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Attribute Based Comparison and Selection of Modular Self-Reconfigurable Robot Using Multiple Attribute Decision Making Approach

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Abstract—From the last decades, there is a significant technological advancement in the field of robotics, and a number of modular self-reconfigurable robots were introduced that can help in space exploration, bucket to stuff, search, and rescue operation during earthquake, etc. As there are numbers of self-reconfigurable robots, choosing the optimum one is always a concern for robot user since there is an increase in available features, facilities, complexity, etc. The objective of this research work is to present a multiple attribute decision making based methodology for coding, evaluation, comparison ranking and selection of modular self-reconfigurable robots using a technique for order preferences by similarity to ideal solution approach. However, 86 attributes that affect the structure and performance are identified. A database for modular self-reconfigurable robot on the basis of different pertinent attribute is generated. This database is very useful for the user, for selecting a robot that suits their operational needs. Two visual methods namely linear graph and spider chart are proposed for ranking of modular self-reconfigurable robots. Using five robots (Atron, Smores, Polybot, M-Tran 3, Superbot), an example is illustrated, and raking of the robots is successfully done, which shows that Smores is the best robot for the operational need illustrated, and this methodology is found to be very effective and simple to use.

Keywords—Self-reconfigurable robots, MADM, TOPSIS, morphogenesis, scalability.

I. INTRODUCTION

MODULAR robots consist of a set of identical robotic modules that can autonomously and dynamically change their geometric structure which best suits the working environment or variety of purpose [1]. Each module consists of its own powerful processor, memory, sensors, camera, communication interface, connection mechanism that allows transfer of electrical powers, mechanical forces and moments, and communication throughout the robot [2], [3]. There are two types of self-reconfigurable robot system; namely, homogeneous as well as heterogeneous. In homogeneous modular system, all modules are identical; a set of common rules must describe the behaviour of each module. The advantage of using homogeneous system is that, in case of failure, all modules can be replaced with any other module, for example ATRON [4] and MTRAN [5]. Heterogeneous modular system has two or more different modules. The system with two different modules are very common, they often consist of link and nodes, e.g. CKBot and CEBot. The self-reconfigurable robots can be used in various applications like space application, bucket to stuff, search and rescue, etc. [6], [7]. These robots are still not adaptable as the liquid metal robots shown in some movies like The Terminator 2: judgment day, Transformer. There are two ways of categorizing modular self-reconfigurable robotic system [8].

A. Based on Regularity of Location for Attaching

Lattice Architecture: Lattice architecture comprises units that have their docking interface, and these units are arranged and connected in a regular 3D pattern (either cubic or hexagonal). In lattice architecture, reconfiguration process for a complex system is simpler and allows a simpler mechanical design. The computational representation can also be simply scaled to a complex system, and their control and motion can be achieved in parallel system [2].

***Chain Architecture*:** Chain architecture comprises modules that are arranged and are connected to form a chain topology. The modules in chain architecture can grasp any point in space and, therefore makes it more versatile. But, to reach any point in space, many units may be required, therefore motion planning and collision detection become difficult to scale [9].

Mobile/hybrid Architecture: Mobile architecture uses the advantage of both lattice architecture and chain architecture. Mobile architecture comprises control and mechanism that is designed for lattice reconfiguration as it is not a complex one. Also, the advantage of chain architecture of reaching any point in space is also put in.

B. Based on Methods of Movements between Those Location

Stochastic reconfiguration: In stochastic reconfiguration, the exact location of the modules is not known, and the configuration relies on unit moving in 2D or 3D environment all over the place in statistical processes and may possibly take unknown paths to move among locations. The units are connected to the main structure so that information regarding to each module can be gathered [9].

Deterministic reconfiguration: In deterministic reconfiguration, the exact location of the modules in the system is known, and the modules are directly manipulated

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from one location to another in chain or lattice. Modules reconfiguration mechanism necessitates a control structure that allows it to coordinate and achieve reconfiguration sequences with neighboring modules [9].

Based on this, a number of reconfigurable robots were introduced, and every robot has different specification and different geometry.

1. The Potential of Self-Reconfigurable Robot

Morphogenesis (self-assembly): Process of changing their configuration to accomplish various tasks is called as morphogenesis or shape shifting. For example, traditional robots are designed with fixed configuration that is having four legged or two legged and they remain the same forever [9]. These robots can morph themselves into different shapes in order to move, step/climb without hindrance [10].

Self-repair: Robot is capable of repairing itself autonomously. The self-repair process involves four steps; (a) Identify failure; (b) Take away the damaged module; (c) Transport the undamaged module to location where the faulty modules were; and (d) Reassemble the module [9].

Self-reproduction: Capability to produce itself is called self-reproduction. Modularity eases self-reproduction for self-reproduction robot as compared to ordinary robot [9].

Scalability: When functionality of arrangement is influenced by number of modules, the system is called scalable [9].

II. METHODOLOGY

A. *MADM for Selection of Modular Self-Reconfigurable Robots*

The selection of modular self-reconfigurable robot depends on number of attributes or factor. The selection of robot, which is most appropriate for the operational need, is a challenge for robot users. There are a number of attribute-based techniques for selection of robot like analytic hierarchy process (AHP), graph theory and matrix representation approach (GTMA), technique for order preferences by similarity to ideal solution (TOPSIS), multi-criteria decision making (MCDM), etc. There is a rapid increase in number of self-reconfigurable robots with different capabilities and different specification. In this research, an effort to create an exhaustive database by identifying number of attribute for modular self-reconfigurable robot that affects the structure and performance is done. The coding scheme and the selection procedure are also demonstrated with example.

B. *MSRR Attributes*

The performance of modular self-reconfigurable robots depends on various attributes/parameters

Table I indicates the information regarding this product in which we can see most of the cells that are having 0 as code given. This 0 indicates that the information relating to the particular cell is not available.

TABLE I
ATTRIBUTES IDENTIFIED, SMORES SPECIFICATION AND ITS CODING SCHEME [11]-[14]

S. No.	Attributes	Information	Code
1	Cost of each module	$ 300	3
2	Type of robot	Self-Reconfigurable	SR
3	Software used	--	0
4	Compactness	--	0
5	Versatility	--	0
6	Number of module used	--	0
7	Number of actuator	5	0
8	Number of active ports	3	0
9	Number of passive ports	1	0
10	Number of male connector	--	0
11	Number of female connector	--	0
12	Weight of each module	0.52 kg	6
13	Power consumption for docking	--	0
14	Power consumption for undocking	--	0
15	Type of energy input	DC	D
16	Power supply	--	0
17	Size of module	--	0
18	Type of cable used	--	0
19	Connection mechanism	magnets	0
20	Battery used	--	0
21	Number of battery used	--	0
22	Storage capacity of battery	--	0
23	Electrical resistance of module	--	0
24	Motor used	--	0
25	Number of motor used	--	0
26	Number of rotational axis	--	0
27	Number of mechanical parts	132	4
28	Docking sequence	--	0
29	Undocking sequence	--	0
30	Number of surfaces for connection	--	0
31	Material used	--	0
32	Thermal conductivity of material	--	0
33	Camera used	--	0
34	Number of unique modules	--	0
35	Maximum rotational torque	--	0
36	Maximum rotational speed	--	0
37	Maximum moving speed	--	0
38	Maximum torsional load	--	0
39	Dock cycle time (sec)	2.3	7
40	Module docking time	--	0
41	Module undocking time	--	0
42	Docking accuracy	--	0
43	Ease of docking	--	0
44	Ease of undocking	--	0
45	Maximum vertical displacement	--	0
46	Maximum horizontal displacement	--	0
47	Reconfiguration time	--	0
48	Reconfiguration speed	--	0
49	Processing speed	--	0
50	Information processing speed	--	0
51	Information transfer rate	--	0
52	Resolution	--	0
53	Repeatability	--	0
54	Battery life	--	0
56	Communication method	--	0
57	Programming flexibility	--	0

S. No.	Attributes	Information	Code
58	Architecture type	Hybrid	H
59	Shape of module	--	0
60	Degree of freedom of each module	4	4
61	Joint orientation	--	0
62	Joint positioning	--	0
63	Type of module configuration	--	0
64	Usage of robot	--	0
65	Working temperature	--	0
66	Working environment	--	0
67	Humidity	--	0
68	Vibrations	--	0
69	Self-assembly	--	0
70	Self-repair	--	0
71	Self-reproduction	--	0
72	Serviceability	--	0
73	Scalability	--	0
74	Motion generation	--	0
75	Maximum number of morphologies	--	0
76	Processor used	--	0
77	Proximity sensor	--	0
78	Tactile sensor	--	0
79	Force/Torque sensor	--	0
80	Joint positioning sensor	--	0
81	Joint orientation sensor	--	0
82	Algorithm used	--	0
83	Number of replacement parts available	--	0
84	Electrical reliability	--	0
85	Mechanical reliability	--	0
86	Common reason for failure	--	0

C. *Coding Scheme*

Coding scheme is developed to simplify identification and characterization of the system. This helps to make procedure computational and user friendly. Each number is given code/number/value based on the system. Attributes are of two types, quantitative/deterministic (value based) and qualitative/qualitative (good, average, poor, etc.). Proposed coding scheme for robot is already illustrated in Table I. The modular self-reconfigurable robots' identification codes are tabulated in Table II.

D. *Illustration of Coding*

Suppose that we want to codify dock cycle time as mentioned in Table I. The coding scheme for different values of dock cycle time is proposed in Table III. Now, for the value of 2.3 seconds, code proposed is 7 (i.e. for 1 to 3, code is 7) and which is assigned in Table I, shell 39. Similarly, for other quantitative attributes, coding can be done in similar way.

For considering qualitative attributes, the assigned values can be used from Table IV, based on the measure for attributes.

The codes for quantitative and qualitative attributes can be assigned by using Tables III and VI. In Table I, we can see that most of the cells are having 0 code. This 0 indicates that the information relating to the particular cell is not available. The specification of the robot SMORES from Table I, is tabulated in Table V.

TABLE II
MSRR IDENTIFICATION CODE

General	1	2	3	4	5				
Physical	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							
Performance	35	36	37	38	39	40	41	42	43
	44	45	46	47	48	49	50	51	52
	53	54	55	56	57				
Structure	58	59	60	61	62	63			
Environment	64	65	66	67	68				
Sophistication in equipment's	69	70	71	72	73	74	75		
Control and feedback system	76	77	78	79	80	81	82		
Availability/ reliability	83	84	85	86					

TABLE III
QUANTITATIVE MEASURE CODE

Dock cycle time	Code
unspecified	0
0 to 0.01	1
0.01 to 0.05	2
0.05 to 0.1	3
0.1 to 0.2	4
0.2 to 0.5	5
0.5 to 1	6
1 to 3	7
3 to 6	8
6>	9

TABLE IV
QUALITATIVE MEASURE CODE (0 TO 1)

Qualitative measure for attribute	Assigned value
Exceptionally low	0.0
Extreme low	0.1
Very low	0.2
Low	0.3
Below average	0.4
Average	0.5
Above average	0.6
High	0.7
Very high	0.8
Extremely high	0.9
Exceptionally high	1.0

TABLE V
MSRR IDENTIFICATION CODE

General	**3**	**SR**	0	0	0				
Physical	0	0	0	0	0	0	**6**	0	0
	DC	0	0	0	0	0	0	0	0
	0	0	0	**4**	0	0	0	0	0
	0	0							
Performance	0	0	0	0	**7**	0	0	0	0
	0	0	0	0	0	0	0	0	0
	0	0	0	0	0				
Structure	**H**	0	**4**	0	0	0			
Environment	0	0	0	0	0				
Sophistication in equipment's	0	0	0	0	0	0	0		
Control and feedback system	0	0	0	0	0	0	0		
Availability/ reliability	0	0	0	0					

E. Three Stage Selection Procedure

Fig. 1 shows steps involved in three stage selection procedure by analytical method [15].

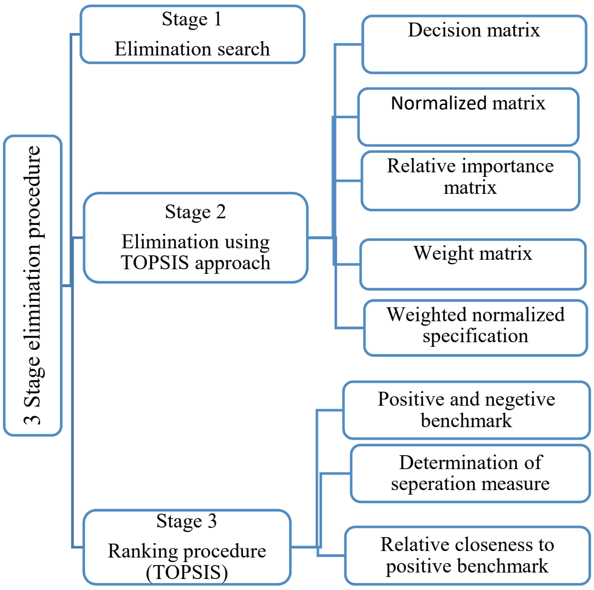

Fig. 1 Three stage selection procedure

1. Elimination Search (Stage 1)

Totally 86 attributes are identified and all of them are not important while selecting a MSRR. There are only few attributes out of 86 attributes which have direct effect on the selection procedure which may be set aside as pertinent attribute. Threshold values of these pertinent attributes are assigned by obtaining information from user/manufacture and group of experts. Hence, this procedure focuses merely on pertinent attributes leaving out the rest. There are large number of alternatives, and based on the threshold value of pertinent attributes the large number of alternatives are converged to manageable number of alternatives.

2. Evaluation Using TOPSIS Approach (Stage 2)

1. Decision Matrix:

$$D = (a_{ij})_{m\times n}$$

i= 1, 2 ….m
j= 1, 2…..n

$$D = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & \ddots & \dots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \qquad (1)$$

where a_{1j} represent value of jth attribute for first alternative.

2. Normalized Matrix (N): Element n_{ij} of a normalized matrix can be calculated as;

$$n_{ij} = \frac{a_{ij}}{(\sum_{i=1}^{m} a_{ij}{}^2)^{1/2}} \qquad (2)$$

3. Relative Importance Matrix (R):

$$r_{ij} = \frac{importance\ of\ ith\ attribute}{importance\ of\ jth\ attribute} \qquad (3)$$

4. Weight Matrix (W): In this step, weight of all attribute is calculated and is formulated using eigenvalues

$$Rx = \lambda x$$

where λ is an eigenvalue of matrix R and x is a corresponding eigenvector. For a n x n matrix (R), there are n Eigen valuesλ_i, for i=1, 2…..n and forλ_i, there are n eigenvectors x_i for i=1, 2……n

Vector W is now established in following ways

i. Taking x_{max} corresponding to λ_{max} as all the elements of x_{max} are either +ve or –ve.
ii. Sum of elements of x_{max} is calculated

$$\alpha = \sum_{i=1}^{n} (x_i)_{max} \qquad (4)$$

1. Weight vector **W** is calculated as

$$W = \frac{(x_{max})}{\alpha} \qquad (5)$$

Such that $\sum_{i=1}^{n} W_i = 1$

2. Weighted Normalized Specification (U):

$$U = W.N$$

$$U= \begin{bmatrix} w_1 n_{1,1} & w_2 n_{1,2} & \cdots & w_n n_{1,n} \\ w_1 n_{2,1} & \ddots & \dots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ w_1 n_{m,1} & w_2 n_{m,2} & \cdots & w_n n_{m,n} \end{bmatrix}$$

$$\begin{bmatrix} u_{1,1} & u_{1,2} & \cdots & u_{1,n} \\ u_{2,1} & \ddots & \dots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ u_{m,1} & u_{m,2} & \cdots & u_{m,n} \end{bmatrix} \qquad (6)$$

3. Ranking Procedure (Stage 3): The ranking of the MSSR can be done either mathematically using TOPSIS method or graphically using line or spider diagram method.

E. TOPSIS Method

1. Positive and Negative Benchmark

For ranking and selection, matrix U is used to obtain negative and positive benchmark robots. These benchmark robots are imaginary robots, which are supposed to have superlative and vilest possible magnitude. The technique for order preferences by similarity to ideal solution (TOPSIS) method is based on the idea that the selected option should have distance closest to positive benchmark robot and far from the negative benchmark robot. The measure confirms that the top ranked robot is nearby positive benchmark robots and far from negative benchmark robots.

2. Determination of Separation Measure

Separation of alternative from positive benchmark

$$S_i^+ = \sqrt{\sum_{j=1}^{n}\left(u_{ij} - u_1^+\right)^2} \tag{7}$$

i= 1, 2 ……….m

Separation of alternative from negative benchmark

$$S_i^- = \sqrt{\sum_{j=1}^{n}(u_{ij} - u_1^-)^2} \tag{8}$$

i= 1, 2 ……….m

3. Relative Closeness to Positive Benchmark

It is the degree of appropriateness of the robot for the chosen application on the basis of pertinent attribute.

$$C^* = \frac{S_i^-}{S_i^+ + S_i^-} \tag{9}$$

i= 1, 2 …….m

This implies that the solution with highest C* value will be given the highest rank and so on. Ranking for the MSSR in accordance with the decreasing values of indices C* indicting the most preferred and the least preferred feasible optimal solution is done.

F. Graphical Method [15]

Selection procedure by graphical method is shown in Fig. 2 [15].

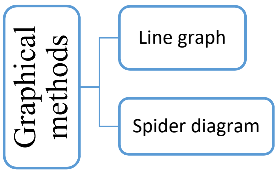

Fig. 2 Graphical methods

1. Linear Graph Representation:

The value of different alternatives can be plotted on a line graph, and the graph will be distinct for all of the candidate MSRR and can be used for comparison purpose. Area under curve can be used for quantification purpose and to compare the candidate MSRR with each other and benchmark MSRR to be defined later.

Line graph can be plotted for any matrix D, matrix N, matrix U for all candidates MSRR as well as benchmark MSSR. Area under the line graph specification of *i*th MSRR can be found out as

$$AD_i^L = \{a_{i,1} + 2\left(a_{i,2} + \cdots + a_{i,n-1}\right) + a_{i,n}\}/2 \qquad 10)$$

2. Spider Diagram

In spider diagram, pertinent attributes are divided 360° on 2D polar space with number of lines equal to pertinent attributes. The angle between two attributes can be calculated as $\theta = 2\pi/n$ where n is number of pertinent attributes. Pertinent attributes, magnitude from normalized and weighted normalized matrix are plotted to obtain spider diagram, also known as polar or radar diagram for MSRR. Area enclosed by polygon indicates the MSRR capabilities.

Area enclosed by the polygon of *i*th robot can be calculated as $2\pi/n$, where n is number of attributes.

$$AD_i^S = \frac{\sin\theta}{2}\sum_{j=1}^{n} a_{ij}\, a_{i,j+1}; \tag{11}$$

where $a_{i,n+1} = a_{i,1}$.

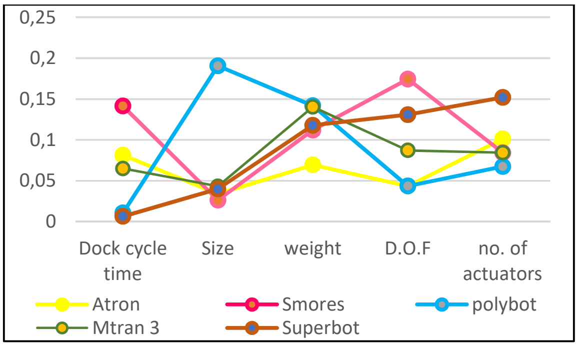

Fig. 3 Line graph plot for evaluation and ranking of MSRRnn

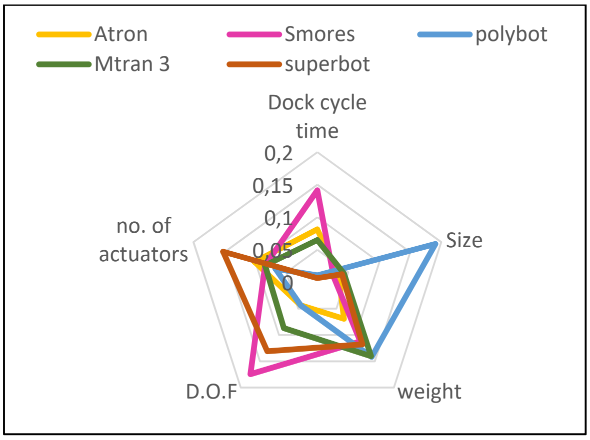

Fig. 4 Spider diagram for evaluation and ranking of MSRR

G. Identification and Graphical Representation of Benchmark MSRR

In the previous section, +ve benchmark MSRR was defined, and the same will be used here for the comparison of the alternative for ranking purpose. The benchmark MSRR and alternatives can be plotted on the line graph and spider diagram. Similarly, the area under the line graph for benchmark robot i.e. AD_B^S, AN_B^S, AU_B^S is also calculated.

1. Coefficient of Similarity (COS):

The value of COS can be any +ve number and will be a measure of the closeness of alternative robot with the benchmark MSRR. The alternative with COS magnitude closer to unity are preferable. There may be some alternatives with are better than the benchmark one, then the value of COS is higher than unity or vice-versa.

Coefficient of similarity (COS) based on decision matrix

$$COS_J^D = AD_j/AD_B \qquad (12)$$

AD_j for jth MSRR based on either linear system or spider diagram method, and AD_B is the area under positive benchmark MSRR. Similarly, COS for normalized and weighted normalized matrix is calculated.

I. Illustrative Example

Suppose that a robot is required for search and rescue operation which can morph into snake shape.

The minimum requirement for this application is as follows.

TABLE VI
REQUIREMENT FOR APPLICATION

1. Number of actuator	Min 4
2. Dock cycle time	15 seconds
3. Weight	0.520 kg
4. Degree of freedom	At least 1
5. Size	2 x $10^5 mm^3$

TABLE VII
ATTRIBUTES FOR SHORT LISTED ROBOTS

	Dock cycle time (sec)	*Size* 10^5 mm^3	*Weight (Kg)*	*DOF*	*No. of actuators*	*Data derived from References*
Atron	4	6.97	0.850	1	6	[4], [16]
Smores	2.3	9	0.526	4	5	[11]
Polybot	30	1.25	0.416	1	4	[3]
Mtran 3	5	5.49	0.420	2	5	[5], [17]
Superbot	50	5.927	0.500	3	9	[18]

J. Graphical Method-Based Ranking

For plotting line graph and spider diagram, weighted normalized specification matrix is used. Afterwards, COS can be calculated from graphs. Calculated value for COS is tabulated as follows. Areas under line for weighted normalized specification for first alternative and for benchmark robot are $AV_1^{VL} = 0.2385 AV_{+B}^{VL} = 0.6536$. Therefore, COS_1^{VL}=$AV_1^{VL}/AV_{+B}^{VL} = 0.3649$. Similarly, for other alternatives, the values are calculated and tabulated in Table VIII.

TABLE VIII
EVALUATION AND RANKING OF THE MSRR

	TOPSIS –ve closeness to the +ve benchmark robot C^* (ix)	Rank based on C^*	COS based on line graph COS^{VL} (X)	Rank based on COS^{VL}	COS based on spider diagram COS^{VS} (xi)	Rank based on COS^{VS}
Atron	0.2635	5	0.3649	5	0.00990	5
Smores	0.5178	1	0.6516	1	0.02516	1
Polybot	0.4688	2	0.6350	2	0.0185	3
Mtran 3	0.3466	4	0.5287	4	0.0165	4
Superbot	0.3872	3	0.5618	3	0.0196	2

III. RESULTS AND DISCUSSION

Ranking obtained using different methods is tabulated in Table VIII. However, before making a decision, user should also consider other factors like economics, international policies, consistency, availability, quality, etc. which are not considered in coding and evaluation. If, due to some constraints, user is unable to buy top ranked robot, user can go for the next choice, i.e. rank 2.

IV. CONCLUSION

This paper presents a procedure named MADM methodology which has not been employed for the selection of modular self-reconfigurable robots till date. This paper successfully presents the results for different robot based on the information we got.

The contribution of this work is summarized as follows:

1. Coding scheme for 86 attributes which are obtained from various research papers is proposed and its usage is shown with an illustrative example.
2. Proposed MADM approach is useful in evaluation, comparison and selection of MSRR for specific application as it takes into account various attributes information.
3. This method permits user to take into account the relative importance of one attribute over other for application specified.
4. Pertinent attribute are identified and the information of pertinent attribute obtained from robot companies catalogues are used for 3 stage selection procedure, graphical methods.
5. Hypothetical positive benchmark and negative benchmark solution are developed. All three methods gave the same results i.e. Smores is the best robot for specified application.
6. The proposed methodology will be helpful for user to choose the best MSRR among the available alternative quickly.

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