 11 | Insufficient applicability due to uncertain site conditions | 2 |
| Reduce costs & enhance profits | 19 | Not reliable and accurate | 1 |
| Enable design freedom | 6 | Needs to develop further | 1 |
| Improve accuracy of planning/design work | 23 | | |
| Allow precise construction | 23 | | |

### 5.3.8 Inspection Robots

The total number of responses for inspection robots is 34 summarized in Table 26. A total of 71% of stakeholders (24) consider inspection robots to be useful on their project sites. Thus, the overall perceived usefulness of this robot is positive. 95% of the respondents (23) consider that inspection robots are relevant to their projects and 82% (25) of the respondents consider that the robot will be able to perform the job with good output quality. However, 15% (5) of the respondents consider that the robot is not relevant to the job. Thus, the overall perceived job relevance and perceived output quality for this robot are moderately positive.

However, only 55% of the stakeholders (15) consider that adopting inspection robots on the projects will be free from effort. 27% (12) of stakeholders disagree that adopting this robot will be free of effort. Thus, the overall perceived ease of use for this robot is moderately positive. This means, to ensure a good adoption rate of inspection robots, efforts need to be made in making this technology easier to use. Some of the barriers identified in adopting the inspection robots on project sites include limited applicability due to uncertain site conditions, and workforce is not skilled to work with robots as it is a complex technology (Table 28).

Table 27 summarizes the level of trust stakeholders have in adopting inspection robots. 75% (24) of the stakeholders indicate that they trust the robot. 3% (1) of stakeholders do not trust the robot and believe that the robot will make errors while performing the task. Major factors contributing to this perception include assisting in monitoring and quality control, saves time by eliminating labor intensive procedures, reduces costs, and enhances profits and workers safety (Table 28). Some other responses received are “robot eliminates the element of subjectivity of human inspection”, “robot is capable to scan and detect beyond what human eyes are capable of”, and “improved QA/QC over human limitations and reduced errors”.

**Table 26 TAM Results Summary – Inspection Robots**

| **TAM Question** | | **No. of Responses** | | | | |
|---|---|---|---|---|---|---|
| | | **Strongly agree** | **Somewhat agree** | **Neither agree nor disagree** | **Somewhat disagree** | **Strongly disagree** |
| Using this robot in my project will be useful in enhancing job performance | Perceived Usefulness | 12 | 12 | 10 | 0 | 0 |
| Using this robot in my project will be free of effort | Perceived Ease of Use | 4 | 11 | 7 | 10 | 2 |
| This robot is relevant to the job | Perceived Job Relevance | 11 | 12 | 6 | 2 | 3 |
| The robot will be able to perform the job well. | Perceived Output Quality | 14 | 11 | 7 | 1 | 1 |

**Table 27 Level of Trust – Inspection Robots**

| **Level of Trust** | **No. of Responses** |
|---|---|
| I trust the robot completely; it will always execute the task accurately | 4 |
| I mostly trust the robot; it may make some errors while executing the task | 20 |
| I neither completely trust robots nor distrust them | 7 |
| I mostly distrust robots as robots may make considerable errors when they execute the task | 0 |
| I distrust robots as they make many errors when they execute the task | 1 |

**Table 28 Summary of Factors Affecting Technology Acceptance – Inspection Robots**

| **Positive** | | **Negative** | |
|---|---|---|---|
| **Factor** | **No. of Responses** | **Factor** | **No. of Responses** |
| Save time by eliminating labor intensive procedures | 27 | Workforce is not skilled to work with robots as it is a complex technology | 1 |
| Assist in monitoring & quality control | 29 | Insufficient applicability due to uncertain site conditions | 1 |
| Enhance worker's safety | 15 | | |
| Reduce costs & enhance profits | 23 | | |
| Enable design freedom | 4 | | |
| Improve accuracy of planning/design work | 20 | | |
| Allow precise construction | 20 | | |
| Other | 3 | | |

### 5.3.9 Robotic Excavators

The total number of responses for robotic excavators is 40 summarized in Table 29. A total of 70% of stakeholders (28) consider robotic excavators to be useful on their project sites. Thus, the overall perceived usefulness of this robot is positive. 73% of the respondents (29) consider that robotic excavators are relevant to their projects. Thus, the overall perceived job relevance for this robot is positive.

However, only 28% of the stakeholders (11) consider that adopting robotic excavators on the projects will be free from effort. 55% (22) of stakeholders disagree that adopting this robot will be free of effort. Thus, the overall perceived ease of use for this robot is negative. Also, 55% (22) of the respondents consider that the robot will be able to perform the job with good output quality. Thus, the perceived output quality for this robot is moderately positive. This means, to ensure a good adoption rate of robotic excavators, efforts need to be made in making this technology easier to use and work needs to be done to improve the quality of work performed by the robotic excavator. Some of the barriers identified in adopting the robotic excavators on project sites include limited applicability due to uncertain site conditions, and currently there are very few companies that manufacture this robot (Table 31).

Table 30 summarizes the level of trust stakeholders have in adopting robotic excavators. 56% (23) of the stakeholders indicate that they trust the robot. 10% (4) of stakeholders do not trust the robot and believe that the robot will make errors while performing the task. Major factors contributing to this perception include assisting in monitoring and quality control, saves time by eliminating labor intensive procedures, reduces costs, enhances profits, improves accuracy of planning/design work, and enhances workers safety (Table 31).

**Table 29 TAM Results Summary – Robotic Excavator**

| **TAM Question** | | **No. of Responses** | | | | |
|---|---|---|---|---|---|---|
| | | **Strongly agree** | **Somewhat agree** | **Neither agree nor disagree** | **Somewhat disagree** | **Strongly disagree** |
| Using this robot in my project will be useful in enhancing job performance | Perceived Usefulness | 13 | 15 | 7 | 3 | 2 |
| Using this robot in my project will be free of effort | Perceived Ease of Use | 2 | 9 | 7 | 12 | 10 |
| This robot is relevant to the job | Perceived Job Relevance | 14 | 15 | 7 | 3 | 1 |
| The robot will be able to perform the job well. | Perceived Output Quality | 8 | 14 | 15 | 3 | 0 |

**Table 30 Level of Trust – Robotic Excavator**

| **Level of Trust** | **No. of Responses** |
|---|---|
| I trust the robot completely; it will always execute the task accurately | 3 |
| I mostly trust the robot; it may make some errors while executing the task | 20 |
| I neither completely trust robots nor distrust them | 14 |
| I mostly distrust robots as robots may make considerable errors when they execute the task | 4 |
| I distrust robots as they make many errors when they execute the task | 0 |

**Table 31 Summary of Factors Affecting Technology Acceptance – Robotic Excavator**

| Positive | | Negative | |
|---|---|---|---|
| **Factor** | **No. of Responses** | **Factor** | **No. of Responses** |
| Save time by eliminating labor intensive procedures | 32 | Insufficient applicability due to uncertain site conditions | 1 |
| Assist in monitoring & quality control | 26 | Very few companies that manufacture robots | 1 |
| Enhance worker's safety | 23 | | |
| Reduce costs & enhance profits | 24 | | |
| Enable design freedom | 7 | | |
| Improve accuracy of planning/design work | 24 | | |
| Allow precise construction | 24 | | |
| Other | 1 | | |

### 5.3.10 Mowing Robots

The total number of responses for mowing robots is 25 summarized in Table 32. A total of 88% (22) of respondents consider that the robot will be able to perform the job with good output quality. Thus, the overall perceived output quality for this robot is positive.

However, only 60% of the stakeholders (15) consider that adopting mowing robots on the projects will be useful and 64% (16) feel that mowing robots are relevant to their project and adopting it will be free from effort. 24% (5) of stakeholders disagree that adopting this robot will be free of effort. Thus, the overall perceived usefulness, ease of use, and perceived job relevance for this robot are moderately positive. This means, to ensure a good adoption rate of mowing robots, efforts need to be made in making this technology easier to use and the robots should be developed to be more project specific.

Table 33 summarizes the level of trust stakeholders have in adopting mowing robots. 88% (21) of the stakeholders indicate that they trust the robot. Major factors contributing to this perception include enhanced safety for workers, saves time by eliminating labor intensive procedures, and reduces costs & enhances profits (Table 34).

**Table 32 TAM Results Summary – Mowing Robots**

| TAM Question | | No. of Responses | | | | |
|---|---|---|---|---|---|---|
| | | **Strongly agree** | **Somewhat agree** | **Neither agree nor disagree** | **Somewhat disagree** | **Strongly disagree** |
| Using this robot in my project will be useful in enhancing job performance | Perceived Usefulness | 12 | 3 | 5 | 3 | 2 |
| Using this robot in my project will be free of effort | Perceived Ease of Use | 8 | 8 | 4 | 5 | 0 |
| This robot is relevant to the job | Perceived Job Relevance | 11 | 5 | 3 | 1 | 5 |
| The robot will be able to perform the job well. | Perceived Output Quality | 14 | 8 | 2 | 1 | 0 |

**Table 33 Level of Trust – Mowing Robots**

| Level of Trust | No. of Responses |
|---|---|
| I trust the robot completely; it will always execute the task accurately | 9 |
| I mostly trust the robot; it may make some errors while executing the task | 12 |
| I neither completely trust robots nor distrust them | 3 |
| I mostly distrust robots as robots may make considerable errors when they execute the task | 0 |
| I distrust robots as they make many errors when they execute the task | 0 |

**Table 34 Summary of Factors Affecting Technology Acceptance – Mowing Robots**

| Positive | | Negative | |
|---|---|---|---|
| **Factor** | **No. of Responses** | **Factor** | **No. of Responses** |
| Save time by eliminating labor intensive procedures | 20 | Workforce is not skilled to work with robots as it is a complex technology | 0 |
| Assist in monitoring & quality control | 9 | High Cost of implementation | 0 |
| Enhance worker's safety | 11 | Insufficient applicability due to uncertain site conditions | 0 |
| Reduce costs & enhance profits | 17 | It is easy to work with labor as compared to robot | 0 |
| Enable design freedom | 4 | Very few companies that manufacture robots | 0 |
| Improve accuracy of planning/design work | 6 | Job security of labor | 0 |
| allow precise construction | 6 | Robotic technology is still immature | 0 |
| Other | 1 | Workforce will be resistant to adopting the change | 0 |

### 5.3.11 Exoskeleton

The total number of responses for exoskeletons is 28. A total of 82% of stakeholders (23) consider exoskeletons to be useful on their project sites. Thus, the overall perceived usefulness of this robot is positive. 89% of the respondents (25) consider that exoskeletons are relevant to their projects and 71% (20) of the respondents consider that the robot will be able to perform the job with good output quality. Thus, the overall perceived job relevance for this robot is positive.

However, only 61% of the stakeholders (17) consider that adopting an exoskeleton on the projects will be free from effort. 32% (9) of stakeholders disagree that adopting this robot will be free of effort. Thus, the overall perceived ease of use for this robot is moderately positive. This means, to ensure a good adoption rate of exoskeletons, efforts need to be made in making this technology easier to use.

**Table 35 TAM Results Summary – Exoskeleton**

| TAM Question | | No. of Responses | | | | |
|---|---|---|---|---|---|---|
| | | **Strongly agree** | **Somewhat agree** | **Neither agree nor disagree** | **Somewhat disagree** | **Strongly disagree** |
| Using this robot in my project will be useful in enhancing job performance | Perceived Usefulness | 13 | 10 | 3 | 2 | 0 |
| Using this robot in my project will be free of effort | Perceived Ease of Use | 8 | 9 | 2 | 6 | 3 |
| This robot is relevant to the job | Perceived Job Relevance | 16 | 9 | 2 | 0 | 1 |
| The robot will be able to perform the job well. | Perceived Output Quality | 14 | 6 | 5 | 2 | 1 |

## 5.4 Level of Autonomy

In the case of Monitoring robots, maximum number of participants (59.5%) preferred supervisory control over the robot. The least preferred level of autonomy for the robot is adaptive and manual control (5.4%). Thus, it can be inferred that most of the stakeholders trust the robot to perform tasks independently.

In the case of Rebar Tying robots, maximum number of participants (42.3%) preferred supervisory control over the robot. The least preferred level of autonomy for the robot is manual control (0%). Thus, it can be inferred that most of the stakeholders trust the robot to perform tasks independently.

For Demolition robots, maximum number of participants (46.9%) preferred adaptive control over the robot. The least preferred level of autonomy for the robot is full autonomy (0%). Thus, it can be inferred that most stakeholders do not trust the robot to perform tasks independently due to the unpredictable nature of excavation works.

For Mowing robots, maximum number of participants (45.8%) preferred full autonomy over the robot. The least preferred level of autonomy for the robot is manual control (0%). Thus, it can be inferred that most of the stakeholders trust the robot to perform tasks independently.

In the case of Inspection robots, maximum number of participants (42.4%) preferred supervisory control over the robot. The least preferred level of autonomy for the robot is manual control (3%). Thus, it can be inferred that mostly the stakeholders trust the robot to perform tasks independently.

In the case of Painting robots, maximum number of participants (42.9%) preferred supervisory control over the robot. The least preferred level of autonomy for the robot is manual control (0%). Thus, it can be inferred that mostly the stakeholders trust the robot to perform tasks independently.

In the case of Brick Laying robots, maximum number of participants (61.3%) preferred supervisory control over the robot. The least preferred level of autonomy for the robot is full autonomy (3.2%). Thus, it can be inferred that mostly the stakeholders trust the robot to perform tasks independently. However, there is low trust on the robot to perform the task well without human involvement.

For Layout robots, maximum number of participants (60%) preferred supervisory control over the robot. The least preferred level of autonomy for the robot is manual control (2.5%). Thus, it can be inferred that mostly the stakeholders trust the robot to perform tasks independently.

For Drones, maximum number of participants (36.2%) preferred adaptive control over the robot. The least preferred level of autonomy for the robot is full autonomy (12.8%). Thus, it can be inferred that mostly the stakeholders trust the robot to perform tasks with the involvement of a human. There is low trust on this robot to perform the tasks independently.

In the case of Robotic Excavators, maximum number of participants (50%) preferred adaptive control over the robot. The least preferred level of autonomy for the robot is full autonomy (0%). Thus, it can be inferred that mostly the stakeholders trust the robot to perform tasks with the involvement of a human. There is low trust on this robot to perform the tasks independently.

**Table 36 Level of Autonomy**

| **Robot Type** | **Manual Control** | **Adaptive Control** | **Supervisory Control** | **Full Autonomy** |
|---|---|---|---|---|
| Robotic Excavator | 2 | 20 | 18 | 0 |
| Layout Robot | 1 | 9 | 24 | 6 |
| Block Laying Robot | 2 | 9 | 19 | 1 |
| Painting Robot | 0 | 8 | 9 | 4 |
| Inspection Robot | 1 | 8 | 14 | 10 |
| Grass Mowing Robot | 0 | 3 | 10 | 11 |
| Drones | 8 | 17 | 16 | 6 |
| Demolition Robots | 10 | 15 | 7 | 0 |
| Rebar Tying Robots | 0 | 8 | 11 | 7 |
| Project Monitoring Robots | 2 | 2 | 22 | 11 |

## 5.5 Decision Making Flowchart

Figure 2 shows the decision-making flowchart developed for this study to decide whether to adopt a robot for a particular task. Once a task is selected to be robotized, the perception of various stakeholders in adopting the robots is measured using the technology acceptance model (TAM) shown in Figure 1. The results of TAM are discussed in section 6.3.

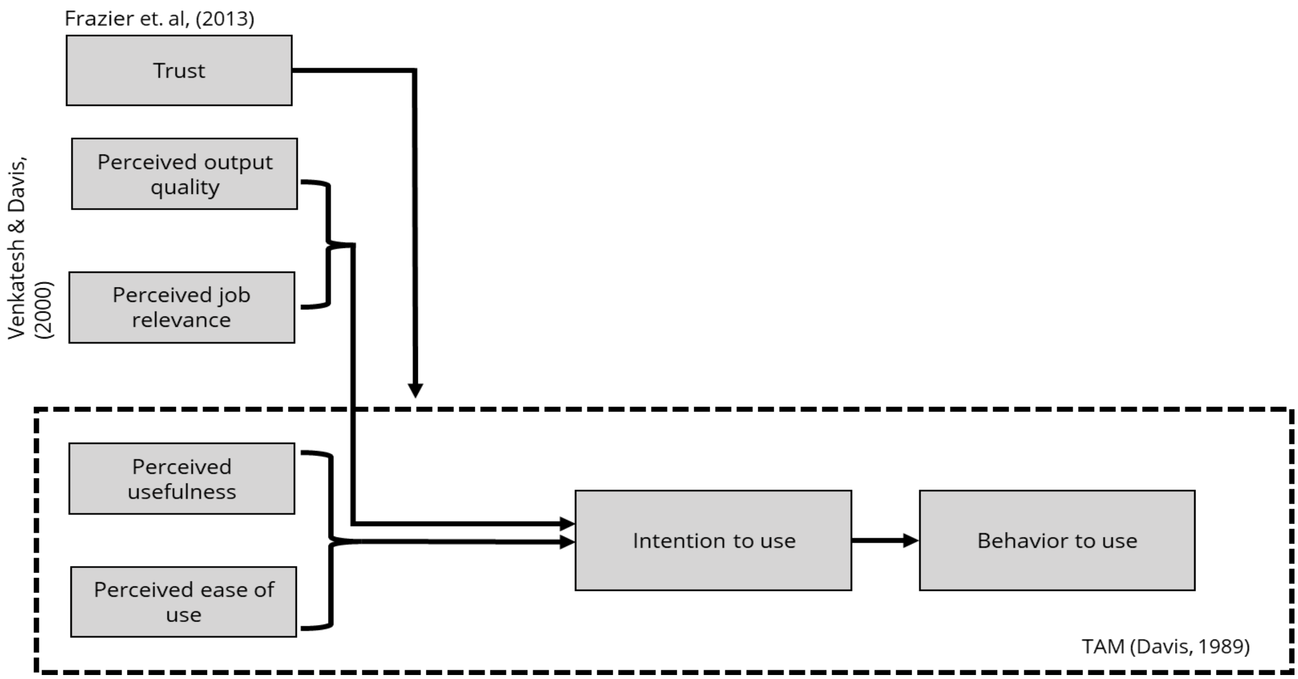


**Figure 1 Technology Acceptance Model**

If the results of TAM indicate that the overall perception to use the technology is positive, the next step is to identify the key factors that impact the adoption of robots. As described in section 2.3, the factors can be organizational factors like low research and development investment by the company towards automation and robotics [7], lack of technology culture in the company [24], and lack of long-term vision and top management support for the adoption of robots [6], [29]. Project specific factors include  complex nature of the project , lack of skill in understanding the application of robotics [7], and technological factors like accuracy of robots [24].

Depending upon the factors, the next decision is to select the level of robot autonomy and the level of Human-Robot Collaboration for the task. Table 36 provides the different levels of robot autonomy selected by participants for each robot specific case. Table 37 provides the different levels of human-robot collaboration selected by the participants for each robot case. It is seen that most of the stakeholders prefer one human – robot team type of collaboration. However, in the case of demolition robots, the most preferred type of collaboration is one human – one robot type.

Table 38 summarizes the median results of the data collected for the level of robot autonomy and the type of human robot collaboration. Once this combination is finalized, the next step is to conduct a pilot case study to test the performance of the human-robot team. If the results of the pilot study indicate a better performance of the human robot team when compared with a traditional human team, a decision can be made to adopt the robot on a large scale. If the results do not indicate better performance, then the human robot collaboration needs to be modified for the next pilot test. In this way, the best combination of the human-robot team can be selected.

**Table 37 Human-Robot Team**

| Robot Type | One Human - One Robot | One Human - Robot Team | Human Team - One Robot | Human Team - Robot Team |
|---|---|---|---|---|
| Robotic Excavator | 7 | 12 | 8 | 12 |
| Layout Robot | 8 | 20 | 7 | 4 |
| Block Laying Robot | 5 | 7 | 9 | 8 |
| Painting Robot | 5 | 9 | 3 | 4 |
| Inspection Robot | 9 | 9 | 4 | 10 |
| Grass Mowing Robot | 7 | 15 | 0 | 2 |
| Drones | 19 | 14 | 2 | 5 |
| Demolition Robots | 12 | 3 | 5 | 2 |
| Rebar Tying Robots | 7 | 13 | 3 | 3 |
| Project Monitoring Robots | 11 | 18 | 4 | 1 |

**Table 38 Median results for Level of Autonomy and Human-Robot Team**

| Robot Case | Median Result of the of Level of Autonomy | Median Result of Human-Robot Team |
|---|---|---|
| Robotic Excavator | Adaptive Control | Human Team - One Robot |
| Layout Robot | Supervisory Control | One Human - Robot Team |
| Block Laying Robot | Supervisory Control | Human Team - One Robot |
| Painting Robot | Supervisory Control | One Human - Robot Team |
| Inspection Robot | Supervisory Control | One Human - Robot Team |
| Grass Mowing Robot | Supervisory Control | One Human - Robot Team |
| Drones | Adaptive Control | One Human - Robot Team |
| Demolition Robots | Adaptive Control | One Human - One Robot |
| Rebar Tying Robots | Supervisory Control | One Human - Robot Team |
| Project Monitoring Robots | Supervisory Control | One Human - Robot Team |

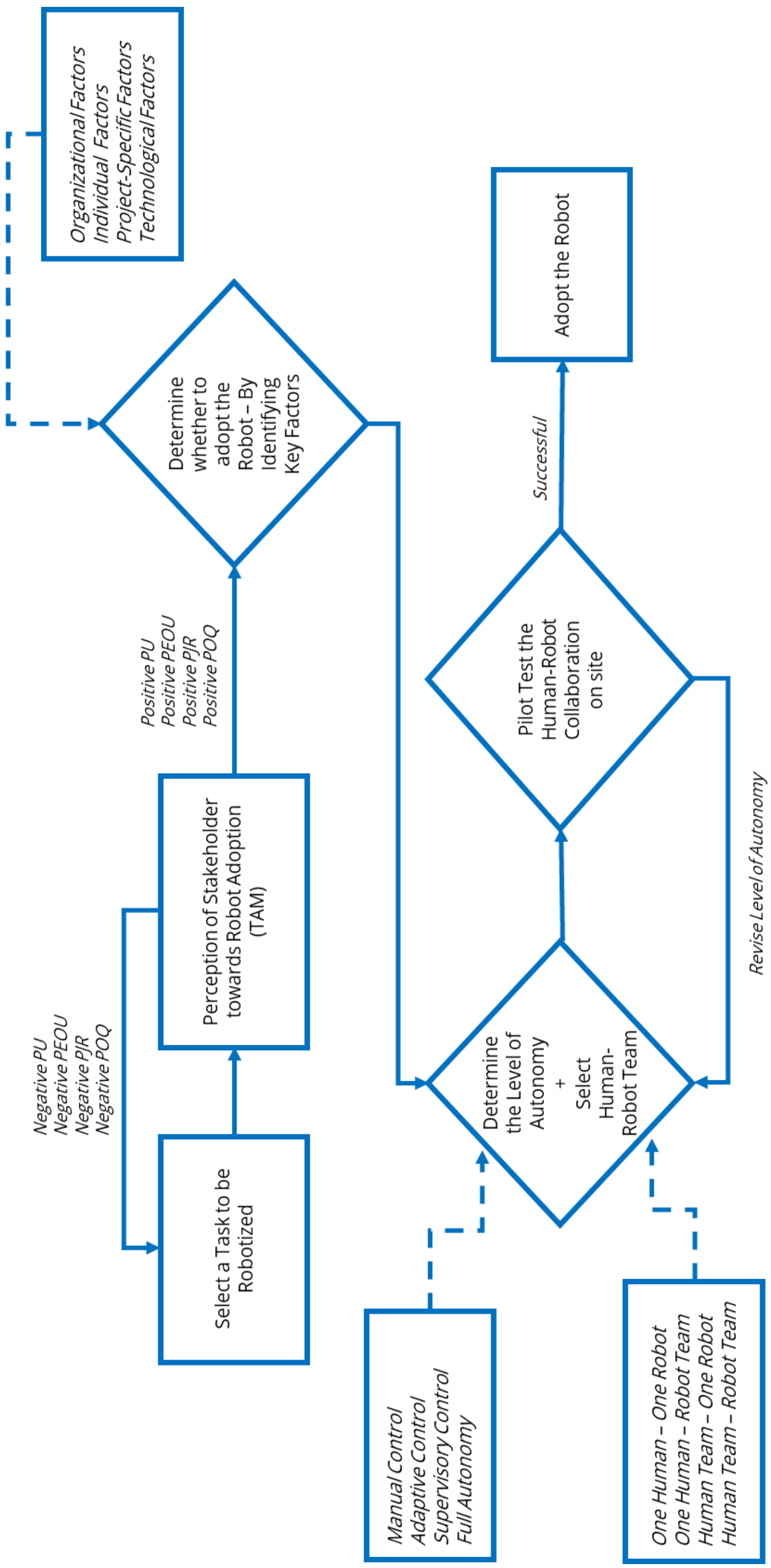


**Figure 2 Decision Making Framework Flowchart**

### 5.5.1 Example Case for Decision Making

To make the results of this study applicable to industry practitioners, an example scenario is provided below to illustrate the use of decision-making framework in practice. The decision-making framework will be refined further during the implementation phase.

Consider a midsize construction project with a scope of foundation, core and shell, waterproofing, finishes, façade, MEP, and landscape. The project manager of the project thinks about using a field printer for marking the layout of the drywall in the project. The project manager needs to follow certain steps to make a decision on adopting a field printer on site.

As per the results of the Technology Acceptance Model for field printer discussed in section 6.3.1, the perceived usefulness, perceived job relevance, and perceived output quality for the robot is very high. However, the perceived ease of use is medium. This means that efforts need to be made for making this technology easy to use. For example, this robot will require a BIM model as its input for doing the layout. Thus, a VDC engineer will be required on the project to make and update the project model.

The next step is to identify the key factors that will impact the robot adoption. As per the results shown in 5.3.1, the major factors that will impact the adoption of layout robots include “high cost of implementation” and “skill of workforce in using complex technology”. These barriers can be mitigated by conducting training for the project team in using this robot. The project manager will have to perform a cost benefit analysis to check if the use of robot will generate savings in terms of schedule or cost as compared to the investment made in the robot and training. If the results of the analysis are positive, the next step is to select the level of robot autonomy and human-robot team.

According to results in Table 38, for layout robots, the level of human-robot collaboration selected is supervisory control which means the robot will do all the work as defined by the human and the human will only supervise the work of the robot. Depending upon the scope of the layout work, the project manager selects one human-robot team type of collaboration. Once the team is selected, a pilot study needs to be done on site to compare the efficiency of layout done by a normal human team and a human-robot team. If the results of pilot study indicate better performance of the human-robot team, then the decision to adopt the robot should be made. If not, then the level of robot autonomy and the human-robot team should be revised, and the pilot should be conducted again.

# 6 CONCLUSIONS

Despite the developments in the field of construction robots, their adoption in projects have been limited. This project aimed to find a reason for the lack of awareness about different construction robots amongst different stakeholders of the construction industry. This project contributes to the knowledge base of the perception that different stakeholders have about the use of robots in the construction industry. Knowing the advantages offered by robots in terms of reducing the human effort in executing tasks, enhanced safety, and better-quality control, it is important that we implement robots in construction projects. This project helped identify the barriers that impact the adoption of a robot in a construction project. It helps in knowing more about the areas that the industry should focus on to ensure adoption of this technology and increase the trust humans have on robots.

The findings of the project can also be used by robot manufacturers in determining the needs of different stakeholders across different sectors of the construction industry and develop specific robots. The desired level of human-robot interaction can be used as a guide by the robot manufacturers in designing the shared construction work environment between the human and the robot. The research used a survey to collect relevant data from various construction industry stakeholders for 11 specific types of robots that were applicable to the construction industry. While perception towards individual types of robots are presented in the analysis and findings section, the main findings from this study are that there was a generally positive perception of different types of robots regarding their job relevance, ease of use, output quality, and usefulness. Furthermore, from a human-robot collaboration perspective, majority of respondents supported shared autonomy between human and robot in different scenarios. This highlights the need for developing more robots that share control with the human when executing construction tasks.

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# 8 APPENDIX A: Survey Questionnaire

Q1 **Title of Research Study: Development of Robotics & Automation Roadmap for Construction Projects**

Investigator: Principal Investigator – Dr. Ashrant Aryal (Assistant Professor, Department of Construction Science, Texas A&M University)

Funded by - The Transportation Consortium of South-Central States (Tran-SET)

**Why am I being asked to take part in this research study?** You are invited to participate in this study because we are trying to learn more about the perception of the construction industry's stakeholders regarding the use of robots in project sites. You were selected as a possible participant in this study because you are a part of the construction industry. You must be 18 years of age or older to participate. Additionally, you should meet at least one of the following criteria to participate in this survey.

1) Currently employed in a construction or related company

2) Past work/internship experience in construction or related company lasting at least one month.

3) Current or former student in a construction-related program at the undergraduate or higher level

**Why is this research being done?** The goal of this survey is to understand the perception of different stakeholders in the construction industry towards construction robots.

**How long will the research last?** This is a one-time survey. It will take about 20-25 minutes to complete the survey in one sitting. You may complete the survey in multiple sittings. However, it is recommended that you try and complete the survey in one sitting.

**What happens if I say "Yes, I want to be in this research"?** If you decide to participate, please do the following:

·You will have to answer a survey which will take approximately 20-25 minutes to complete.

·Please ensure that you answer all the questions with certainty in your mind. Avoid randomly selecting any options.

**What happens if I do not want to be in this research?** Your participation in this study is voluntary. You can decide not to participate in this research, and it will not be held against you. You can leave the study at any time.

**Is there any way being in this study could harm me?** There are no sensitive questions in this survey that should cause discomfort. However, you can skip any question you do not wish to answer or exit the survey at any point.

**What happens to the information collected for the research?** You may view the survey host's confidentiality policy at: https://www.qualtrics.com/privacy-statement/. Your email address or other contact information will be stored separately from your survey data. Providing your contact information is optional if you wish to be contacted for the second phase of the project that will involve interviews. All identifiable information will be kept on a password protected computer and is only accessible by the research team. Compliance offices at Texas A&M may be given access to the study files upon request. Your information will be kept confidential to the extent allowed by law. The results of the research study may be published but your identity will remain confidential.

**Who can I talk to?** Please feel free to ask questions regarding this study. If you have additional questions or concerns, you can contact –

· Chintan Vora, cvora@tamu.edu (979-326-8285).

· Dr. Ashrant Aryal, ashrantaryal@tamu.edu (979-848-7000).

You may also contact the Human Research Protection Program at Texas A&M University (which is a group of people who review the research to protect your rights) by phone at 1-979-458-4067, toll free at 1-855-795-8636, or by email at irb@tamu.edu for:

· additional help with any questions about the research

· voicing concerns or complaints about the research

· obtaining answers to questions about your rights as a research participant

· concerns in the event the research staff could not be reached

· the desire to talk to someone other than the research staff

If you want a copy of this consent for your records, you can print it from the screen.

➢ If you wish to participate, please click the "I Agree" button and you will be taken to the survey.

➢ If you do not wish to participate in this study, please select "I Disagree" or select X in the corner of your browser.

IRB NUMBER: IRB2022-0161

IRB APPROVAL DATE: 03/25/2022

- o Yes, I consent
- o No, I do not consent

Q2 Select the Industry you are currently working in

- o Commercial
- o Residential
- o Transportation
- o Heavy Civil/ Infrastructure (other than transportation)
- o Other ________________________________________________

Q3 What is the role that you currently handle in your project or organization

- Part of Top Management (VP/CEO/COO/CFO)
- Project Manager / Assistant Project Manager
- Superintendent
- Project Engineer
- Foreman
- Trade/Craftsman
- Estimator
- Project Controls
- Architect/ Designer
- Other ________________________________________________

Q4 How many years of experience do you have in the above selected construction industry

- 1-5 years
- 5-10 years
- 10-20 years
- More than 20 years

Q5 Please enter the location of your project site

City ________________________________________________

State ________________________________________________

Q6 Please answer the below demographic information related questions -

Select your gender

- Male
- Female
- Non-binary / third gender
- Prefer not to say

Q7 Please select your ethnicity

- ○ White
- ○ Black or African American
- ○ American Indian or Alaska Native
- ○ Asian
- ○ Native Hawaiian or Pacific Islander
- ○ Other ________________________________________________

Q8 Please select your level of education

- ○ Less than high school
- ○ High school graduate
- ○ Some college
- ○ 2-year degree
- ○ 4-year degree
- ○ Professional degree
- ○ Doctorate

Q9 Select the options that closely match with the scope of your project. (you can select multiple options)

- ☐ Typical Concrete & Steel
- ☐ Finishing - Exterior or Interior
- ☐ Waterproofing
- ☐ Roads, Highway & its accessories
- ☐ Bridges
- ☐ Landscaping
- ☐ Repair & Maintenance

- ☐ Precast

Q10 Select the most appropriate statement indicating your awareness about the use of robots in the construction industry

- o I have witnessed the use of robots in my project
- o I have witnessed robots being used in other projects of my company
- o I have witnessed robots being used in other construction companies
- o I have read about construction robots in some news/advertisements but I have never witnessed robots being used in the construction industry
- o I am in-aware about the use of robots in the construction industry

Q11 Can you think of some tasks that you would want to be done by a robot at a project site? (You can select multiple options)

- ☐ Loading & unloading of materials
- ☐ Shifting of heavy materials
- ☐ Demolition activities in a project
- ☐ Welding
- ☐ Excavation
- ☐ Bricklaying
- ☐ Survey, Layout
- ☐ Plastering, Painting
- ☐ Inspection of project progress
- ☐ Other ________________________________________________

Q12 In the next part of the survey, you will be shown different robots that are currently used in the construction industry and you will be asked to answer questions related to it. Each case will take approximately 2 minutes to complete. Based on your experience/interest, please select the robots that you are familiar with or want to know more about. (You can select multiple options)

- ☐ Robotic Excavator

- Field Printer
- Block Laying Robot
- Painting Robot
- Inspection Rob0ts
- Grass Mowing Robots
- Unmanned Aerial Vehicles (Drones)
- Demolition Robots
- Rebar Tying Robots
- Progress Monitoring Robots
- Exoskeleton

Q13 **Robotic Excavator -**

- This is a robotic excavator which can be used for the execution of main tasks such as excavating trenches, excavating building pads, grading, etc.
- It includes an all-weather enclosure, proximity radar, 360° cameras, GPS, and a powerful liquid-cooled computer. It enables real-time data monitoring from a remote location.
- The robot works completely autonomously with an option to be tele operated. Trench placement and profiles match the plans, thus eliminating rework.


Source – Built Robotics

Web - https://www.builtrobotics.com

How much do you agree or disagree with the following statements -

| | Strongly agree | Somewhat agree | Neither agree nor disagree | Somewhat disagree | Strongly disagree |
|---|---|---|---|---|---|
| Using this robot in my project will be useful in enhancing job performance | | | | | |
| Using this robot in my project will be free of effort | | | | | |
| This robot is relevant to the job | | | | | |
| The robot will be able to perform the job well. | | | | | |

Q14 If you were to use the robotic excavator shown above in your project, what level of human involvement and robot automation do you think is ideal for excavation tasks.

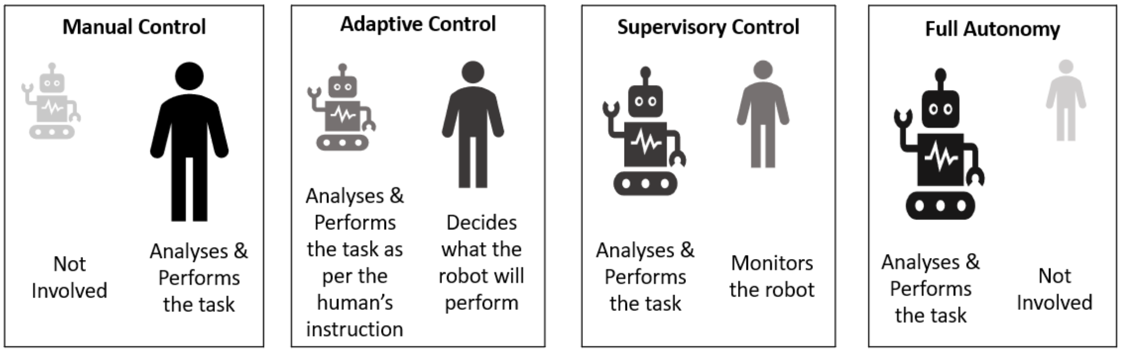
Please refer to the following explanation of different levels of robot autonomy before selecting your answer.

1)Manual Control – human operates the machine, either directly operating the machine or operating it remotely with a controller.

2)Adaptive Control – human plans and assigns specific tasks, robot adapts the plan based on site conditions and executes the task. Human monitors and intervenes if needed.

3)Supervisory Control – robot plans and executes the task. Human supervises and can intervene if needed, and robot learns from human intervention for future tasks.

4)Full Autonomy – Robot plans and executes the task without any human involvement.




Based in the above classification, what level of robot autonomy do you think is ideal for excavation tasks?

- o Manual Control
- o Adaptive Control
- o Supervisory Control
- o Full Autonomy

Q15 You selected ${Q14/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction. Please select the level of trust you feel when allowing the robot to work on your site.

- o I trust the robot completely, it will always execute the task accurately
- o I mostly trust the robot, it may make some errors while executing the task
- o I neither completely trust robots nor distrust them
- o I mostly distrust robots as robots may make considerable errors when they execute the task
- o I distrust robots as they make many errors when they execute the task

Q16 You selected ${Q14/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (You can select multiple options)

- ☐ Enhance worker's safety
- ☐ Assist in monitoring & quality control
- ☐ Save time by eliminating labor intensive procedures
- ☐ Reduce costs & enhance profits
- ☐ Improve accuracy of planning/design work, allow precise construction
- ☐ Enable design freedom
- ☐ Other ________________________________________________

Q17 You selected ${Q14/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (You can select multiple options)

- ☐ Workforce is not skilled to work with robots as it is a complex technology
- ☐ High Cost of implementation
- ☐ Insufficient applicability due to uncertain site conditions
- ☐ Job security of labor, workforce will be resistant to adopting the change
- ☐ It is easy to work with labor as compared to robot
- ☐ Robotic technology is still immature, not reliable and accurate, needs to develop further
- ☐ Very few companies that manufacture robots
- ☐ Other ________________________________________________

Q18 Which of the following scenarios would you be most comfortable in adopting at your project site?

- o One Human - One Robot
- o Human Team - One Robot
- o One Human - Robot Team

- Human Team - Robot Team

Q19 What would be the level of comfort ________________ in sharing a space at the project site with a robot as compared to that of a human worker?

| | Much higher | Slightly higher | About the same | Slightly lower | Much lower |
|---|---|---|---|---|---|
| you would feel | | | | | |
| your team would feel | | | | | |

Q20 **Construction Layout Robot** –

- A field printer can autonomously print the full-scale layout on the construction surface using a BIM model as its input.
- This robot can be used in supporting roles such as layout or grid markings. This layout will help in checking the accuracy of installed openings & also help in identifying any potential clashes at an early stage allowing time for corrections.
- Allowing the robot to print the layout will lead to schedule savings and allow the skilled workforce to focus on other tasks.


Source - Dusty Robotics Web - https://www.dustyrobotics.com

How much do you agree or disagree with the following statements -

| | Strongly agree | Somewhat agree | Neither agree nor disagree | Somewhat disagree | Strongly disagree |
|---|---|---|---|---|---|
| Using this robot in my project will be useful in enhancing job performance | | | | | |
| Using this robot in my project will be free of effort | | | | | |
| This robot is relevant to the job | | | | | |
| The robot will be able to perform the job well. | | | | | |

Q21 If you were to use the robotic field printer shown above in your project, what level of human involvement and robot automation do you think is ideal for layout marking tasks.

Please refer to the following explanation of different levels of robot autonomy before selecting your answer.

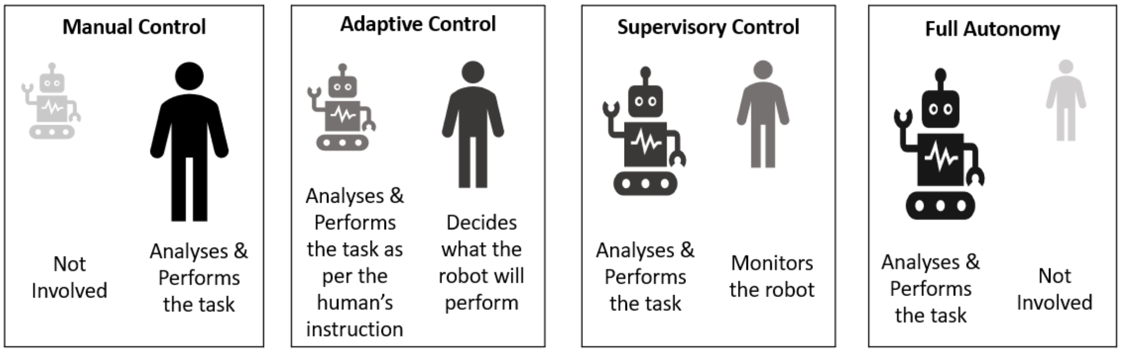
1) Manual Control – human operates the machine, either directly operating the machine or operating it remotely with a controller.

2) Adaptive Control – human plans and assigns specific tasks, robot adapts the plan based on site conditions and executes the task. Human monitors and intervenes if needed.

3) Supervisory Control – robot plans and executes the task. Human supervises and can intervene if needed, and robot learns from human intervention for future tasks.

4) Full Autonomy – Robot plans and executes the task without any human involvement.

Based on the above classification, what level of robot autonomy do you think is ideal for layout marking tasks?




- o Manual Control
- o Adaptive Control
- o Supervisory Control
- o Full Autonomy

Q22 You selected ${Q21/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction. Please select the level of trust you feel when allowing the robot to work on your site.

- o I trust the robot completely, it will always execute the task accurately
- o I mostly trust the robot, it may make some errors while executing the task
- o I neither completely trust robots nor distrust them
- o I mostly distrust robots as robots may make considerable errors when they execute the task
- o I distrust robots as they make many errors when they execute the task

Q23 You selected ${Q21/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- □ Enhance worker's safety

- ☐ Assist in monitoring & quality control
- ☐ Save time by eliminating labor intensive procedures
- ☐ Reduce costs & enhance profits
- ☐ Improve accuracy of planning/design work, allow precise construction
- ☐ Enable design freedom
- ☐ Other ________________________________________________

Q24 You selected ${Q21/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- ☐ Workforce is not skilled to work with robots as it is a complex technology
- ☐ High Cost of implementation
- ☐ Insufficient applicability due to uncertain site conditions
- ☐ Job security of labor, workforce will be resistant to adopting the change
- ☐ It is easy to work with labor as compared to robot
- ☐ Robotic technology is still immature, not reliable and accurate, needs to develop further
- ☐ Very few companies that manufacture robots
- ☐ Other ________________________________________________

Q25 Which of the following scenarios would you be most comfortable in adopting at your project site?

- o One Human - One Robot
- o Human Team - One Robot
- o One Human - Robot Team
- o Human Team - Robot Team

Q26 What would be the level of comfort ________________ in sharing a space at the project site with a robot as compared to that of a human worker?

| | Much higher | Slightly higher | About the same | Slightly lower | Much lower |
|---|---|---|---|---|---|
| you would feel | | | | | |
| your team would feel | | | | | |

Q27 **Block Laying Robot -**

- The block-laying robot builds block walls based on the inputs from a 3D CAD model.
- This robot can be used for building block walls. Unique optimization software converts wall sketches into block positions and minimizes handling and waste of block products to improve the efficiency of construction.

Company – FBR

Web - https://www.fbr.com.au/view/hadrian-x

How much do you agree or disagree with the following statements -

| | Strongly agree | Somewhat agree | Neither agree nor disagree | Somewhat disagree | Strongly disagree |
|---|---|---|---|---|---|
| Using this robot in my project will be useful in enhancing job performance | | | | | |
| Using this robot in my project will be free of effort | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| This robot is relevant to the job | | | | | |
| The robot will be able to perform the job well. | | | | | |

Q28

If you were to use the block laying shown above in your project, what level of human involvement and robot automation do you think is ideal for block work tasks.

Please refer to the following explanation of different levels of robot autonomy before selecting your answer.

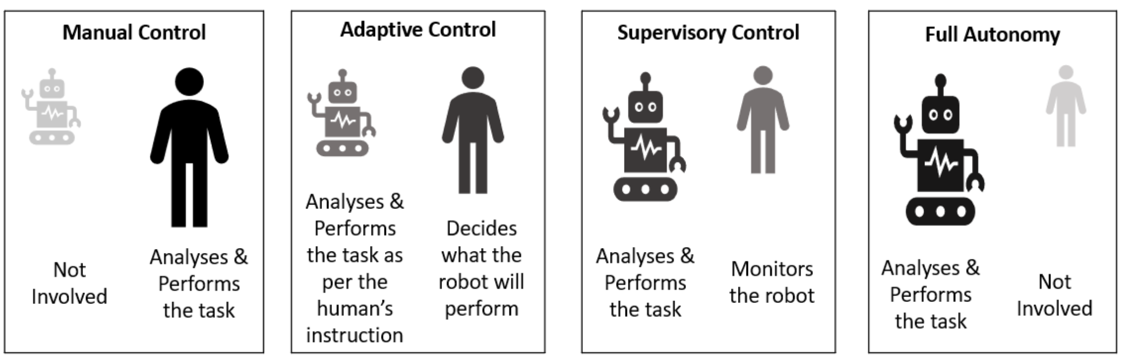
1) Manual Control – human operates the machine, either directly operating the machine or operating it remotely with a controller.

2) Adaptive Control – human plans and assigns specific tasks, robot adapts the plan based on site conditions and executes the task. Human monitors and intervenes if needed.

3) Supervisory Control – robot plans and executes the task. Human supervises and can intervene if needed, and robot learns from human intervention for future tasks.

4) Full Autonomy – Robot plans and executes the task without any human involvement.

Based on the above classification, what level of robot autonomy do you think is ideal for block work tasks?




- o Manual Control
- o Adaptive Control
- o Supervisory Control
- o Full Autonomy

Q29 You selected ${Q28/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction. Please select the level of trust you feel when allowing the robot to work on your site.

- I trust the robot completely, it will always execute the task accurately
- I mostly trust the robot, it may make some errors while executing the task
- I neither completely trust robots nor distrust them
- I mostly distrust robots as robots may make considerable errors when they execute the task
- I distrust robots as they make many errors when they execute the task

Q30 You selected ${Q28/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- ☐ Enhance worker's safety
- ☐ Assist in monitoring & quality control
- ☐ Save time by eliminating labor intensive procedures
- ☐ Reduce costs & enhance profits
- ☐ Improve accuracy of planning/design work, allow precise construction
- ☐ Enable design freedom
- ☐ Other ________________________________________________

Q31 You selected ${Q28/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- ☐ Workforce is not skilled to work with robots as it is a complex technology
- ☐ High Cost of implementation
- ☐ Insufficient applicability due to uncertain site conditions
- ☐ Job security of labor, workforce will be resistant to adopting the change
- ☐ It is easy to work with labor as compared to robot
- ☐ Robotic technology is still immature, not reliable and accurate, needs to develop further

- ☐ Very few companies that manufacture robots
- ☐ Other ________________________________________________

Q32 Which of the following scenarios would you be most comfortable in adopting at your project site?

- ○ One Human - One Robot
- ○ Human Team - One Robot
- ○ One Human - Robot Team
- ○ Human Team - Robot Team

Q33 What would be the level of comfort ______________ in sharing a space at the project site with a robot as compared to that of a human worker?

| | Much higher | Slightly higher | About the same | Slightly lower | Much lower |
|---|---|---|---|---|---|
| you would feel | | | | | |
| your team would feel | | | | | |

Q34 **Painting Robot -**

- This robot can autonomously paint large wall sections & ceilings without the use of scissor lifts.
- This robot can be used for spray painting tasks. Developed for industrial applications, the robot uses a spray nozzle to quickly apply paint to building interiors.

Company – Transforma

Web - https://www.transformarobotics.com/pictobot

How much do you agree or disagree with the following statements -

| | Strongly agree | Somewhat agree | Neither agree nor disagree | Somewhat disagree | Strongly disagree |
|---|---|---|---|---|---|
| Using this robot in my project will be useful in enhancing job performance | | | | | |
| Using this robot in my project will be free of effort | | | | | |
| This robot is relevant to the job | | | | | |
| The robot will be able to perform the job well. | | | | | |

Q35 If you were to use the painting robot shown above in your project, what level of human involvement and robot automation do you think is ideal for painting tasks.

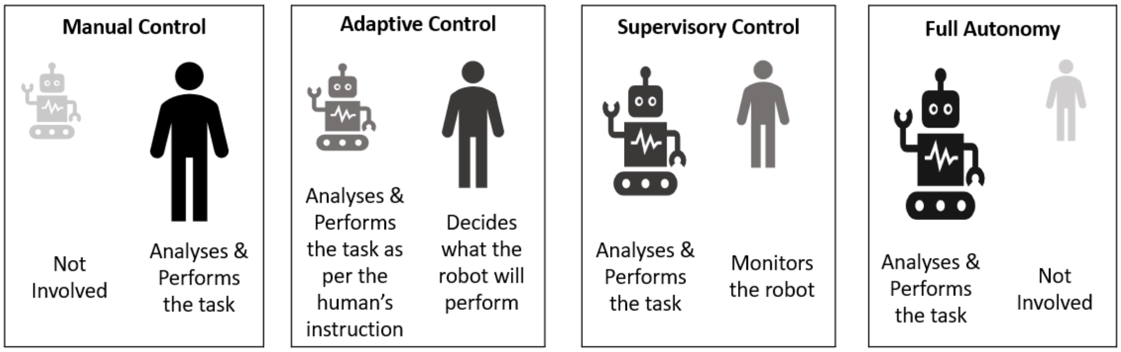
Please refer to the following explanation of different levels of robot autonomy before selecting your answer.

1) Manual Control – human operates the machine, either directly operating the machine or operating it remotely with a controller.

2) Adaptive Control – human plans and assigns specific tasks, robot adapts the plan based on site conditions and executes the task. Human monitors and intervenes if needed.

3) Supervisory Control – robot plans and executes the task. Human supervises and can intervene if needed, and robot learns from human intervention for future tasks.

4) Full Autonomy – Robot plans and executes the task without any human involvement.




Based on the above classification, what level of robot autonomy do you think is ideal for painting tasks?

- o Manual Control
- o Adaptive Control
- o Supervisory Control
- o Full Autonomy

Q36 You selected ${Q35/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction. Please select the level of trust you feel when allowing the robot to work on your site.

- o I trust the robot completely, it will always execute the task accurately
- o I mostly trust the robot, it may make some errors while executing the task
- o I neither completely trust robots nor distrust them
- o I mostly distrust robots as robots may make considerable errors when they execute the task
- o I distrust robots as they make many errors when they execute the task

Q37 You selected ${Q35/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- ☐ Enhance worker's safety

- ☐ Assist in monitoring & quality control
- ☐ Save time by eliminating labor intensive procedures
- ☐ Reduce costs & enhance profits
- ☐ Improve accuracy of planning/design work, allow precise construction
- ☐ Enable design freedom
- ☐ Other ________________________________________________

Q38 You selected ${Q35/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- ☐ Workforce is not skilled to work with robots as it is a complex technology
- ☐ High Cost of implementation
- ☐ Insufficient applicability due to uncertain site conditions
- ☐ Job security of labor, workforce will be resistant to adopting the change
- ☐ It is easy to work with labor as compared to robot
- ☐ Robotic technology is still immature, not reliable and accurate, needs to develop further
- ☐ Very few companies that manufacture robots
- ☐ Other ________________________________________________

Q39 Which of the following scenarios would you be most comfortable in adopting at your project site?

- o One Human - One Robot
- o Human Team - One Robot
- o One Human - Robot Team

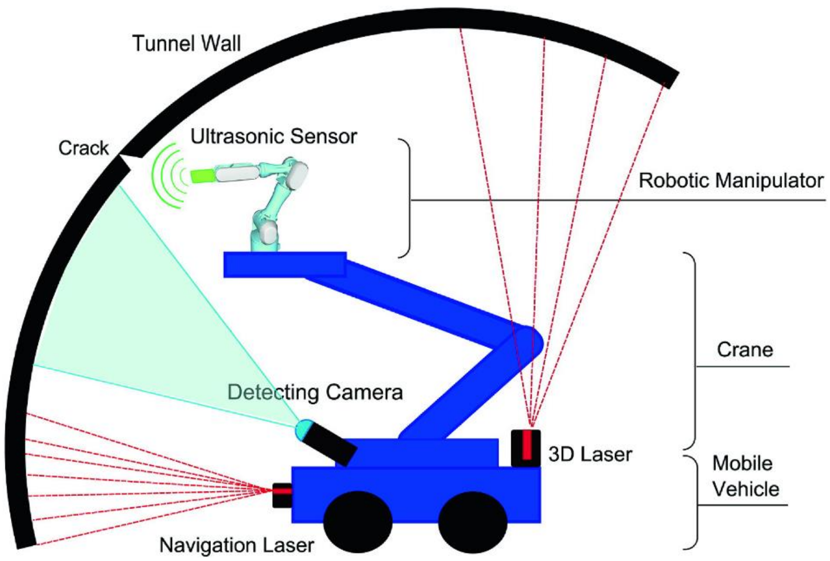
- Human Team - Robot Team

Q40 What would be the level of comfort __________________ in sharing a space at the project site with a robot as compared to that of a human worker?

| | Much higher | Slightly higher | About the same | Slightly lower | Much lower |
|---|---|---|---|---|---|
| you would feel | | | | | |
| your team would feel | | | | | |

Q41 **Inspection Robot -**

- This robot can be used to monitor the structural health of a tunnel or a pipeline.
- This robotic system has been developed with intelligent vision and control for the inspection and structural evaluation of tunnels & pipelines.
- The robot is a multi-sensor platform that carries a variety of condition assessment tools inside the pipeline in a single deployment.
- This will allow the inspection and structural evaluation of the interior walls of the tunnels & pipelines without human intervention,




Company - Robotnik & Pure Technologies

Web - https://robotnik.eu/projects/robinspect-en/

Web - https://puretechltd.com/technology/purerobotics-pipeline-inspection-system/

How much do you agree or disagree with the following statements -

| | Strongly agree | Somewhat agree | Neither agree nor disagree | Somewhat disagree | Strongly disagree |
|---|---|---|---|---|---|
| Using this robot in my project will be useful in enhancing job performance | | | | | |
| Using this robot in my project will be free of effort | | | | | |
| This robot is relevant to the job | | | | | |
| The robot will be able to perform the job well. | | | | | |

Q42

If you were to use the inspection robot shown above in your project, what level of human involvement and robot automation do you think is ideal for inspection tasks.

Please refer to the following explanation of different levels of robot autonomy before selecting your answer.

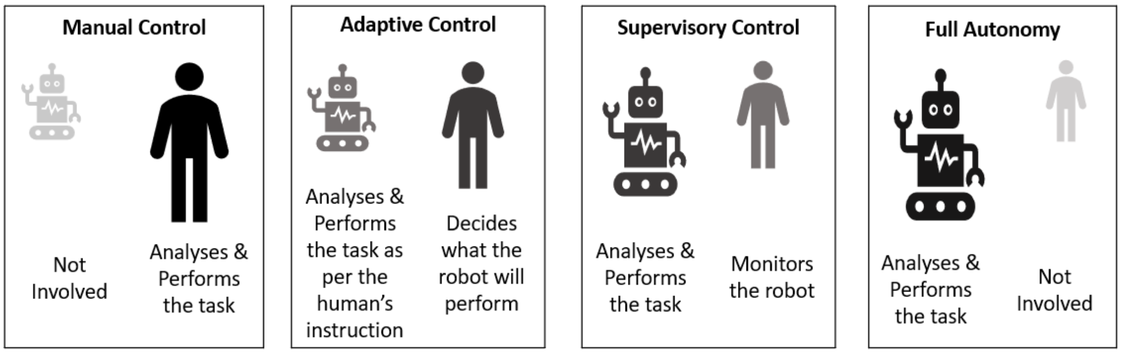
1) Manual Control – human operates the machine, either directly operating the machine or operating it remotely with a controller.

2) Adaptive Control – human plans and assigns specific tasks, robot adapts the plan based on site conditions and executes the task. Human monitors and intervenes if needed.

3) Supervisory Control – robot plans and executes the task. Human supervises and can intervene if needed, and robot learns from human intervention for future tasks.

4) Full Autonomy – Robot plans and executes the task without any human involvement.

Based on the above classification, what level of robot autonomy do you think is ideal for inspection tasks?




- ○ Manual Control
- ○ Adaptive Control
- ○ Supervisory Control
- ○ Full Autonomy

Q43 You selected ${Q42/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction. Please select the level of trust you feel when allowing the robot to work on your site.

- ○ I trust the robot completely, it will always execute the task accurately
- ○ I mostly trust the robot, it may make some errors while executing the task
- ○ I neither completely trust robots nor distrust them
- ○ I mostly distrust robots as robots may make considerable errors when they execute the task
- ○ I distrust robots as they make many errors when they execute the task

Q44 You selected ${Q42/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- □ Enhance worker's safety

- ☐ Assist in monitoring & quality control
- ☐ Save time by eliminating labor intensive procedures
- ☐ Reduce costs & enhance profits
- ☐ Improve accuracy of planning/design work, allow precise construction
- ☐ Enable design freedom
- ☐ Other ________________________________________________

Q45 You selected ${Q42/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- ☐ Workforce is not skilled to work with robots as it is a complex technology
- ☐ High Cost of implementation
- ☐ Insufficient applicability due to uncertain site conditions
- ☐ Job security of labor, workforce will be resistant to adopting the change
- ☐ It is easy to work with labor as compared to robot
- ☐ Robotic technology is still immature, not reliable and accurate, needs to develop further
- ☐ Very few companies that manufacture robots
- ☐ Other ________________________________________________

Q46 Which of the following scenarios would you be most comfortable in adopting at your project site?

- o One Human - One Robot
- o Human Team - One Robot
- o One Human - Robot Team
- o Human Team - Robot Team

Q47 What would be the level of comfort _________________ in sharing a space at the project site with a robot as compared to that of a human worker?

| | Much higher | Slightly higher | About the same | Slightly lower | Much lower |
|---|---|---|---|---|---|
| you would feel | | | | | |
| your team would feel | | | | | |

Q48 **Grass Mowing Robot -**

- This is a robotic grass mower, that can be used in the mowing of grass as required. It receives electronic updates and can mow any type of grass fully autonomously.
- The technology can be extended to snow removal, sweeping, sidewalk repairs, and pest control. The robot uses light detection and ranging (LiDAR — a laser-based computer vision technology), cameras, GPS, and ultrasonic sensors to maneuver across diverse terrain.
- Robots are monitored while in use and incorporate a safety-rated system capable of detecting perimeter breaches.

Company - Electric Sheep

Web - https://www.landscapemanagement.net/electric-sheep-robotics-plans-to-launch-autonomous-mower/

How much do you agree or disagree with the following statements -

| | Strongly agree | Somewhat agree | Neither agree nor disagree | Somewhat disagree | Strongly disagree |
|---|---|---|---|---|---|
| Using this robot in my project will be useful in enhancing job performance | | | | | |
| Using this robot in my project will be free of effort | | | | | |
| This robot is relevant to the job | | | | | |
| The robot will be able to perform the job well. | | | | | |

Q49 If you were to use the grass mowing robot shown above in your project, what level of human involvement and robot automation do you think is ideal for grass mowing tasks.

Please refer to the following explanation of different levels of robot autonomy before selecting your answer.

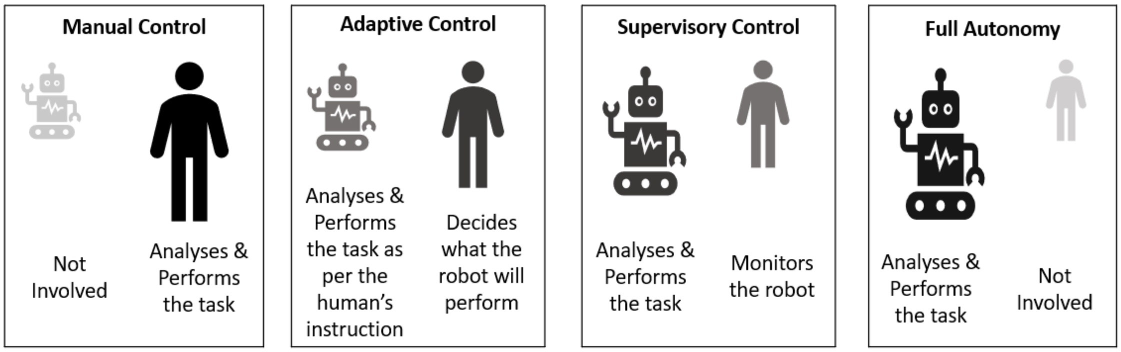
1) Manual Control – human operates the machine, either directly operating the machine or operating it remotely with a controller.

2) Adaptive Control – human plans and assigns specific tasks, robot adapts the plan based on site conditions and executes the task. Human monitors and intervenes if needed.

3) Supervisory Control – robot plans and executes the task. Human supervises and can intervene if needed, and robot learns from the human intervention for future tasks.

4) Full Autonomy – Robot plans and executes the task without any human involvement.

Based on the above classification, what level of robot autonomy do you think is ideal for grass mowing tasks?




- o Manual Control
- o Adaptive Control
- o Supervisory Control
- o Full Autonomy

Q50 You selected ${Q49/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction. Please select the level of trust you feel when allowing the robot to work on your site.

- o I trust the robot completely, it will always execute the task accurately
- o I mostly trust the robot, it may make some errors while executing the task
- o I neither completely trust robots nor distrust them
- o I mostly distrust robots as robots may make considerable errors when they execute the task
- o I distrust robots as they make many errors when they execute the task

Q51 You selected ${Q49/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- ☐ Enhance worker's safety
- ☐ Assist in monitoring & quality control

- ☐ Save time by eliminating labor intensive procedures
- ☐ Reduce costs & enhance profits
- ☐ Improve accuracy of planning/design work, allow precise construction
- ☐ Enable design freedom
- ☐ Other ________________________________________________

Q52 You selected ${Q49/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- ☐ Workforce is not skilled to work with robots as it is a complex technology
- ☐ High Cost of implementation
- ☐ Insufficient applicability due to uncertain site conditions
- ☐ Job security of labor, workforce will be resistant to adopting the change
- ☐ It is easy to work with labor as compared to robot
- ☐ Robotic technology is still immature, not reliable and accurate, needs to develop further
- ☐ Very few companies that manufacture robots
- ☐ Other ________________________________________________

Q53 Which of the following scenarios would you be most comfortable in adopting at your project site?

- o One Human - One Robot
- o Human Team - One Robot
- o One Human - Robot Team
- o Human Team - Robot Team

Q54 What would be the level of comfort _________________ in sharing a space at the project site with a robot as compared to that of a human worker?

| | Much higher | Slightly higher | About the same | Slightly lower | Much lower |
|---|---|---|---|---|---|
| you would feel | | | | | |
| your team would feel | | | | | |

Q55 **Unmanned Aerial Vehicles (Drones)**

Robotic drones are used in the construction industry for various purposes Drones have been found to be useful in the following areas - Monitor Building Progress, Topographic Mapping and Analysis, Soil Analysis, Surveying, Digital Mapping, Inspections, Physical Construction Monitoring, 3D Renderings. Drones can be teleoperated.

Company - DJI Enterprises

Web - https://enterprise.dji.com/

How much do you agree or disagree with the following statements -

| | Strongly agree | Somewhat agree | Neither agree nor disagree | Somewhat disagree | Strongly disagree |
|---|---|---|---|---|---|
| Using this robot in my project will be useful in enhancing job performance | | | | | |
| Using this robot in my project will be free of effort | | | | | |
| This robot is relevant to the job | | | | | |
| The robot will be able to perform the job well. | | | | | |

Q56

If you were to use drone shown above in your project, what level of human involvement and robot automation do you think is ideal for monitoring/survey tasks.

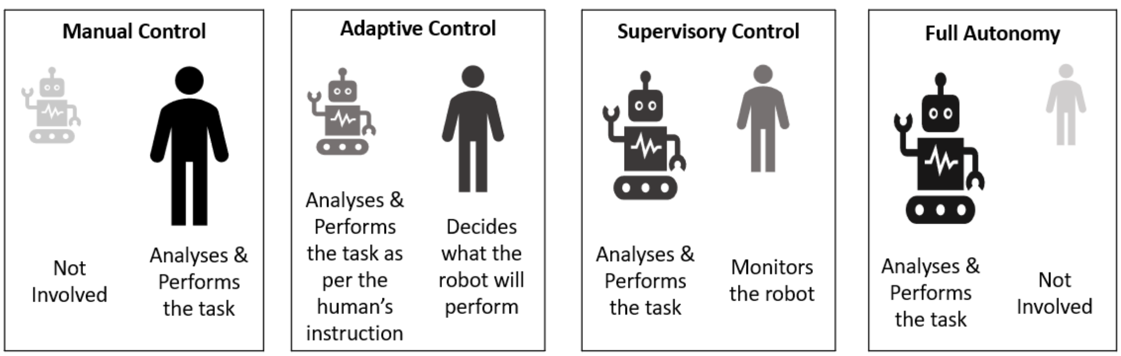
Please refer to the following explanation of different levels of robot autonomy before selecting your answer.

1) Manual Control – human operates the machine, either directly operating the machine or operating it remotely with a controller.

2) Adaptive Control – human plans and assigns specific tasks, robot adapts the plan based on site conditions and executes the task. Human monitors and intervenes if needed.

3) Supervisory Control – robot plans and executes the task. Human supervises and can intervene if needed, and robot learns from the human intervention for future tasks.

4) Full Autonomy – Robot plans and executes the task without any human involvement.




Based on the above classification, what level of robot autonomy do you think is ideal for monitoring/survey tasks?

- o Manual Control
- o Adaptive Control
- o Supervisory Control
- o Full Autonomy

Q57 You selected ${Q56/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction. Please select the level of trust you feel when allowing the robot to work on your site.

- o I trust the robot completely, it will always execute the task accurately
- o I mostly trust the robot, it may make some errors while executing the task

- I neither completely trust robots nor distrust them
- I mostly distrust robots as robots may make considerable errors when they execute the task
- I distrust robots as they make many errors when they execute the task

Q58 You selected ${Q56/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- Enhance worker's safety
- Assist in monitoring & quality control
- Save time by eliminating labor intensive procedures
- Reduce costs & enhance profits
- Improve accuracy of planning/design work, allow precise construction
- Enable design freedom
- Other ________________________________________________

Q59 You selected ${Q56/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- Workforce is not skilled to work with robots as it is a complex technology
- High Cost of implementation
- Insufficient applicability due to uncertain site conditions
- Job security of labor, workforce will be resistant to adopting the change
- It is easy to work with labor as compared to robot
- Robotic technology is still immature, not reliable and accurate, needs to develop further
- Very few companies that manufacture robots
- Other ________________________________________________

Q60 Which of the following scenarios would you be most comfortable in adopting at your project site?

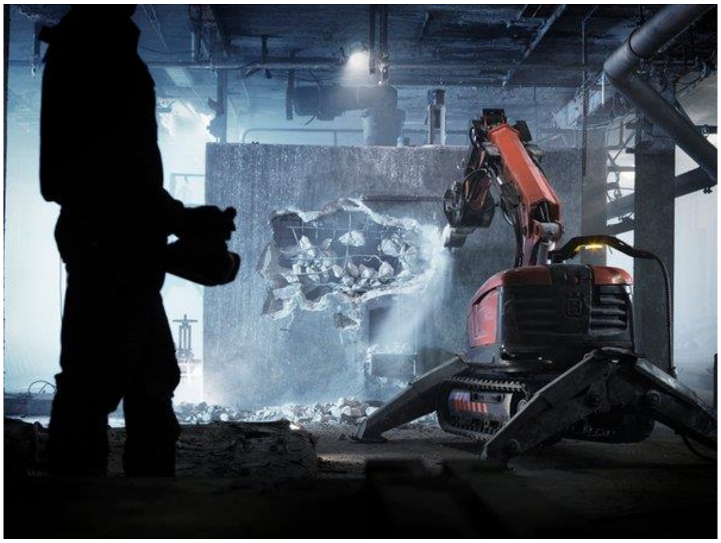
- One Human - One Robot
- Human Team - One Robot
- One Human - Robot Team
- Human Team - Robot Team

Q61 What would be the level of comfort ________________ in sharing a space at the project site with a robot as compared to that of a human worker?

| | Much higher | Slightly higher | About the same | Slightly lower | Much lower |
|---|---|---|---|---|---|
| you would feel | | | | | |
| your team would feel | | | | | |

Q62 **Demolition Robots** –

Remote-controlled demolition robots are the very latest in demolition machines, featuring high power, low weight and functional design with the ability to be teleoperated. They are effective in terms of completing the demolition tasks without causing harm to the operator.



Company - Husqvarna

Web - https://www.husqvarnacp.com/us/machines/demolition-robots/

How much do you agree or disagree with the following statements?

| | Strongly agree | Somewhat agree | Neither agree nor disagree | Somewhat disagree | Strongly disagree |
|---|---|---|---|---|---|
| Using this robot in my project will be useful in enhancing job performance | | | | | |
| Using this robot in my project will be free of effort | | | | | |
| This robot is relevant to the job | | | | | |
| The robot will be able to perform the job well. | | | | | |

Q63

If you were to use a demolition robot shown above in your project, what level of human involvement and robot automation do you think is ideal for demolition tasks.

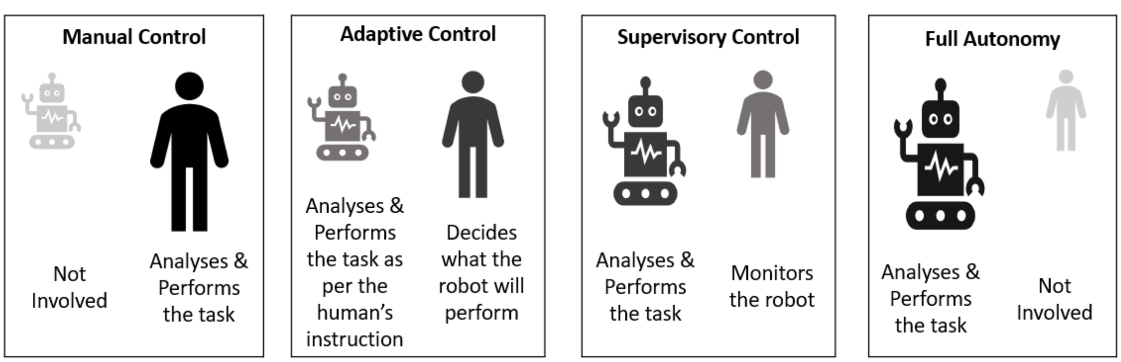
Please refer to the following explanation of different levels of robot autonomy before selecting your answer.

1) Manual Control – human operates the machine, either directly operating the machine or operating it remotely with a controller.

2) Adaptive Control – human plans and assigns specific tasks, robot adapts the plan based on site conditions and executes the task. Human monitors and intervenes if needed.

3) Supervisory Control – robot plans and executes the task. Human supervises and can intervene if needed, and robot learns from the human intervention for future tasks.

4) Full Autonomy – Robot plans and executes the task without any human involvement



Based on the above classification, what level of robot autonomy do you think is ideal for demolition tasks?

- o Manual Control
- o Adaptive Control
- o Supervisory Control
- o Full Autonomy

Q64 You selected ${Q63/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction. Please select the level of trust you feel when allowing the robot to work on your site.

- o I trust the robot completely, it will always execute the task accurately
- o I mostly trust the robot, it may make some errors while executing the task
- o I neither completely trust robots nor distrust them
- o I mostly distrust robots as robots may make considerable errors when they execute the task
- o I distrust robots as they make many errors when they execute the task

Q65 You selected ${Q63/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- ☐ Enhance worker's safety
- ☐ Assist in monitoring & quality control
- ☐ Save time by eliminating labor intensive procedures
- ☐ Reduce costs & enhance profits
- ☐ Improve accuracy of planning/design work, allow precise construction
- ☐ Enable design freedom
- ☐ Other ________________________________________________

Q66 You selected ${Q63/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- ☐ Workforce is not skilled to work with robots as it is a complex technology
- ☐ High Cost of implementation
- ☐ Insufficient applicability due to uncertain site conditions
- ☐ Job security of labor, workforce will be resistant to adopting the change
- ☐ It is easy to work with labor as compared to robot
- ☐ Robotic technology is still immature, not reliable and accurate, needs to develop further
- ☐ Very few companies that manufacture robots
- ☐ Other ________________________________________________

Q67 Which of the following scenarios would you be most comfortable in adopting at your project site?

- ☐ One Human - One Robot
- ☐ Human Team - One Robot
- ☐ One Human - Robot Team
- ☐ Human Team - Robot Team

Q68 What would be the level of comfort _________________ in sharing a space at the project site with a robot as compared to that of a human worker?

| | Much higher | Slightly higher | About the same | Slightly lower | Much lower |
|---|---|---|---|---|---|
| you would feel | | | | | |
| your team would feel | | | | | |

Q69 **Rebar Tying Robots -** This is a rebar tying robot used in tying rebar cages. This robot works autonomously in tying the rebar once the mesh has been laid. It takes less than half shift time to set up & then works at the rate of up to 1100 ties/hr and can work from day to night


Company - Advanced Construction Robotics

Web - https://www.tybotllc.com/tybot

How much do you agree or disagree with the following statements -

| | Strongly agree | Somewhat agree | Neither agree nor disagree | Somewhat disagree | Strongly disagree |
|---|---|---|---|---|---|
| Using this robot in my project will be useful in enhancing job performance | | | | | |
| Using this robot in my project will be free of effort | | | | | |
| This robot is relevant to the job | | | | | |
| The robot will be able to perform the job well. | | | | | |

Q70 If you were to use a rebar tying robot shown above in your project, what level of human involvement and robot automation do you think is ideal for rebar tying tasks.

Please refer to the following explanation of different levels of robot autonomy before selecting your answer.

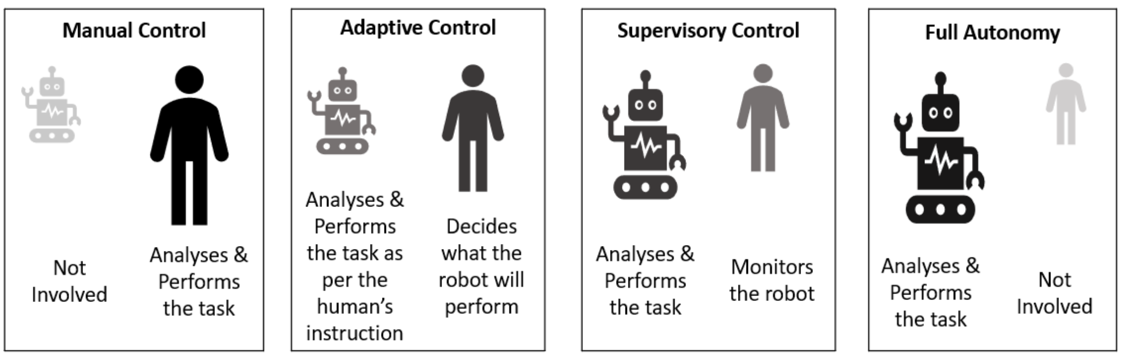
1) Manual Control – human operates the machine, either directly operating the machine or operating it remotely with a controller.

2) Adaptive Control – human plans and assigns specific tasks, robot adapts the plan based on site conditions and executes the task. Human monitors and intervenes if needed.

3) Supervisory Control – robot plans and executes the task. Human supervises and can intervene if needed, and robot learns from the human intervention for future tasks.

4) Full Autonomy – Robot plans and executes the task without any human involvement.

Based on the above classification, what level of robot autonomy do you think is ideal for rebar tying tasks?




- o Manual Control
- o Adaptive Control
- o Supervisory Control
- o Full Autonomy

Q71 You selected ${Q70/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction. Please select the level of trust you feel when allowing the robot to work on your site.

- o I trust the robot completely, it will always execute the task accurately
- o I mostly trust the robot, it may make some errors while executing the task
- o I neither completely trust robots nor distrust them
- o I mostly distrust robots as robots may make considerable errors when they execute the task
- o I distrust robots as they make many errors when they execute the task

Q72 You selected ${Q70/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- ▢ Enhance worker's safety
- ▢ Assist in monitoring & quality control
- ▢ Save time by eliminating labor intensive procedures
- ▢ Reduce costs & enhance profits
- ▢ Improve accuracy of planning/design work, allow precise construction
- ▢ Enable design freedom
- ▢ Other ________________________________________________

Q73 You selected ${Q70/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- ▢ Workforce is not skilled to work with robots as it is a complex technology
- ▢ High Cost of implementation
- ▢ Insufficient applicability due to uncertain site conditions
- ▢ Job security of labor, workforce will be resistant to adopting the change
- ▢ It is easy to work with labor as compared to robot
- ▢ Robotic technology is still immature, not reliable and accurate, needs to develop further
- ▢ Very few companies that manufacture robots
- ▢ Other ________________________________________________

Q74 Which of the following scenarios would you be most comfortable in adopting at your project site?

- o One Human - One Robot
- o Human Team - One Robot
- o One Human - Robot Team

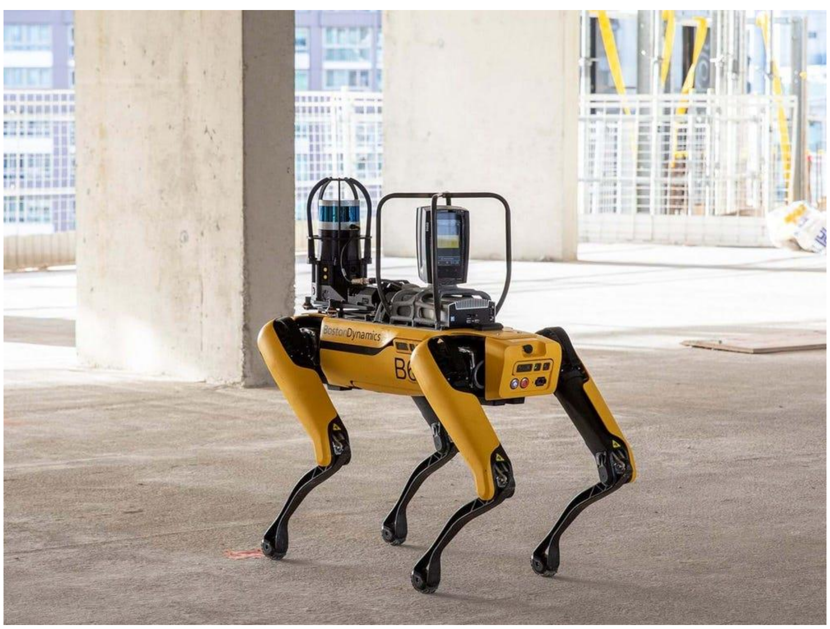
- o Human Team - Robot Team

Q75 What would be the level of comfort ________________ in sharing a space at the project site with a robot as compared to that of a human worker?

| | Much higher | Slightly higher | About the same | Slightly lower | Much lower |
|---|---|---|---|---|---|
| you would feel | | | | | |
| your team would feel | | | | | |

Q76 **Project Monitoring Robots -**

- This is a progress monitoring robot. This robot can autonomously capture 360° images and video indoors or on challenging exterior sites.
- Frequently captured site progress snapshots can be contextualized in construction documents and used to automate insights and work-in-place reporting through emerging AI technologies



Company - Boston Dynamics

Web - https://www.bostondynamics.com/products/spot

How much do you agree or disagree with the following statements -

| | Strongly agree | Somewhat agree | Neither agree nor disagree | Somewhat disagree | Strongly disagree |
|---|---|---|---|---|---|
| Using this robot in my project will be useful in enhancing job performance | | | | | |
| Using this robot in my project will be free of effort | | | | | |
| This robot is relevant to the job | | | | | |
| The robot will be able to perform the job well. | | | | | |

Q77 If you were to use a progress monitoring robot shown above in your project, what level of human involvement and robot automation do you think is ideal for progress monitoring tasks.

Please refer to the following explanation of different levels of robot autonomy before selecting your answer.

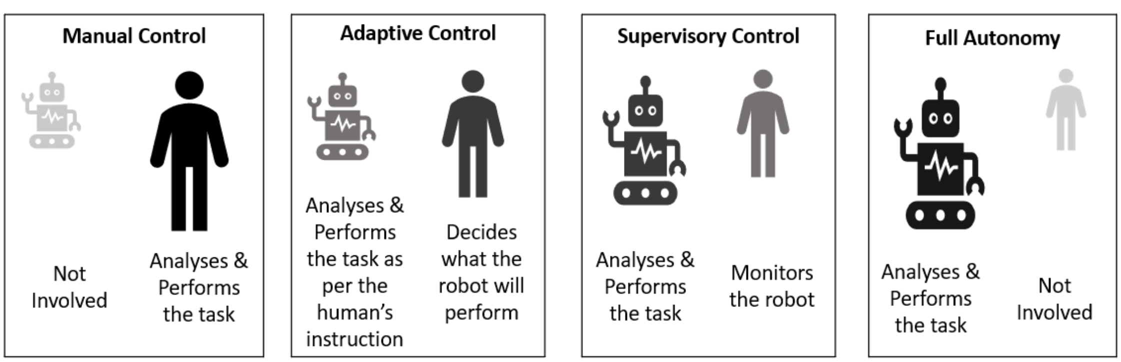
1) Manual Control – human operates the machine, either directly operating the machine or operating it remotely with a controller.

2) Adaptive Control – human plans and assigns specific tasks, robot adapts the plan based on site conditions and executes the task. Human monitors and intervenes if needed.

3) Supervisory Control – robot plans and executes the task. Human supervises and can intervene if needed, and robot learns from the human intervention for future tasks.

4) Full Autonomy – Robot plans and executes the task without any human involvement.

Based on the above classification, what level of robot autonomy do you think is ideal for progress monitoring tasks?




- o Manual Control

- Adaptive Control
- Supervisory Control
- Full Autonomy

Q78 You selected ${Q77/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction. Please select the level of trust you feel when allowing the robot to work on your site.

- I trust the robot completely, it will always execute the task accurately
- I mostly trust the robot, it may make some errors while executing the task
- I neither completely trust robots nor distrust them
- I mostly distrust robots as robots may make considerable errors when they execute the task
- I distrust robots as they make many errors when they execute the task

Q79 You selected ${Q77/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- ☐ Enhance worker's safety
- ☐ Assist in monitoring & quality control
- ☐ Save time by eliminating labor intensive procedures
- ☐ Reduce costs & enhance profits
- ☐ Improve accuracy of planning/design work, allow precise construction
- ☐ Enable design freedom
- ☐ Other ________________________________________________

Q80 You selected ${Q77/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- ▢ Workforce is not skilled to work with robots as it is a complex technology
- ▢ High Cost of implementation
- ▢ Insufficient applicability due to uncertain site conditions
- ▢ Job security of labor, workforce will be resistant to adopting the change
- ▢ It is easy to work with labor as compared to robot
- ▢ Robotic technology is still immature, not reliable and accurate, needs to develop further
- ▢ Very few companies that manufacture robots
- ▢ Other ________________________________________________

Q81 Which of the following scenarios would you be most comfortable in adopting at your project site?

- o One Human - One Robot
- o Human Team - One Robot
- o One Human - Robot Team
- o Human Team - Robot Team

Q82 What would be the level of comfort ________________ in sharing a space at the project site with a robot as compared to that of a human worker?

| | Much higher | Slightly higher | About the same | Slightly lower | Much lower |
|---|---|---|---|---|---|
| you would feel | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| your team would feel | | | | | |

Q83 **Exoskeleton -** The upper-body exoskeleton is a robotic device worn by the worker. Exoskeleton assists with reducing arm and shoulder muscle fatigue during long periods of overhead work while giving you freedom of movement and a full range of motion. The ultralight exoskeleton, weighing in at less than 5 lbs., offers dynamic support and control through easy adjustability for a wide range of body types.


Company - Ekso Bionics

Web - https://eksobionics.com/ekso-evo/

How much do you agree or disagree with the following statements -

| | Strongly agree | Somewhat agree | Neither agree nor disagree | Somewhat disagree | Strongly disagree |
|---|---|---|---|---|---|
| Using this robot in my project will be useful in enhancing job performance | | | | | |
| Using this robot in my project will be free of effort | | | | | |
| This robot is relevant to the job | | | | | |
| The robot will be able to perform the job well. | | | | | |

Q84 Would you prefer to adopt an exoskeleton shown in the previous question in your project?

o Yes

o No

Q85 You selected ${Q84/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- ☐ Enhance worker's safety
- ☐ Assist in monitoring & quality control
- ☐ Save time by eliminating labor intensive procedures
- ☐ Reduce costs & enhance profits
- ☐ Improve accuracy of planning/design work, allow precise construction
- ☐ Enable design freedom
- ☐ Other ________________________________________________

Q86 You selected ${Q84/ChoiceGroup/SelectedChoices} in the previous question as your desired level of Human-Robot Interaction, select from the following options that you feel influenced to reach this decision. (you can select multiple options)

- ☐ Workforce is not skilled to work with robots as it is a complex technology
- ☐ High Cost of implementation
- ☐ Insufficient applicability due to uncertain site conditions
- ☐ Job security of labor, workforce will be resistant to adopting the change
- ☐ It is easy to work with labor as compared to robot
- ☐ Robotic technology is still immature, not reliable and accurate, needs to develop further
- ☐ Very few companies that manufacture robots
- ☐ Other ________________________________________________

Q87 There is change in the working site conditions due to the pandemic like shortage of manpower, maintaining social distance, doing remote work etc. These conditions can be met by adopting robots in your project site. Please Compare your perception towards adopting robots in your project site before the covid-19 pandemic and after the covid-19 pandemic

| | Extremely likely | Somewhat likely | Neither likely nor unlikely | Somewhat unlikely | Extremely unlikely |
|---|---|---|---|---|---|
| **Perception to use robots before the covid-19 pandemic** | | | | | |
| **Perception to use robots after the covid-19 pandemic** | | | | | |

Q88 Thank you for taking this survey. If you are interested in knowing about the results of this survey, please feel free to share your information so we can contact you later. Please note that this information will not be linked to the responses you provided.

Name ______________________________________________

Email ______________________________________________