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IDENTIFYING AND PRIORITISING FUTURE ROBOT CONTROL RESEARCH WITH MULTI-CRITERIA DECISION-MAKING

Summary

The gap between researchers who carry out scientific exploration and practitioners who can make use of the research results is well known. In addition, while practitioners place a high value on research, they do not read many research papers. This paper attempts to define and prioritise future research in robotics using the analytical hierarchy process (AHP). Fifteen research alternatives and gaps, five performance criteria, eight industry types, and six production processes, investigated by both academics and practitioners, are filtered to six alternatives, four performance criteria, three industry types, and three production processes, respectively, based on the most important factors in decision-making. Subsequently, they are analysed by the Expert Choice software. This research aims at bridging the gap between academics and practitioners in robotics research and at conducting research that is relevant to industry. The results indicate that the research in multi-robot control ranked first with 26.8%, followed by the research in safe control with 23.3% and the research in remote robot supervision with 19.0%. The research in force control ranked fourth with 17.8%, followed by the research in 3D vision and wireless communication with 8.4% and 6.4%, respectively. Based on the results, the academics involved in robotics research should direct their effort to the research activities that received the highest priority in the AHP model.

Key words: *future research in robotics, multi-criteria decision-making, analytical hierarchy process, qualitative analysis*

1. Introduction

Today, much scientific research focuses on multi-robot control, safe control, force control, remote robot supervision, and wireless communication [1]. Prioritising research directions occurs in health care sciences and services [2], health policy and services, and economics, whereas there is no research focusing on future directions in the research into robotics control. According to the web of science core collection search [3], in the period 1905-2019, there have been 74,153 studies with a title identifying and prioritising future robot control research with multi-criteria decision-making (MCDM). 52% of the research include proceeding papers and 42% articles; 80% of them were published between 2008 and 2018. 95% of the studies were conducted in 24 countries, where the USA, China, and Japan excelled and Iran and Turkey were the only Middle Eastern countries contributing to the robotics control research.

The presence of a research plan in robotics control is valuable in guiding the efforts of researchers in applying the results of scientific research to industrial evolution. This area needs specialized research to be directed and carried out. This would allow specialized areas and their associated sub-disciplines, which determine the areas of scientific interest over time, to be prioritised compared to other area specializations. In this way, growing demands or emergency events occurring in society can be addressed. Prioritising research directions can assist in finding research topics for the next planning horizon, in directing financial support to areas of research preferred by community without neglecting other key scientific areas, in encouraging the formation of scientific research teams and centres, encouraging practical multidisciplinary engineering disciplines, and supporting scientific publishing. The prioritisation scheme is intended to rank a subset of alternatives with respect to a pre-defined set of criteria for complex decision-making problems.

We can consider the aspects of scientific research in the field of robotics control from several points of view, such as robot types, performance criteria, industry types, and production processes. Most research found in robotics control literature concentrates on one or two aspects by dealing with a single problem, such as the study by Xue et al. [4]. The research can have one or more objectives. In the case of multiple objectives, the researcher attempts to find a satisfactory trade-off between many conflicting criteria and achieve the best solution. The pairwise comparisons between alternatives in prioritising research directions can be based on objective and/or subjective attributes. Objective attributes are numerical, such as the cost of a robot. Subjective attributes are qualitative, such as the programming flexibility of a robot. Additionally, the pairwise comparisons are based on beneficial and/or non-beneficial attributes. Beneficial attributes are those whose higher values are desirable, such as load carrying capacity, programming flexibility, and speed. The non-beneficial attributes are those whose lower values are desirable, such as cost and repeatability. When prioritising one robotic control research direction over another, the decision maker seeks to maximize the performance measure through altering the attributes.

The robot plays a very important role in modern manufacturing industries [5], where it is a major asset in key manufacturing processes, such as painting and welding in the automotive industry [6], metal cutting and forming in the assembly industry [7], and labour-related tasks in dangerous work areas. Moreover, in the space industry robots play an important role in imaging and investigating the characteristics of components in space research [8]. The heavy use of robots in industrial applications results from their stable quality and productivity level, cost minimization, and safety improvements in dangerous environments [9]. The selection of robots for a particular application and manufacturing environment is a difficult task for decision makers. Robot selection has become more complicated due to the increase in complexity, advanced features, and facilities of robots. The decision maker must identify and select the best-suited robot to achieve the desired output with respect to many criteria. MCDM is a complex decision-making tool involving both quantitative and qualitative factors. In recent years, several MCDM techniques and approaches have been utilised for choosing optimal probable options. Robotics research area alternatives can be defined by solving a certain problem related to functionality to optimize criteria for a certain application by specifying a manufacturing process type.

MCDM is a complex technique that defines criteria weights, the relationship between alternatives, and solution trade-offs through mathematical techniques [10]. The analytical hierarchy process (AHP) is an MCDM technique that enables the decision maker to choose one or more trade-off scenarios suitable to available resources. It has various applications from the construction industry [11], network selection and supply chain management [12] to healthcare services [13], material selection [14], risk assessment [15] and energy management.

Robot selection for a given industrial application is a challenging and complicated procedure. In robot selection research, alternatives are clearly defined for finding solutions to certain problems, which refers to optimizing predefined criteria related to manufacturing area to choose the appropriate robots. Koulouriotis and Ketipi [16] provided a comprehensive integrated review and annotated taxonomy for robot evaluation and selection until 2014. Parameshwaran et al. [17] presented an integrated approach for optimal robot selection by considering both objective and subjective criteria by sequentially using the fuzzy Delphi/AHP/TOPSIS framework and VIKOR validation and the Brown-Gibson model. VIKOR is closest to the ideal solution. Sen et al. [18] explored the preference ranking organization method for enrichment evaluation as an efficient decision-making tool which provides the complete ranking order of all available alternatives. Sen et al. highlighted the application potential of preference ranking organization methods in relation to the robot selection problem when subjected to a set of quantitative evaluation data collected from the literature.

Simion et al. [19] applied the AHP method to select the most favourable industrial robot configuration for arc welding of a tracked mini-robot housing, which is used in military applications. The study highlighted the usefulness of the AHP in automated technological processes to facilitate and simplify the robot selection from a set of alternatives that carry out one or more tasks. Wang et al. [20] explored two key issues of robot evaluation and selection: assessment representation and robot rankings. Wang et al. developed a decision support model which utilised a cloud model and TODIM (a Portuguese acronym equivalent to interactive multi-criteria decision-making) for robot selection with hesitant linguistic information, which was used along with an entropy-based combination weighting technique to estimate the criteria weights. The TODIM approach is proposed for robot selection for automobile manufacturers, which validates the benefits and effectiveness of a robot through a comparative analysis. The results highlighted its unique advantages in a complex environment. Zhou et al. [21] proposed a VIKOR-based implementation method for integrating a fuzzy extended analytical hierarchy to select the mobile robot option with the smallest fuzzy utility value. The results highlight the sensitivity analysis, effectiveness, and robustness of the VIKOR extended approach.

Liu et al. [22] proposed a novel robot selection model by integrating the quality function development (QFD) theory and the qualitative flexible multiple criteria method under the interval-valued Pythagorean uncertain linguistical context. A modified qualitative flexible multiple criteria technique is utilised to generate the ranking order of alternative robots to determine the most suitable robot. Narayanamoorthy et al. [23] proposed using interval valued intuitionistic hesitant fuzzy entropy to determine the importance of criteria and the interval valued intuitionistic hesitant fuzzy VIKOR method to rank alternatives to perform complicated and hazardous tasks. The interval-valued intuitionistic hesitant fuzzy set includes a set of several possible interval-valued intuitionistic fuzzy membership and non-membership values to enhance the quality and efficiency of the work.

Kapoor and Tak [24] used the AHP method with selection criteria factors such as cost, velocity, repeatability, load capacity, stability, compliance, and accuracy. Chatterjee [25] used the AHP method with selection criteria factors such as load capacity, repeatability, maximum tip speed, memory capacity, and manipulator reach. Tansel [26] also used the AHP method with selection criteria factors such as pay load, repeatability, vertical reach, robot mass, axis motion range, and maximum axis speed. Abdel-Malek [27] used the decision support system method with selection criteria factors such as robot type (articulated robots, SCARA robots, etc.), degrees of freedom, pay load, horizontal reach, vertical reach, velocity, repeatability, and power supply. Bhangale et al. [28] utilised the optimal reciprocal collision avoidance and the technique for order of preference by similarity to ideal solution (TOPSIS) method with

selection criteria such as load capacity, repeatability, maximum speed, type of drive, memory capacity, manipulator reach, and degree of freedom. Tao et al. [29] used the data envelopment analysis, AHP, TOPSIS, and axiomatic fuzzy set (AFS) theory selection criteria such as cost, load capacity, velocity, and repeatability error. Karsak [30] used QFD and the fuzzy linear regression method along with selection criteria such as load capacity, repeatability, vertical reach, horizontal reach, and warranty period.

Vahdani et al. [31] used fuzzy TOPSIS selection criteria such as purchase cost, load capacity, and positioning accuracy. Bhattacharya et al. [32] highlighted the QFD and AHP drive system, geometrical dexterity, path measuring system, robot size, robot material, robot weight, initial operating cost, pay load, accuracy, life-expectancy, robot velocity, programming flexibility, and total cost. Karsak et al.[33] used a fuzzy regression-based decision-making approach and selection criteria such as cost, velocity, repeatability, and load capacity. Chatterjee et al. [34] used the VIKOR and ELECTRE methods and selection criteria such as velocity, load capacity, cost, repeatability, vendor service quality, and programming flexibility. Kumar and Garg [35] proposed a distance-based approach, with selection criteria such as velocity, repeatability, load capacity, degree of freedom, stability, compliance, and accuracy. Koulouriotis and Ketipi [36] used fuzzy digraph and matrix methods and selection criteria such as man–machine interface, programming flexibility, repeatability error, purchase cost, and velocity.

In this study, after a rigorous review of articles addressing the application of MCDM to selection problems in different areas, such as robot selection, site allocation, knowledge management and supply chain design, the concomitant problems and opportunities that exist in implementing the AHP in prioritising future robot research are revealed. Based on the existing literature, it is evident that no studies integrate the MCDM technique in prioritising research directions, especially in the field of robotics control and in directing scientific research in general. Accordingly, this study seeks to motivate researchers to further explore state-of-the-art tools, including MCDM, and their applications in directing scientific research activities. The main objective of this research is to disseminate researcher approaches toward improving strategies, tools, and techniques of MCDM in the scientific research sector with a particular focus on its implementation.

The objective of this study is to prioritise research directions in the field of robotics control based on academics' and practitioners' opinions. This research adopted the general AHP approach introduced by Saaty [37]. The adopted hierarchy includes levels of goals, criteria, sub-criteria, and processes for alternative research topics. This study allows researchers in the robotics control domain to strengthen and focus their efforts for industry purposes and to reduce the inherent gap between academic research and industrial needs. It directs the budding robotic research efforts in the developing countries to the area of using robots in automation. Given the problem criteria, application field, processes, and robotics research alternatives, we hypothesized that researcher's and industrial expert's preferences are not equal for each research direction in the field of robotics. Since this problem is not examined in details in the literature, we focused on solving the prioritisation problem using an MCDM and presented results to direct the research efforts and optimize the resources available in a certain planning period to create a research plan. This type of problem treatment presents a new way of conducting robotics research by focusing and directing its efforts.

This paper is composed of four sections. In the second section, the adopted AHP model is illustrated. The third section applies the solution methodology to prioritise future research in robotics control based on the opinion and judgement of academic and industrial experts and the results are discussed. The fourth section provides conclusions and recommendations for future research.

2. Materials and methods

In this study, the Saaty [37] procedure was implemented to design and develop an AHP model. The efficacy of the AHP model depends on the diversity and expertise opinion of the population, hence a diverse population from both the academic and the industrial sector was established, and a sample of people from both developed and developing countries were selected as illustrated in Table 1, where n_a and n_e represent the number of academic and industrial expertise participants for a corresponding country, respectively. The number of participants is indicated in the ordered pair in parentheses. The total number of respondents was 629, however, there were 548 completed and validated questionnaires including 377 academics and 274 practitioners from 24 countries. The questionnaires were prepared online for respondents. The academics were selected based on their publication of robotic research articles in renowned journals, and industrial experts were contacted based on their involvement with pioneer robotics companies that have existed for over a decade. Participants were contacted, and their consent for the participation in the study was obtained via email. The responses are protected and will not be revealed unless a written consent from the respondent is acquired. Expert Choice [38] was used to conduct the AHP, and IBM SPSS V25.0.0 was used to calculate the geometric mean of the collected data.

Table 1 Sample characteristics

Country	(n_a, n_e)	Country	(n_a, n_e)	Country	(n_a, n_e)
People's Republic of China	(12,13)	France	(21,13)	Turkey	(14,9)
USA	(9,7)	Canada	(24,19)	Australia	(12,10)
Japan	(28,23)	India	(23,18)	Taiwan	(18,14)
Germany	(15,11)	Spain	(18,10)	Switzerland	(5,4)
Italy	(12,7)	Iran	(19,15)	Russia	(10,8)
South Korea	(11,8)	Singapore	(20,14)	Mexico	(18,13)
England	(14,12)	Netherlands	(15,10)	Sweden	(12,8)
Brazil	(20,13)	Portugal	(13,4)	Malaysia	(14,11)

The AHP was executed in Expert Choice, a widely-used MCDM software package. This process translated the answers of participants to the questions regarding the pairwise comparisons of level alternatives with the next highest corresponding level in the hierarchy. Five online 60-80-minute group sessions with a panel of experts were conducted to validate and refine the decision context, model content, and hierarchy. A questionnaire in the form of a comparison matrix was used to collect participant opinions. Fig. 1 shows the online questionnaire created to measure the relative pairwise comparison matrix of the main criteria with respect to the goal. Each participant decided on the relative pairwise comparison value of the main criteria with respect to the goal. It was required to circle a number per row using a scale value range from 1 to 9. The "1" value indicates that the two alternatives have equal importance regarding the higher hierarchy level, while "3" indicates a moderate importance and "9" represents an extreme importance. Fig. 2 illustrates the relative pairwise comparison matrix of the main criteria with respect to cost, while Fig. 3 shows the relative pairwise comparison matrix of the main criteria with respect to automotive industry. 410 participants filled the pairwise comparison matrices, and the data were entered into the IBM Statistics v 25.0.0 software to calculate the geometric mean, which was then entered into Expert Choice. We used the ideal synthesis mode, which is designed to identify the single best alternative or the most important criterion [39].

A sensitivity analyses was performed to understand the impacts of objectives and weights on the results. Minimizing the cost, maximizing the tip speed/velocity, maximizing the robot repeatability, and maximizing the manipulator reach priorities were increased to 100%, and the analysis was conducted in the distributive mode. The distributive mode produced results that evaluated alternatives or criteria proportionately. The consistency index was used to evaluate the transitivity of the weights [40]. An inconsistency percentage of less than 10% was accepted by the general AHP theory as defined by Saaty.

Fig. 1 Relative pairwise comparison matrix of main criteria with respect to goal.

Fig. 2 Relative pairwise comparison matrix of main criteria with respect to cost.

Fig. 3 Relative pairwise comparison matrix of main criteria with respect to automotive industry.

3.   Results and discussion

When using a descriptive analysis for the sample presented in Table 1 in terms of mean, standard deviation (SD), minimum value (Min), maximum value (Max), median (Med), and mode, it is noted that a) the observations for n_a had a mean of 15.71, SD of 5.32, Min of 5, Max of 28, Med of 14.50, and mode of 12.00, and b) the observations for n_e had a mean of 11.42, SD of 4.51, Min of 4.00, Max of 23, Med of 11.00, and mode of 13.00. The number of academic participants was higher than the number of industrial experts in all countries that participated in the questionnaire by an average value of 4.29.

3.1   Priorities of the main criteria with respect to goal

As depicted in Table 2, repeatability has more weight than cost, speed, and robot reach. This result indicates that a robot's ability to return to the same position repeatedly is a vital indicator for robotic research as industrial robots have to repeatedly perform the same task millions of times [17]. Cost of the robot is ranked second, as cost is a deciding factor for many of the small and medium-sized enterprises in their decision whether to utilise a robot for their operations. It has been a constant endeavour of robot suppliers and researchers to create a cost-effective robot. The speed and reach of the robot falls further on the priority list; if a robot possesses high repeatability with cost effectiveness, then its speed should also be high to complete the task in less time and with a higher manipulator reach.

3.2 Priorities of the sub-criteria with respect to cost

Robot selection based on cost is shown in Table 2. The electric and electronic industries, which have a market share of 32% (according to the International Federation of Robotics Report), require cost-effective robots. As these industries require products which possess an economic advantage over their competitors, for the products to be delivered to customers, cost has a greater weight compared to other industries. In the electric and electronic industries, the key operation that robots perform is assembly of electronic components, as depicted by its weight of 65.9%. Next in the cost criterion is the automotive industry where welding is the primary operation for which robots are purchased because of the need for high weld quality and consistency [41]. Assembly robots have revolutionized the automotive industry. They were the first robots which found acceptance in the industry and to this day they drive research as the complexity of products to be assembled is constantly increasing. The metal and machine industry, which is prioritised third in the selection of robots with reference to cost, requires welding operations to be automated using robots and has a weight of 68.3%.

The scope of the robotic research in industry with cost as the main criterion includes multi-robot control, force control, safe control, remote robot supervision, 3D vision, and wireless communication. Welding robots play a critical role in the automotive and metal and machine industries; hence, the multi-robot control of welding robots is ranked high in the robotic research areas. Assembly robots are imperative in the electric and electronic industries and force control [42] in assembly lines has also great potential.

3.3 Priorities of the sub-criteria with respect to maximum tip speed/velocity

The speed of the robot is taken into consideration while selecting a robot in an industry as it affects productivity of a firm. The priority of speed is weighted third in the main criteria for robot selection. An increase in speed significantly affects the repeatability of the robot [43]; hence, in industries such as electric, electronic, and automotive where repeatability is a prime factor in efficient operation speed takes a back seat as depicted by the weights. Speed is distinctly prioritised in the metal and machine industries for welding operations [44, 45]. It is also valued in assembly operations in the electric, electronic, and automotive industry. The ranking of robotic research areas with speed as a criterion is safe control (speed with safety), remote robot supervision, force control, wireless communication, multi-robot control, and 3D vision. The study of speed for remote robot supervision is vital as is indicated by the rankings; a supervising robot with high speed and safety requirements is a Herculean task for researchers.

3.4 Priorities of the sub-criteria with respect to repeatability

Repeatability of operations is of prime importance to automotive, electric and electronic industries compared to metal and machine industries as designated by the weights of the sub-criteria. Welding an automobile requires producing precise welds, and welding robots are required to execute this repeatedly [45], which is depicted by the higher weight of 64.9%. Assembly operations of electric and electronic components also require a high degree of repeatability as systems continue to mature with stringent requirements, which opens up areas of research for researchers in multi-robot control, safe control, and remote robot supervision. Repeatability in the metal and machine industries is essential with welding and the assembly of components compared to material handling. The scope of robotic research with repeatability as the criterion includes multi-robot control, safe control, remote robot supervision, force control, 3D vision, and wireless communication.

3.5   Priorities of the sub-criteria with respect to manipulator reach

Manipulator reach is the least favoured criterion compared to repeatability, cost, and speed. Robot reach primarily refers to grasping the components in the metal and machine industry [46] and to reaching out to extreme points to perform welding operations. Correspondingly, in the automotive industry, the reach of the robot is of utmost importance for welding operations [47], whereas robot reach in the electronic and electrical industries is used for assembly operations requiring dexterity [48]. The hierarchy of robotic research areas regarding robot reach as the main criterion is multi robot control, force control, safe control, remote robot supervision, 3D vision, and wireless communication. Based on the AHP comparison of the overall weights, the hierarchy of robotics research areas in order of overall priority are: multi-robot control (0.268), safe control (0.233), remote robot supervision (0.190), force control (0.178), 3D vision, and wireless communication.

Table 2 Results of pairwise comparisons of the total weights of alternatives using Expert Choice

Criteria	Criterion weight	Sub-criteria	Local sub-criterion weight	Sub-subcriterion	Local sub-subcriterion weight	Global sub-subcriterion weight	Multi-robot control (612)	Safe control (56)	Force control (495)	3D vision (70)	Remote robot supervision (2)	Wireless communication (66)
Cost	0.334	Auto	0.327	W	0.570	0.062	0.021	0.018	0.008	0.006	0.006	0.004
				A	0.333	0.036	0.012	0.003	0.011	0.004	0.004	0.002
				M	0.097	0.011	0.002	0.003	0.002	0.001	0.001	0.001
		Electr	0.413	W	0.185	0.026	0.009	0.005	0.004	0.003	0.003	0.001
				A	0.659	0.091	0.027	0.010	0.023	0.008	0.016	0.006
				M	0.156	0.022	0.001	0.006	0.002	0.003	0.007	0.003
		Metam	0.260	W	0.683	0.059	0.023	0.010	0.009	0.005	0.010	0.003
				A	0.200	0.017	0.007	0.003	0.002	0.002	0.003	0.001
				M	0.117	0.010	0.001	0.003	0.003	0.001	0.002	0.001
Cost total			1.000			3.000	0.334	0.103	0.062	0.063	0.033	0.052	0.022
Cost rank							1	3	2	5	4	6
Max tip speed/velocity	0.136	Auto	0.345	W	0.218	0.010	0.001	0.004	0.002	0.001	0.001	0.002
				A	0.715	0.034	0.003	0.011	0.006	0.003	0.006	0.006
				M	0.067	0.003	0.000	0.001	0.001	0.000	0.001	0.000
		Electr	0.109	W	0.333	0.005	0.000	0.002	0.001	0.000	0.001	0.001
				A	0.570	0.008	0.000	0.003	0.001	0.001	0.002	0.001
				M	0.097	0.001	0.000	0.000	0.000	0.000	0.000	0.000
		Metam	0.547	W	0.574	0.043	0.004	0.015	0.007	0.003	0.011	0.002
				A	0.361	0.027	0.003	0.009	0.005	0.002	0.007	0.001
				M	0.065	0.005	0.000	0.001	0.002	0.000	0.001	0.000
Max tip speed/velocity total			1.000			3.000	0.136	0.012	0.046	0.024	0.011	0.030	0.014
Max tip speed/velocity rank							5	1	3	6	2	4
Repeatability	0.451	Auto	0.413	W	0.649	0.121	0.051	0.018	0.013	0.008	0.024	0.006
				A	0.279	0.052	0.019	0.012	0.005	0.003	0.011	0.003
				M	0.072	0.013	0.001	0.005	0.002	0.001	0.003	0.001
		Electr	0.327	W	0.279	0.041	0.004	0.014	0.006	0.004	0.011	0.002
				A	0.649	0.096	0.010	0.033	0.014	0.009	0.025	0.006
				M	0.072	0.011	0.004	0.002	0.001	0.001	0.002	0.000
		Metam	0.260	W	0.582	0.068	0.030	0.012	0.008	0.004	0.012	0.002
				A	0.348	0.041	0.006	0.003	0.020	0.002	0.008	0.001
				M	0.069	0.008	0.000	0.004	0.002	0.001	0.001	0.001
Repeatability total			1.000			2.999	0.451	0.125	0.103	0.070	0.033	0.097	0.023
Repeatability rank							1	2	4	5	3	6
Manipulator reach	0.08	Auto	0.352	W	0.701	0.020	0.008	0.003	0.003	0.002	0.002	0.001
				A	0.240	0.007	0.003	0.001	0.002	0.000	0.001	0.000
				M	0.590	0.017	0.001	0.007	0.004	0.002	0.001	0.001
		Electr	0.089	W	0.285	0.002	0.000	0.000	0.000	0.000	0.000	0.000
				A	0.653	0.005	0.000	0.001	0.002	0.000	0.001	0.000
				M	0.062	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		Metam	0.559	W	0.649	0.029	0.013	0.007	0.003	0.002	0.002	0.001
				A	0.279	0.012	0.002	0.001	0.006	0.001	0.002	0.001
				M	0.072	0.003	0.000	0.001	0.000	0.001	0.000	0.000
Manipulator reach total			1.000			3.531	0.095	0.028	0.022	0.022	0.008	0.010	0.005
Manipulator reach rank							1	3	2	5	4	6
Grand total							0.268	0.233	0.178	0.084	0.190	0.064
Overall priority/Rank							1	2	4	5	3	6

Auto: Automotive industry; Electr: Electric/electronic industry; Metam: Metal & machine industry; W: Welding; A: Assembly; M: Material handling

4. Conclusions

This study investigated the criteria and indicators of the robotics research to concentrate the efforts of the research community to addressing industrial needs. Diverse multi-national experts from both industry and academia participated in the priority evaluation of the robotics research. The level of importance of the subcriteria is based on the pairwise comparisons conducted by experts. Based on the AHP comparison of the overall weights, the hierarchy of robotic research areas in descending order is: multi-robot control, safe control, remote robot supervision, force control, 3D vision, and wireless communication. This hierarchy indicates how research efforts should be channelled out to the development of effective industrial robotics.

The natural expansion of this research may involve exploring the applicability of using Fuzzy-AHP, TOPSIS, and other MCDM techniques for solving the research direction prioritisation problem. This research can also be extended to explore the relationship between the descriptive variable as a multivariate analysis and structure equation modelling for a cause-and-effect analysis of the factors affecting goals and objectives. Therefore, the advantages and disadvantages of the decision-making trial and evaluation laboratory compared to other methods remain unknown and can be further examined. Integrating the AHP with the QFD to prioritise research direction in the field of robotics control is a candidate research area related to the topic of this study. Availability of resources, planning horizons, and national/international directions can also be included in future research.

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