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Attribute based specification, comparison and selection of a robot

P.P. Bhangale *, V.P. Agrawal, S.K. Saha

Department of Mechanical Engineering, Indian Institute of Technology Delhi, Hauz Khas, New Delhi-110016, India

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Abstract

The problem of robot selection has been of concern to manufacturers for many years. This problem has become more difficult in recent years due to increasing complexity, available features, and facilities offered by different robotic products. The objective of this research is to generate and maintain reliable and exhaustive database of robot manipulators based on their different pertinent attributes. This database can be used to standardize the robot selection procedure when the manufacturing firm has decided to use the robot for a particular operation. This will help the robot user to save time by providing him a tool for selecting the robot system most suited for his operational needs. The robot selection procedure allows rapid convergence from a very large number of candidate robots to a manageable shortlist of potentially suitable robots using 'elimination search' based on the few critical selection attributes. Subsequently, the selection procedure proceeds to rank the alternatives in the shortlist by employing different attributes based specification methods and graphical methods. The ranks of the candidate robots are calculated with respect to the best possible robot, say +ve benchmark robot, for particular application. This ranking will provide a good guidance for the robot user to select the robot. It will also provide a good insight to the robot manufacturer so that he can improve his product or introduce new product to fulfill the need of customer. It will help the designer at various design stages, while the maintenance people can plan maintenance strategy to reduce the down time

* Corresponding author.
E-mail addresses: prasad_bhangale@rediffmail.com (P.P. Bhangale), vagrawal@mech.iitd.ernet.in (V.P. Agrawal), saha@mech.iitd.ernet.in (S.K. Saha).

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and maintenance efforts. This is an attempt to create exhaustive database by identifying maximum possible number of attributes for robot manipulators. The coding scheme and the selection procedures, mathematical and graphical, are illustrated with example.

Keywords: Manipulator; Selection; MADM; TOPSIS; Pertinent attributes; Normalization; Weighted normalization; Coefficient of similarity; Ranking

1. Introduction

There has been rapid increase in the number of robot systems and robot manufacturers. Robots with vastly different capabilities and specifications are available for a wide range of applications. The selection of the robot to suit a particular application and production environment, from the large number of robots available in the market today has become a difficult task. Various considerations such as availability, management policies, production systems compatibility, and economics need to be considered before a suitable robot can be selected. The complexity of problem can be better appreciated when one realizes that there are over 75 attributes that have to be considered in the selection of robot for particular application. Moreover, many of them are conflicting in nature and have different units, which cannot be unified and compared as they are.

There are a number of reported studies concerning the selection of robots for manufacturing applications. Paul and Nof [17] compared humans to robots in order to determine which of the two was better suited for a given job. Kamali et al. [11] looked at the problem from the point of view of selecting robot from other alternate methods of production such as manual or hard automation. Nof and Lechtman [15], using the method-time-motion (MTM) concept for manual operation, developed a robot time and motion (RTM) system. Vukobratovic [19] found that the spherical configuration was superior to the jointed-arm, cylindrical, or rectangular robot designs in terms of speed and energy consumption. Gupta and Goel [5] made an attempt to present a comprehensive scheme to check feasibility of robotization for an application. Dooner [4] presented a paper in which he simulated robot operation in the workspace and used the workspace as an aid to robot selection. Huang and Ghandforoush [8] stated the procedure to evaluate and select the robot depending on the investment, budget requirements and comparing the suppliers of the robots. But they had assumed that the user knows which robot to buy and the question was from whom to buy. Offodile et al. [16] developed coding and evaluation of robotic systems and used it to store the robot characteristics as a database. This information was used for robot selection using economic modeling. While creating the database (ROBOCODE), the authors have ignored some very important attributes, or may be the technology was not developed to the extent. Some important attributes, which need immediate attention, are manipulability, singularities present in the workspace, difference in the computational complexity of dynamic equations governing the robot, etc. Madhuraj [13] selected robot considering cost as one criterion and used to shortlist the robots for the particular applications. In the contemporary work, Hinson [6,7] stated that the working environment of the robot is a major selection factor. He also taken help of work envelop of the robot for its evaluation. While Jones [10] used marginal value function to evaluate and rank the robots.

Agrawal et al. [1] used Multiple Attribute Decision Making (MADM) approach TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) to evaluate, rank and select robots for particular application according to the requirements of the users. The pertinent attributes identified in the paper were less and more emphasis has been given to put forward TOPSIS methodology applied to robot selection. Same methodology is used for optimum selection of grippers for robotic applications [2]. Recently Khouja and Kumar [12] used options theory and investment evaluation procedure for selection of robots. Braglia and Petroni [3] did investment evaluation using data envelopment analysis for robot selections and Wang et al. [20] used fuzzy logic technique in MADM approach for machine selection in flexible manufacturing.

2. Manipulator attributes

Proper identification of manipulator attributes is critically important when comparing various alternative robots. Therefore, whenever a robot user goes to the supplier for purchase of new robot, this identification of attributes attain significant importance. Sometimes mere articulation of what attributes are important in the context of particular alternatives under consideration can lead to a rational choice without formal application of some quantitative or semi-quantitative methodology. However, in most cases the user needs to be assisted in identifying the robot attributes wisely and accordingly the application.

The final product of industry will directly depend on the proper choice of the robot. So the robots should be selected with proper identification of attributes. If the robot attributes identification is done carefully, the selection of the robot for particular application will be precise, which will boost the productivity [14].

2.1. Quantification and measurement of the attributes

The robot manipulator will be expressed in detailed manner with the attributes identified e.g., payload capacity 35 kg; repeatability 0.1 mm; horizontal reach 0.8 m, etc. But all attributes are not quantitative, e.g., built quality, after-sales service, etc. The robots can be rated on the scale of 1–5 or 1–10 for these attributes. A similar approach has to be used for the informative attributes, which just tell you information about some attribute of the robot such as the drives are electrical or the robot has a polar coordinate system, which will be denoted by some number whose numerical value will have no significance. They cannot be used for the mathematical treatment since they are just a representation and numeric value has no significance.

There may be some attributes of which quantification is not readily available and has to be done by some mathematical model or modeling, simulation and analysis. Such as reliability can be expressed by Mean Time Between Failure (MTBF) or Mean Time To Repair (MTTR) methods, while for some attributes like life expectancy, thorough experimentation is required if not provided by the manufacturer.

Quantification of many of the attributes is not readily available from the manufacturer. But if the manufacturer will make it a standard practice to identify, quantify and provide these attributes, it will be helpful to himself apart from robot designer, user, maintenance personnel, etc.

2.1.1. Usefulness to the manufacturer

The quantification and monitoring of the attribute magnitudes will help the manufacturer to control them closely so that he can fulfill the demand of the user precisely. Moreover, he can find out the market trend by observing the attributes magnitudes. This will help the manufacturer to modify his product to suit the future needs of the robot user. He can use the database to produce optimum robots in the minimum possible time. The robot manufacturer can also use these attributes for the SWOT (Strength–Weakness–Opportunity–Threat) analysis of his product.

2.1.2. Usefulness to the user

This identification of the attributes will help the user for the database storage and its retrieval. This will generate the computerized database, which can be used in different formats for different purposes by different people in the organization. It also will help the user to select the best possible robot for the particular application whenever it is required. The user will know exactly what are the physical characteristics and performance parameters of the robot. This will keep the user well informed about the capabilities of the robot while putting it to use.

2.1.3. Usefulness to the designer

For the designer at conceptual design stage, this identification will help to generate various alternative designs, which can be developed as modular robots. Using the modular robots approach, the optimum robots according to the market requirements can be designed in very little time. He can identify the critical attributes, which directly affects the performance. The designer can change these critical attributes and monitor them to control particular parameters so that the required performance can be obtained from the robot. Designer can use these attributes for cause and effect analysis, where he can find out the effects of manipulating these attributes on the robot performance.

2.1.4. Usefulness to the maintenance personnel

The maintenance personnel will also get benefited from this database, since they will know what exactly lies below the cover of the robot. They can plan the maintenance schedules to minimize the break down time and effectively implement the condition monitoring for preventive maintenance. They can predict the health of the robot at any given time and ensure the availability of the robot for usage.

2.2. Identification of new attributes

Till date many researchers had tried to solve the robot selection problem with various methods, but summarily they had overlooked many important characteristics of robotic system, which has to be taken into consideration.

The characteristics equations of the system, i.e., dynamic and kinematic equations of the robot, their characteristics were ignored till now. These equations are very important since the operational performance of the robot manipulator depends on them. The computational simplicity of the aforementioned dynamics equations of motion is also an index of performance characteristics of robot. Simpler the equations better is the robot. So this simplicity has been identified as an attribute. The number of joints, axes, and degree of freedom (DOF) were taken into account but the sequence of joints and their respective orientations and arrangements had not been considered. This number of joints, their sequence and orientation constitutes the manipulator architecture or structure. This structure is very important salient feature of the manipulator and also affects the performance. The robots with same number of joints and joint sequence but with different joint orientations will have different performance characteristics. This architecture should also get representation in the attributes and hence various pertinent attributes have been identified to define it.

The robot operating in its workspace does not operate with same ease everywhere. At some places it can operate in more prehensile manner while at some places it may face problems in moving or applying force in particular direction. This ease of operation is termed as manipulability of the robot. This manipulability can be quantified as manipulability measure and can be used as an attribute. The attributes pertaining to the drive system of the robot are also identified in details. These main attributes have been broken down to sub-attributes and sub-sub-attributes successfully so that the robot manipulator can be identified in very precise and detailed manner. Similarly the motion provided by actuators and motion gained with the basic structure of robot, i.e., motion transformation is also an important robot characteristics.

Further research is necessary for the evaluation and quantification of these newly identified attributes. Moreover, these quantification methods are required to be standardized to guide the manufacturers so that they can quantify the attributes on their own and provide to the user directly.

2.3. Coding scheme

The manipulator attributes are found out based on its broad area as general parameters, physical parameters, performance based, etc. They are given as follows:

General

1. DH parameters
2. Price range
3. Type of robot
4. Coordinate system

Physical

5. Motion transformation from actuator to link
6. Means used for rotary to rotary motion conversion
7. Means used for rotary to linear motion conversion
8. Mounting arrangement of the robot
9. Type of actuators
10. Power source requirement
11. Electrical drive system
12. Hydraulic drive system
13. Type of cables used

14. Cable layout
15. Material used for links
16. Link cross sections
17. Weight of the robot
18. Size of the robot
19. Type of gears used for power transmission
20. Type of gear train used
21. Type of flexible drive system used
22. Link length ratios
23. Type of grippers supported
24. Link masses and inertia properties
25. Number of offset joints
26. Natural frequency
27. Number of axes
28. Space requirements of the robot
29. Types of end effectors
30. Number of end effectors
31. AC Voltage requirement
32. AC Current supply
33. AC Power consumption
34. AC Phase
35. AC Frequency

Performance

36. Payload of the robot
37. Overload capacity of the robot
38. Workspace
39. Stroke
40. Dexterity
41. Dexterous workspace
42. Manipulability measure
43. Singularities present
44. Computational complexity of dynamic equations
45. Maximum speed end effector
46. Accuracy
47. Repeatability
48. Resolution
49. Force output

Structure/architecture

50. Type of basic robot configuration
51. Classification by type of mechanism

52. Degree of freedom
53. Robot arm configuration
54. Type of joints
55. Number of joints
56. Joint sequence
57. Joint orientations

Application

58. Usage of robot
59. Working environment

Sophistication of equipment

60. Maintainability
61. Assemblability
62. Dissemblability
63. Safety features

Control and feedback system

64. Control of robotic joints
65. Gripper control
66. Classification by control method
67. Memory capacity of the robot controller
68. Sensors
69. Internal state sensors
70. External state sensors
71. Tactile sensors
72. Slip sensor
73. Robotic arc welding sensors
74. Force and torque sensors
75. Type of memory
76. Programming method
77. Number of input channels of the controller
78. Number of output channels of the controller
79. Input channels for robot
80. Output channels for robot

Availability/reliability

81. Down time
82. Common reason for down time
83. Reliability

Table 1
Manipulator identification coding scheme

General	1	2	3	4							
Physical	5	6	7	8	9	10	11	12	13	14	15
	16	17	18	19	20	21	22	23	24	25	26
	27	28	29	30	31	32	33	34	35		
Performance	36	37	38	39	40	41	42	43	44	45	46
	47	48	49								
Structure...	50	51	52	53	54	55	56	57			
Application	58	59									
Sophistication...	60	61	62	63							
Control...	64	65	66	67	68	69	70	71	72	73	74
	75	76	77	78	79	80					
Availability...	81	82	83								

The above-mentioned attributes can be tabulated in the form of coding scheme as shown in Table 1.

2.4. Illustration of coding

The proposed coding scheme explained above is illustrated here with example. Suppose we are codifying the maximum speed of the manipulator, it can be done as follows.

2.4.1. Maximum speed of manipulator

The maximum linear velocity at tip coordinate frame can be coded as follows:

Maximum speed in m/s	Code
Unspecified	0
0–0.01	1
0.01–0.05	2
0.05–0.1	3
0.1–0.2	4
0.2–0.5	5
0.5–1	6
1–2	7
2–5	8
>5	9

This code will be used to specify the maximum speed of the manipulator in the respective shell number 45, since it is allotted to it, as shown in the Tables 2 and 3. Here the manipulator under consideration has the maximum speed of 1 m/s, which can be given code 7.

Table 2
Example. PUMA 560C Robotic manipulator[a]

Sr. no.	Attribute	Information	Code
1	DH parameters	–	0
2	Price range	–	0
3	Type of robot	Articulated	A
4	Coordinate system	Spherical	S
5	Motion transformation from actuator to link	–	0
6	Means used for rotary to rotary motion conversion	–	0
7	Means used for rotary to linear motion conversion	–	0
8	Mounting arrangement of the robot	–	0
9	Type of actuators	Electrical	E
10	Power source requirement	DC	D
11	Electrical drive system	–	0
12	Hydraulic drive system	–	0
13	Type of cables used	–	0
14	Cable layout	Partial concealed	2
15	Material used for links	–	0
16	Link cross sections	–	0
17	Weight of the robot	–	0
18	Size of the robot	–	0
19	Type of gears used for power transmission	–	0
20	Type of gear train used	–	0
21	Type of flexible drive system used	–	0
22	Link length ratios	–	0
23	Type of grippers supported	–	0
24	Link masses and inertia properties	–	0
25	Number of offset joints	–	0
26	Natural frequency	–	0
27	Number of axes	–	0
28	Space requirements of the robot	–	0
29	Types of end effectors	–	0
30	Number of end effectors	–	0
31	AC Voltage requirement	–	0
32	AC Current supply	–	0
33	AC Phase	–	0
34	AC Frequency	–	0
35	Power consumption	0.6 kw	3
36	Payload of the robot	4 kg	5
37	Overload capacity of the robot	–	0
38	Workspace	–	0
39	Stroke	–	0
40	Dexterity	–	0
41	Dexterous workspace	–	0
42	Manipulability measure	–	0
43	Singularities present	–	0
44	Computational complexity of dynamic equations	–	0
45	Maximum speed end effector	1.0 m/s	7
46	Accuracy	–	0
47	Repeatability	±0.1 mm	5
48	Resolution	–	0
49	Force output	–	0

(*continued on next page*)

Table 2 (*continued*)

Sr. no.	Attribute	Information	Code
50	Type of basic robot configuration	–	0
51	Classification by type of mechanism	–	0
52	Degree of freedom	–	0
53	Robot arm configuration	–	0
54	Type of joints	–	0
55	Number of joints	–	0
56	Joint sequence	–	0
57	Joint orientations	–	0
58	Usage of robot	–	0
59	Working environment	–	0
60	Maintainability	–	0
61	Assemblability	–	0
62	Dissemblability	–	0
63	Safety features	–	0
64	Control of robotic joints	Numerical	5
65	Gripper control	–	0
66	Classification by control method	–	0
67	Memory capacity of the robot controller	–	0
68	Sensors	–	0
69	Internal state sensors	–	0
70	External state sensors	–	0
71	Tactile sensors	–	0
72	Slip sensor	–	0
73	Robotic arc welding sensors	–	0
74	Force and torque sensors	–	0
75	Type of memory	–	0
76	Programming method	Teach Pendant	1
77	Number of input channels of the controller	–	0
78	Number of output channels of the controller	–	0
79	Input channels for robot	–	0
80	Output channels for robot	–	0
81	Down time	–	0
82	Common reason for down time	–	0
83	Reliability	–	0

[a] http://www.rpautomation.com/Robotspecs/robotspecs2.htm

This table clearly indicates that the information supplied by the manufacturer to the user is meager and it is required to be more elaborate.

Here we can see that most of the cells are having 0 as code in them. The 0 represents that the information relating to the particular cell is not available to the authors. This information is not provided by the manufacturer, but the authors think that this information also should be provided to make the database exhaustive. Moreover, the database storage, retrieval and the selection procedure will be more precise and accurate. This coding scheme can be used as it is for the visual comparison between two robots up to certain extent. It allows faster comparison in various formats.

Table 3
Manipulator identification code

General	0	0	A	S							
Physical	0	0	0	0	E	D	0	0	0	2	0
	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	3		
Performance	5	0	0	0	0	0	0	0	0	7	0
	5	0	0								
Structure...	0	0	0	0	0	0	0	0			
Application	0	0									
Sophistication...	0	0	0	0							
Control...	5	0	0	0	0	0	0	0	0	0	0
	0	1	0	0	0	0					
Availability...	0	0	0								

3. The 3-stage selection procedure

3.1. Elimination search

Though all the attributes have been identified, all of them would not be important while selecting the robot for particular application. There will be few attributes, which will have direct effect on the selection procedure. This small number of attributes may be set-aside as 'pertinent attributes' as necessitated by the particular application and/or the user. The threshold values to these 'pertinent attributes' may be assigned by obtaining information from the user and the group of experts. Henceforth the selection procedure focuses solely on the pertinent attributes leaving out the rest. On the basis of the threshold values of the pertinent attributes, a shortlist of robots is obtained. This may be achieved by scanning the database for pertinent attributes, one at a time, to eliminate the robot alternatives, which have one or more pertinent attribute values that fall short of the minimum required (threshold) values. To facilitate this search procedure an identification system has been made for all the robots in the database.

3.2. Evaluation procedure

A mini-database is thus formed which comprises these satisfying solutions i.e., alternatives which have all attributes satisfying the acceptable levels of aspiration. The problem is now one of finding out the optimum or best out of these satisfying solutions. The selection procedure therefore needs to rank these solutions in order of merit.

The first step here will be to represent all the information available from the database about these satisfying solutions in the matrix form. Such a matrix is called as decision matrix, **D**. Each row of this matrix is allocated to one candidate robot and each column to one attribute under consideration. Therefore an element d_{ij} of the decision matrix **D**, gives the value of jth attribute in the row (non-normalized) form and units, for the ith robot. Thus if the number of short-listed robots is 'm' and the number of pertinent attributes is 'n', the decision matrix is an $m \times n$ matrix.

3.2.1. Normalized specifications

The next step is construction of the normalized specification matrix, **N**, from the decision matrix, **D**. Normalization is used to bring the data within particular range or scale, moreover, it provides the dimensionless magnitudes. This phenomenon is used to calculate the normalized specification matrix. The normalized specification matrix will have the magnitudes of all the attributes of the robots on the common scale of 0 to 1. It is a sort of value, which indicates the standing of that particular attribute magnitude when compared to the whole range of the magnitudes for all candidate robots.

An element n_{ij} of the normalized matrix **N** can be calculated as

$$n_{ij} = d_{ij} \Bigg/ \left(\sum_{i=1}^{m} d_{ij}^2 \right)^{1/2} \tag{1}$$

where d_{ij} is an element of the decision matrix, **D**.

The next step is to obtain information from the user or the group of experts on the relative importance of one attribute with respect to another. This information is sought in terms of a ratio. Information on all such pair-wise comparisons is stored in a matrix called as relative importance matrix, '**A**', which is $n \times n$ matrix. Here a_{ij} will contain the relative importance of ith attribute over the jth attribute. The symmetric terms of this matrix will be reciprocals of each other while the diagonal will be unity.

The information stored in **A** matrix is on pair-wise basis. It is to be modified into representation that gives the relative weights of all attributes taken together so that the cumulative sum of the weights is equal to unity. The eigen vector method, which allows for some inconsistencies in the judgment of relative importance of attributes while making pair-wise comparisons is used to find the weights. These inconsistencies arise due to inaccurate human judgments [9].

The eigen vector method seeks to find weight vector **w** from the eigen value problem associated with the matrix, **A**, i.e.,

$$\mathbf{Ax} = \lambda \mathbf{x} \tag{2}$$

where λ is the eigen value of **A** and **x** is the corresponding eigen vector [18]. For $n \times n$ **A** there are n eigen values λ_i, for $i = 1,\ldots,n$, and corresponding to λ_i, there are n eigen vectors $\mathbf{x}_i$, for $i = 1,\ldots,n$. vector **w** is now found in the following manner:

1. Take eigen vector, $\mathbf{x}_{\max}$ corresponding to the largest eigen value $\lambda_{\max}$, as all the elements of $\mathbf{x}_{\max}$ are either positive or negative [1,9].
2. Find the sum of the elements of $\mathbf{x}_{\max}$ as

$$\alpha = \sum_{i=1}^{n} (\mathbf{x}_i)_{\max} \tag{3}$$

3. Find weight vector **w** as

$$\mathbf{w} = (\mathbf{x}_{\max})/\alpha \text{ such that } \sum_{i=1}^{n} \mathbf{w}_i = 1. \tag{4}$$

3.2.2. Weighted normalized specification

The weights obtained from the relative importance matrix have to be applied to the normalized specifications since all attributes have different importance while selecting the robot for particular application. The matrix, which combines the relative weights and normalized specification of the candidates, is weighted normalized matrix, '**V**'. It will give the true comparable values of the attributes. This can be obtained as follows:

$$\mathbf{V} = \begin{bmatrix} w_1 n_{1,1} & w_2 n_{1,2} & \cdots & w_n n_{1,n} \\ w_1 n_{2,1} & \ddots & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ w_1 n_{m,1} & w_2 n_{m,2} & \cdots & w_n n_{m,n} \end{bmatrix} = \begin{bmatrix} v_{1,1} & v_{1,2} & \cdots & v_{1,n} \\ v_{2,1} & \ddots & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ v_{m,1} & v_{m,2} & \cdots & v_{m,n} \end{bmatrix} \tag{5}$$

3.3. Ranking and selection procedure

The ranking of the robots can be done by either mathematically (TOPSIS method) or graphically (Line graph and Spider diagram methods).

3.3.1. TOPSIS method

The weighted normalized matrix **V** is used to obtain the +ve and −ve benchmark robots, where the both benchmark robots are hypothetical robots, which supposed to have best and worst possible attribute magnitudes. The TOPSIS method is based on the concept that the chosen option (optimum) should have the shortest distance from the +ve benchmark robot (best possible robot) and be farthest from the −ve benchmark robot (worst possible robot). The measure ensures that the top ranked robot is closest to +ve benchmark robot and farthest from −ve benchmark robot.

Here, we calculate separation measures from +ve and −ve benchmark robots, respectively, as S_i^* and S_i^- as follows.

The separation from the +ve benchmark robot is given by

$$S_i^* = \left[\sum_{j=1}^{n} (v_{ij} - v_1^*)^2\right]^{1/2} \quad (i = 1, 2, \ldots, m) \tag{6}$$

and separation from the −ve benchmark robot is given by

$$S_i^- = \left[\sum_{j=1}^{n} (v_{ij} - v_1^-)^2\right]^{1/2} \quad (i = 1, 2, \ldots, m) \tag{7}$$

Then the relative closeness to the +ve benchmark robot, C^*, which is a measure of the suitability of the robot for the chosen application on the basis of attributes considered, is calculated. A robot with the largest C^* is preferable.

$$C^* = S_i^- / (S_i^* + S_i^-) \tag{8}$$

Ranking of the candidate robots in accordance with the decreasing values of indices C^* indicating the most preferred and the least preferred feasible optional solutions is done.

3.3.2. Graphical methods

Till now we have seen the mathematical representation of the specifications, normalized and weighted normalized specifications. There are many methods to evaluate the robots using mathematical approach [9]. But we are trying to explore graphical way to process the available data and select the robot. The graphical representation methods like line graph and spider diagram can be used for this purpose.

3.3.2.1. Line graph representation We have specification matrix **D**, normalized and weighted normalized specification matrices **N** and **V**, respectively, containing information of the candidate robots. These matrices can be represented graphically using line graph by plotting the magnitude of the attributes on the vertical axis and the attributes on the horizontal axis. Please note that the attributes, of which minimum values are preferred such as accuracy, repeatability, cost, etc., we use the reciprocals of the magnitudes to plot so that it will bring consistency where all the attributes are to be maximized to reach the best possible solution. If we plot the values for different candidate robots, we can obtain the line graph for them. These graphs will be distinct for all of the candidate robots and can be used as comparison basis. The area under the curve can be used to quantification purpose and to compare the candidate robots with each other and benchmark robot to be defined later (Fig. 1).

These line graphs can be plotted for specifications, normalized and weighted normalized specifications of all the candidate robots as well as the benchmark robot. The area under the curve can be obtained as follows.

Let the width between the two parameters on horizontal axis as unity and d_{ij}, n_{ij}, and v_{ij} are the elements of **D**, **N**, and **V** matrices.

Area under the line graph of specification of ith robot can be found out as

$$\mathrm{AD}_i^L = (d_{i,1} + 2(d_{i,2} + \cdots + d_{i,n-1}) + d_{i,n})/2 \tag{9}$$

Similarly, area under the graph of normalized and weighted normalized specifications of the ith robot, i.e., AN_i^L and AV_i^L using their respective elements.

3.3.2.2. Spider diagram In this method, the attributes have been considered to be forming the spider diagram. So the angle θ between the attribute axes can be calculated as $\theta = 2\pi/n$, where n number of attributes are under consideration. The attributes, normalized and weighted normalized specifications magnitudes are plotted to obtain the spider diagram, also known as polar or radar diagram, as shown in Fig. 2 for different candidate robots.

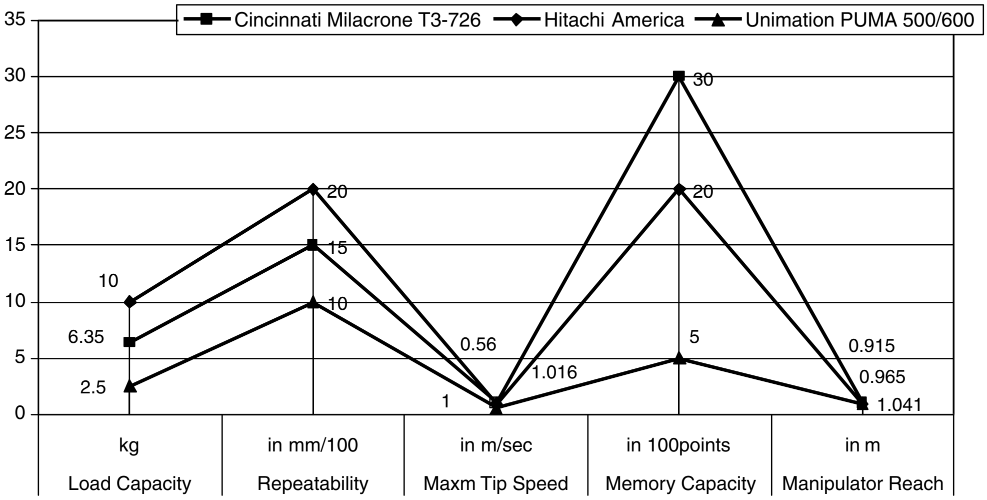

Fig. 1. Line graph plot for the specifications and the area under the curve is shaded.

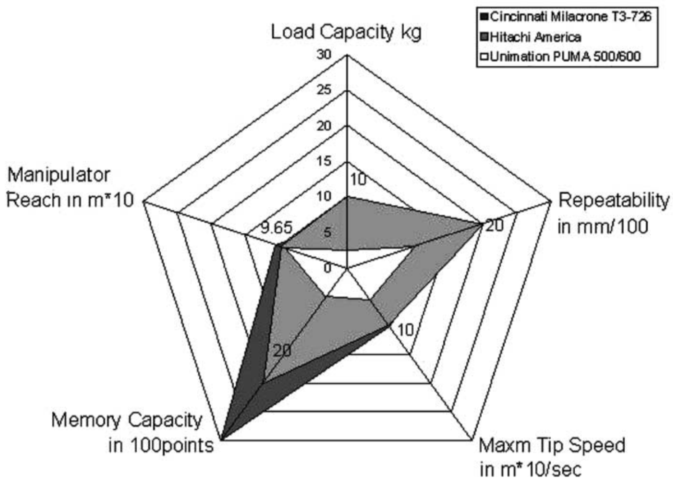

Fig. 2. Spider diagram polygon for the specifications and the area enclosed is shaded.

Here the area enclosed by the polygon formed on the spider diagram is the indication of the robot capabilities. All the specification magnitudes are boiled down to this single index. This area enclosed by the polygon of the *i*th robot can be calculated as follows.

In the spider diagram, $\theta = 2\pi/n$, where n is the number of attributes.

Let d_{ij} represents the value of *j*th attribute in the *i*th robot along θ_i.
Let n_{ij} represents the normalized value of the *j*th attribute in the *i*th robot along θ_i.
Let v_{ij} represents the weighted normalized value of the *j*th attribute in the *i*th robot along θ_i.

$$\mathrm{AD}_i^S = \frac{\sin\theta}{2}\sum_{j=1}^{n} d_{ij}d_{i,j+1}; \quad \text{where } d_{i,n+1} = d_{i,1}. \tag{10}$$

Similarly for normalized and weighted normalized specifications areas enclosed by polygons, i.e., AN_i^S and AV_i^S, respectively, are calculated.

3.3.2.3. Identification and graphical representation of the benchmark robot. The same +ve benchmark robot, defined earlier, is used here for the comparison of the candidate robots for the ranking purpose. The areas under the line graph for +ve benchmark robot, i.e., AD_B^L, AN_B^L, and AV_B^L are calculated. The areas enclosed by the polygon of spider diagram for benchmark robot, i.e., AD_B^S, AN_B^S, and AV_B^S are also calculated. All the candidate robots will be compared with the +ve benchmark robot for the evaluation purpose. It will show the suitability of the robot for the particular task.

3.3.2.4. Ranking and selection of the robots. Now we have specification matrix along with normalized specification and weighted specification matrices ready for all the candidate robots along with the +ve benchmark robot. We need a measure to compare the candidates with benchmark robot so that they can be ranked and selected.

3.3.2.5. Coefficient of similarity (COS). The evaluation and ranking of the robots using the novel graphical methods can be done by their similarity to +ve benchmark robots. Let the Coefficient of similarity (COS) is the ratio of area under the curve or enclosed by the polygon for the candidate to that of the benchmark robot. The value of COS can be any +ve fraction ($0 \leqslant \mathrm{COS} \leqslant 1$) and will be a measure of the closeness of candidate robot with the benchmark robot. The candidates with COS magnitude closer to unity are preferable, since it indicates the closeness to the +ve benchmark robot.

Coefficient of similarity (COS) based on decision matrix

$$\mathrm{COS}_j^D = \mathrm{AD}_j/\mathrm{AD}_I \tag{11}$$

AD_j for jth robot and different methods, i.e., line graph, etc.

Coefficient of similarity (COS) based on normalized specifications matrix

$$\mathrm{COS}_j^N = \mathrm{AN}_j/\mathrm{AN}_I \tag{12}$$

AN_j for jth robot and different methods, i.e., line graph, etc.

Coefficient of similarity (COS) based on weighted normalized matrix

$$\mathrm{COS}_j^V = \mathrm{AV}_j/\mathrm{AV}_I \tag{13}$$

AV_j for jth robot and different methods, i.e., line graph, etc.

Thus the COS calculations for all the n number of candidate robots and for both graphical methods, viz., line graph and spider diagram methods using the weighted normalized specifications. Though the COS based on the specifications and normalized specifications were also calculated but they are not significant from the selection point of view. They indicate how the preferences changed during the normalization and weight application process. It can be used for monitoring the process.

4. Illustrative example

Suppose we want to select a robot for some pick-n-place operation, where it has to avoid some obstacles. The minimum requirement for this application is as follows:

1. Load capacity	minimum 2 kg
2. Repeatability	0.5 mm
3. Maximum tip speed	at least 255 mm/s
4. Type of drives (actuators)	electrical only
5. Memory capacity	at least 250 points/steps
6. Manipulator reach	500 mm
7. Degree of freedom	at least 5

From the database generated, after 'elimination search' we can find out manageable number of candidate robots and their pertinent attributes. They are tabulated in Table 4.

Here repeatability is the type of attribute of which is the minimum magnitude is preferable and hence the reciprocal of the values in column representing repeatability should be used to form the decision matrix, **D**.

The procedure for the selection of the robot is as follows:

Step 1. Formation of decision matrix, '**D**', i.e., the matrix which will contain all the magnitudes of specifications. The rows of the matrix are the candidate robots, with their attribute values listed in columns.

$$\mathbf{D} = \begin{bmatrix} 60 & 2.5 & 2540 & 500 & 990 \\ 6.35 & 6.667 & 1016 & 3000 & 1041 \\ 6.8 & 10 & 1727.2 & 1500 & 1676 \\ 10 & 5 & 1000 & 2000 & 965 \\ 2.5 & 9.8 & 560 & 500 & 915 \\ 4.5 & 12.5 & 1016 & 350 & 508 \\ 3 & 10 & 1778 & 1000 & 920 \end{bmatrix} \tag{14}$$

Table 4
Attributes for the short-listed candidate robots

	Load capacity in kg	Repeatability in mm	Maximum tip speed in mm/sec	Memory capacity in points or steps	Manipulator reach in mm
ASEA-IRB 60/2	60	0.4	2540	500	990
Cincinnati Milacrone T^3-726	6.35	0.15	1016	3000	1041
Cybotech V15 Electric Robot	6.8	0.10	1727.2	1500	1676
Hitachi America Process Robot	10	0.2	1000	2000	965
Unimation PUMA 500/600	2.5	0.10	560	500	915
United States Robots Maker 110	4.5	0.08	1016	350	508
Yaskawa Electric Motoman L3C	3	0.1	1778	1000	920

Step 2. Construction of Relative importance matrix **A**.

A group of experts will determine the relative importance of the attributes with respect to each other. The symmetric terms will be reciprocals of each other.

$$\mathbf{A} = \begin{bmatrix} 1 & 1 & 2 & 0.5 & 0.33 \\ 1 & 1 & 0.5 & 2 & 2 \\ 0.5 & 2 & 1 & 3 & 2 \\ 2 & 0.5 & 0.33 & 1 & 0.33 \\ 3 & 0.5 & 0.5 & 3 & 1 \end{bmatrix} \tag{15}$$

Step 3. Finding out the maximum eigen value of the relative importance matrix **A**.

$$(\mathbf{A} - \lambda_{\max}\mathbf{I}) = \begin{bmatrix} 1-\lambda & 1 & 2 & 0.5 & 0.33 \\ 1 & 1-\lambda & 0.5 & 2 & 2 \\ 0.5 & 2 & 1-\lambda & 3 & 2 \\ 2 & 0.5 & 0.33 & 1-\lambda & 0.33 \\ 3 & 0.5 & 0.5 & 3 & 1-\lambda \end{bmatrix} \tag{16}$$

$$(\mathbf{A} - \lambda_{\max}\mathbf{I}) = 0$$

$$\lambda = 6, -0.2095 \pm 2.2910i, -0.2762 \pm 0.4806i$$

$$\lambda_{\max} = 6$$

$$(\mathbf{A} - \lambda_{\max}\mathbf{I}) = \begin{bmatrix} -5 & 1 & 2 & 0.5 & 0.33 \\ 1 & -5 & 0.5 & 2 & 2 \\ 0.5 & 2 & -5 & 3 & 2 \\ 2 & 0.5 & 0.33 & -5 & 0.33 \\ 3 & 0.5 & 0.5 & 3 & -5 \end{bmatrix} \tag{17}$$

Step 4. Calculating weights for each attribute using the eigen vector associated with maximum eigen value.

$$(\mathbf{A} - \lambda_{\max}\mathbf{I})\mathbf{w} = 0 \tag{18}$$

$$\begin{bmatrix} -5 & 1 & 2 & 0.5 & 0.33 \\ 1 & -5 & 0.5 & 2 & 2 \\ 0.5 & 2 & -5 & 3 & 2 \\ 2 & 0.5 & 0.33 & -5 & 0.33 \\ 3 & 0.5 & 0.5 & 3 & -5 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ w_5 \end{bmatrix} = 0 \tag{19}$$

$$w_1 + w_2 + w_3 + w_4 + w_5 = 1 \tag{20}$$

$$w_1 = 0.1761$$

$$w_2 = 0.2042$$

$$w_3 = 0.2668$$

$$w_4 = 0.243$$

$$w_5 = 0.2286$$

Step 5. Calculating the normalized specification matrix.

This normalization helps to provide the dimensionless elements of the matrix.

$$r_{ij} = d_{ij} \bigg/ \left(\sum_{i=1}^{m} d_{ij}^2 \right)^{1/2} \tag{21}$$

$$\mathbf{N} = \begin{bmatrix} 0.9702 & 0.10875 & 0.6355 & 0.1217 & 0.3559 \\ 0.1029 & 0.29 & 0.2542 & 0.7304 & 0.3741 \\ 0.1102 & 0.435 & 0.4321 & 0.3652 & 0.6023 \\ 0.1632 & 0.2175 & 0.2504 & 0.4869 & 0.3468 \\ 0.0404 & 0.4263 & 0.1398 & 0.1217 & 0.3285 \\ 0.0735 & 0.54375 & 0.2542 & 0.0852 & 0.1825 \\ 0.0485 & 0.435 & 0.4449 & 0.2435 & 0.3303 \end{bmatrix} \tag{22}$$

Step 6. Calculating the weighted normalized specification matrix.

Here we incorporate the relative importance of the attributes with their normalized value to create unique parameter for the candidate robot.

$$\mathbf{V} = \begin{bmatrix} 0.1709 & 0.0222 & 0.1696 & 0.0151 & 0.0814 \\ 0.0181 & 0.0592 & 0.0678 & 0.0908 & 0.0855 \\ 0.0194 & 0.0888 & 0.1153 & 0.0454 & 0.1355 \\ 0.0287 & 0.0444 & 0.0668 & 0.0605 & 0.0793 \\ 0.0071 & 0.087 & 0.0373 & 0.0151 & 0.0751 \\ 0.0129 & 0.111 & 0.0678 & 0.0106 & 0.0417 \\ 0.0085 & 0.0888 & 0.1187 & 0.0303 & 0.0755 \end{bmatrix} \tag{23}$$

This weighted normalized specification matrix is all-inclusive matrix, which takes care of the attribute values and their relative importance. So this matrix will be able to provide good basis for comparison with each other and with the benchmark robot. Various methods, graphical and non-graphical, explained previously can be applied for this comparison and ranking purposes.

4.1. TOPSIS method for ranking

The weighted normalized attributes for the +ve and −ve benchmark robots can be obtained as

$$\begin{aligned} V^* &= (0.1709, 0.111, 0.1696, 0.0908, 0.1355) \\ V^- &= (0.0071, 0.0222, 0.0373, 0.0106, 0.0417) \end{aligned} \tag{24}$$

$$\begin{aligned} S_1^* &= 0.1286, \quad S_1^- = 0.214 \\ S_2^* &= 0.1972, \quad S_2^- = 0.104 \\ S_3^* &= 0.1687, \quad S_3^- = 0.1438 \\ S_4^* &= 0.1982, \quad S_4^- = 0.757 \\ S_5^* &= 0.233, \quad S_5^- = 0.073 \\ S_6^* &= 0.225, \quad S_6^- = 0.0941 \\ S_7^* &= 0.1916, \quad S_7^- = 0.1122 \end{aligned} \tag{25}$$

Relative closeness to the ideal solution

$$\begin{aligned} C_1^* &= 0.625 \\ C_2^* &= 0.345 \\ C_3^* &= 0.460 \\ C_4^* &= 0.793 \\ C_5^* &= 0.239 \\ C_6^* &= 0.295 \\ C_7^* &= 0.369 \end{aligned} \tag{26}$$

4.2. Graphical method based ranking

The element values of weighted normalized specification matrix are used for the line graph or spider diagram plotting. Subsequently, COS can be calculated from graphs. The calculated COS is tabulated as follows.

Suppose the area under the line graph for weighted normalized specifications of first candidate robot and for benchmark robot are $\mathrm{AV}_1^L = 0.333$; $\mathrm{AV}_{+B}^L = 0.5246$. The coefficient of similarity based on the weighted normalized specification of the first candidate robot is

$$\mathrm{COS}_1^{\mathrm{VL}} = \mathrm{AV}_1^L / \mathrm{AV}_{+B}^L = 0.635 \tag{27}$$

Similarly closeness of the candidate robots with the +ve benchmark robot obtained form TOPSIS and the graphical methods are tabulated as shown in Table 5.

Thus the robots are ranked in order of preference based on the attributes selected. For the purchase of a new robot, the management can use the above ranking effectively to select the robot, which will be best suitable for the application and is based on this set together with other considerations.

Table 5
Evaluation and Ranking of the candidate robots using various methods

	TOPSIS—closeness to the +ve benchmark robot C^*	Rank based on C^*	COS based on Line Graph COS^{VL}	Rank based on COS^{VL}	COS based on Spider diagram COS^{VS}	Rank based on COS^{VS}
ASEA-IRB 60/2	0.625	2	0.635	1	0.284	2
Cincinnati Milacrone T^3-726	0.345	5	0.515	4	0.232	3
Cybotech V15 Electric Robot	0.460	3	0.627	2	0.296	1
Hitachi America Process Robot	0.793	1	0.431	5	0.173	5
Unimation PUMA 500/600	0.239	7	0.345	7	0.069	7
United States Robots Maker 110	0.295	6	0.414	6	0.121	6
Yaskawa Electric Motoman L3C	0.369	4	0.533	3	0.201	4

5. Role of user in selection

Here one can see, the ranking done by TOPSIS and graphical methods vary from each other. Even for both graphical methods the ranking is not same. The user should find out which method is the best suited for him and his application. Thus the robots are ranked in order of preference based on the attributes should be selected. However, before a final decision is taken to purchase a new robot, the following factors come into picture: (1) Economic considerations, (2) Availability, (3) Management constraints, corporate policies, (4) International market policies, which were not previously considered in coding and evaluation. Even if the above consideration, say, economic considerations, does not allow the user to buy the top ranked robot, the user knows which one to go for as the next choice. For example, 2nd and 3rd ranked robots may be costing the same, but as our result indicate, the 2nd ranked robot will perform better in other aspects even though their price is same.

6. Conclusions

The paper presents a robot selection procedure based on the Multiple Attribute Decision Making (MADM) approach, which is a concept used not so frequently for this purpose. It identifies the various attributes needing to be considered for the optimum evaluation and selection of robots. It also provides a coding system for robots depicting the various attributes. It recognizes the need for, and processes the information about, relative importance of attributes for a given application without which inter-attribute comparison is not possible. It presents the result of the information processing in terms of a merit value, which is used to rank the robots in the order of their suitability for the given application. The contributions of this work can be summarized as

1. The method is especially suitable for generating database of robots available in the market and their subsequent retrieval. It provides coding scheme to produce electronic database of globally available robots.

2. This database will be helpful to all sorts of people related to robots from manufacturer, designers, and users to maintenance personnel. It will be helpful to improve the overall productivity of the organization.
3. Here by identifying 83 attributes of the robots, the attempt has been made to codify most of the robot characteristics, which will define the robot precisely and accurately. The coding scheme is illustrated with example.
4. Evaluation and ranking based on the mathematical and graphical approaches along with the illustrative examples are given.

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