Green and Sustainable Mobile Robots Design - a MCDM Approach

V. Sathiya (sathiyav2105@gmail.com)
EGS Pillay Engineering College https://orcid.org/0000-0003-0148-0088
M. Chinnadurai
EGS Pillay Engineering College
S. Ramabalan
EGS Pillay Engineering College

Research Article

Keywords: Green Robotics, Sustainability, MCDM, ISM, ANP

Posted Date: October 20th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-930297/v1

Green and sustainable mobile robots design - a MCDM approach

V. Sathiya,
Department of Electronics and Communication Engineering,
E.G.S. Pillay Engineering College, Nagapattinam-611002,
Tamil Nadu, India.
E-mail: sathiyav2105@gmail.com

M. Chinnadurai,
Department of Computer Science and Engineering,
E.G.S. Pillay Engineering College, Nagapattinam-611002,
Tamil Nadu, India.
E-mail: mchinna81@gmail.com

S. Ramabalan,
Department of Mechanical Engineering,
E.G.S. Pillay Engineering College, Nagapattinam-611002,
Tamil Nadu, India.
E-mail: cadsrb@gmail.com

Green and sustainable mobile robots design - a MCDM approach

Abstract
To safeguard the environment, products and technologies are made friendlier to it. In this context, more research works were already done in computing and supply chain management fields. But, only less amount of research happened in Robotics field. Particularly green robotics was not addressed well. This research work tries to address green robotics with two real world case studies. Further correlation between green robotics, green computing and green supply chain is also discussed. The strategies which are bringing sustainability in robotics are discussed. Adoption of green concepts from first stage (robot design and fabrication) to final stage (robot application) is addressed. The metrics used to verify green concepts are discussed. The criteria used in this study are green material selection (as per international standards), energy saving, cost saving and green computing. Two numerical examples – design of two educational mobile robots are presented. The problems were solved in a MCDM approach. A hybrid method, ISM-ANP was employed to crack the problems. The simulation results ensure that effectiveness of the proposed MCDM method.

Keywords Green Robotics· Sustainability· MCDM· ISM· ANP

Introduction

Nowadays electronic gadgets like computers, cell phones, etc are doing unimaginable works. They benefits for people in many ways. But, they pollute the water and land due to the substances present in their parts. Because, they consume more electrical energy. They use heavy batteries. Due to improper disposal of batteries and other parts, pollution is increased further. Sustainability concepts in robotics field are not defined well by considering all aspects of robotics including software, hardware, task assignment, environmental reactions and solution strategies. There is a gap while addressing sustainability in robotics. There is only little discussion about green robotics and its implementation strategies. So this work discusses green robotics' concepts by proposing a solution to a real world problem. All activities of robot making and usage are revisited in green nature aspect. A Multi Criteria Decision Making (MCDM) approach is used for design of two mobile robots. Robots are educational line follower mobile robots used in laboratories. A hybrid method (Interpretive Structural Modeling (ISM) method and Analytic Network Process (ANP)) is utilized for solving the problem. Four important criteria are selected related to reduction of pollution, energy consumption and other problems caused by robot parts and batteries. The chosen criteria are green material selection (as per international standards), energy saving, cost saving and green computing. These criteria are selected for making the environment as green and peaceful conscience.

Production chains and green computing

The known information is that electronics preserve the nature by saving resources like wood, paper, etc. But they give some environmental threats in all stages of their life cycle. They are made of silicon, plastics, rubber and other hazardous materials. They need electricity for their working. They spoil land, water and air. When they are obsolete, they have to be disposed of carefully. Plastics and electronics are main sources of land and water pollution. Since, they are not biodegradable. Now the industries are moving towards green initiatives. They concentrate on reuse, recyclable material, renewable energy, green supply-chains, reverse supply-chains, etc (Ming-Lang Tseng et al. 2019; Thoo Ai Chin et al. 2015; Yıldızbaşi et al. 2020).

Green computing is mainly concern about reducing power consumption of computing machineries like laptop, tablet, computers, and their peripheral components without affecting computing efficiency. Main initiatives in this field are: energy consumption management, reduction in no. of hardware items, sharing underutilized resources – virtualization, data sharing in cloud, advanced communication networks, etc (Shahla Asadi et al. 2017; Shahla Asadi et al. 2019; Asadi et al. 2018; Sri Fatiany Abdul Kader Jailani and Lili Marziana Abdullah. 2017; Molla et al. 2011). To ensure the use of technology, International standards and certification seals (EcoLables or EcoSeals) were created. Their aims are ensuring: good energy efficiency of processes and products and also not using hazardous materials in environment. Even though they are not accepted universally, some of these certifications are popular in the market. There is no such exclusive standard to robots.

Green Robotics

Robots are used in major segments of all fields. They have more applications in all areas - land, space, underwater, mountains, etc. Also they are used in science, engineering, medical, home, military, research, educational and other fields (Xiao et al. 2020). AGV, RGV and UAV are extensions of them. So, robots come in the same category of green computing and green supply chain. However, due to some inherent characteristics of robotics, it cannot be fit directly. First, there is no general purpose robot. Since, for performing each task, robot needs specific sensors, end-effectors and actuators. Second, robots work well in known environments, but not in unstructured environments (hostile or remote). Their intelligence is to be improved further. Third, robots work based on their programmes. If any mistake present in the programme, robots fail or meet accidents or do unpredicted events in the environment. Finally, robots' performance is based on their software, hardware and middleware components, controller, image processing devices, etc. Further based on task requirement, the robot's consumption of electrical energy varies. For example, in idle condition, few parts of robot like sensor, controller, and end-effector are to be in ON condition. So the robot consumes electric power. Green robotics is adoption of ecologically conscious practices in robotics field. It reduces damage to the environment and people. Also it maintains good quality and performance. It increases energy efficiency. It avoids toxic materials disposal in the environment. During design, fabrication and applications of robots, eco-friendly concepts are used. E.g. Selection of actuators, sensors and controllers is done according to robot's environment and application. Green robotics includes concepts of green supply chains, green computing and eco-friendly strategies depend on robot's environment and task. The main aims of Green Robotics are (Ming-Lang Tseng et al. 2019; Thoo Ai Chin et al. 2015; Yıldızbaşi et al. 2020; Shahla Asadi et al. 2017; Shahla Asadi et al. 2019; Asadi et al. 2018; Sri Fatiany Abdul Kader Jailani and Lili Marziana Abdullah. 2017; Molla et al. 2011; Alves Filho et al. 2018):

1. Related to green supply chain and green production – (a) Eco-friendly manufacturing and disposal processes, (b) Increase robot life by avoiding parts incompatibility with market

standards, (c) make reusable robot and its parts, (d) make reconfigurable robot, (e) make multi-purpose robot, (f) Adopt eco-friendly certifications and standards for processes and products, (g) Adopt best methodology for choosing eco-friendly materials, (h) Construct modular robots, (i) Use middleware solutions and multi-robots.
2. Related to green computing – (a) Reduce energy consumption during performing task, (b) avoid energy wastage caused by unnecessary software and hardware, (c) Configure robot software for optimal performance, (d) Use optimal algorithms according to dynamics, kinematics, motion, task and environment of the robot, (e) Reduce communication overhead between robots or robot's parts, (f) Eliminate unused softwares and their features, (g) Develop context-sensitive software, (h) To avoid energy wastage, use environmental characteristics, (i) Use energy saving communication-protocols, (j) Ensure good relation between energy saving, data accuracy and service quality.
3. Related to interaction with the environment - (a) Avoid waste disposal during working of robot, (b) Avoid or reduce damage to people and the environment due to accidents, (c) Reduce the risk of energy consumption by outdoor parameters, (d) Use mechanisms to avoid failures and accidents, (e) During doing a task , set automatic recharging of batteries.

Available solution strategies for green robotics

Already few researchers tried to use green strategies during design and fabrication of robots. For green robot manufacturing, specific certifications and standards are not available. Few general-purpose standards are available in ISO 14000 (Dawes 2015). ISO 14001 has a set of procedures for environmental management systems. It includes environmental aspects and impacts; environmental policy; legal obligations; plans of environmental activities, objectives and targets; monitoring, reporting and measurement program; program internal evaluation or audit; management review system; and a documented system. Suppose the user fabricates the robot, then there is no standard available to ensure the eco-friendly nature starting from selection of material to functioning of the robot.

For material selection of electronic components, in European Union, two standards namely REACH and RoHS are adopted. RoHS discusses about reduction of environment hazards of electrical and electronic products (Cusack and Perrett 2006). REACH details evaluation of biodegradation, environment hazards and risks (Rudén and Hansson 2010). WEEE policy sets aims for recycling, reuse and collection of electronic materials. EPEAT certification gives a basis to establish green production-chain of electronic products (GEC 2015). "IEEE environmental assessment standards 1680" classify electronic products in three categories namely bronze, silver and gold. It considers the following points for classification: environment damage; product life; product life extension; energy consumption; disposal of product; product performance; packaging; air pollution, and spare parts availability. The requirements vary with respect to type of product.

Material selection affects robot's reliability and durability. So, robot parts' material is to be selected by considering performance, cost, safety, aesthetics, risks and impact in the environment. Yoshiaki Itoh et al. (2016) used aluminium; steel and plastic as material. The educational robots need to have a modular structure (Jacob Nielsen and Henrik Hautop Lund 2005; Paul Moubarak Pinhas Ben-Tzvi 2012). Robot structure needs more flexibility to modify it easily. In general, educational robots are multi-functional kits. The robots need few mechanisms like magnets for making their structure as easily changeable. Multipurpose robots have versatile software which accommodates changes in the environment and hardware items. Middleware technologies can be used by the robots for connection of components, communication among the components and data collection (Mohd Javaid et al. 2021). Newer technologies like wireless sensor networks can be used for data collection (Sivakumar et al. 2021). Another concept for making robots as versatile is swarm robotics (Yu Peng et al. 2019). A group of tiny robots are doing a common work as a team. Each robot is a separate entity. But for doing a common job, it acts as a team member. For doing different types of jobs, different configurations of robot team are established. Sathiya and Chinnadurai (2019) suggested to use a best controller or an optimal control algorithm for energy saving. Sathiya et al. (2021) presented a solar energy based design for energy saving by mobile robots. A trade-off between energy consumption, performance, communication delay and security of mobile robot is to be established.

Metrics for Green Robotics

Few standards like ISO 14001 and EPEAT are available to ensure the environment consciousness. But, they are not supporting to measure sustainability in a distinctive way. The major difficulty in implementing eco-friendly strategies in robotics is, globally accepted metrics are not available. From the literature (Alves Filho et al. 2018), few metrics are identified for ensuring green strategies in robotics. Metrics' classifications are narrated below:

1. Objectives – Energy saving; Eco-friendly; Cost effective; Compliance with requirements; high performance
2. Abstraction level – Detailed; Abstract
3. Unit type – Qualitative; percentage; absolute value
4. Acquisition form – Estimated; Historical; Instant
5. Component – Software, Hardware, Process
6. Obtaining phase – Post-use; Use; Pre-execution

Research Gap

MCDM is a fastest growing and most important subfield of management science and operations research. MCDM selects the best feasible and practically possible solution for a problem based on its criteria and constraints (Manjunatheshwara and Vinodh 2018). MCDM can be used for getting solutions to all daily life problems. In general, all practical problems are having more number of criteria and constraints. Criteria are conflicting or non-conflicting types. Constraints are equal and non-equal types. So a compromising solution is to be selected by a design. MCDM helps for it. MCDM is used in almost all fields. Many MCDM techniques are developed so far. Some of them are most popular. From a survey done by Abbas Mardani et al. (2015), it is observed that (1) Analytic Hierarchy Process (AHP) was ranked as the first popular method among all MCDM methods. (2) Hybrid MCDM methods were ranked as second popular methods. (3) For major application of MCDM methods, the first rank was given to environment, sustainability and energy areas. Table 1 tabulates MCDM tools used in robotics field. MCDM techniques such as TOPSIS-Entropy, EDAS, VIKOR, WPM, TOPSIS, GRA, PROMETHEE, FBWM-PROMETHEE, AHP, FAHP and FTOPSIS, HTL-QUALIFLEX, ITL-TOPSIS, TOPSIS-ARAS, and COPRAS-ARAS were used in industrial robotics field to identify the best robot for various applications. Fuli Zhou et al. (2018) used Fuzzy extended VIKOR method to select the best mobile robot for a hospital pharmacy. In mobile robot field, few researchers used MCDM methods for path exploration work while the robot is operated in indoor and rescue environments. Patrick Taillandier et al. (2011) used PROMETHEE method to identify new path for mobile robot while it is operated in rescue environment. Xinkai Zuo et al. (2020) used RAGV graphs for autonomous exploration of mobile robot in indoor environment. Nicola Basilico and Francesco Amigoni (2011) used few MCDM methods to find exploration strategies in search and rescue environments. Alves Filho et al. (2018) used a multi-objective optimization approach to crack a green mobile robot design problem. From the above literature, it is identified that green robotics was not discussed much. Further no literature discussed green robotics as a problem of MCDM. Also ISM-ANP method was not used by any researcher for green robotics.

Table 1 MCDM tools used in robotics

References	Robot type	Purpose	Application	Techniques
Varun Chodha et al. (2021)	Industrial robot	Robot Selection	Robot Arc Welding	TOPSIS-Entropy
Neşe Yalçin and Nuşin Uncu (2019)	Industrial robot	Robot Selection	Industry use	EDAS
Mehdi Keshavarz Ghorabaee (2016)	Industrial robot	Robot Selection	Industry use	Interval Type-2 fuzzy sets VIKOR method
Vijay Manikrao Athawale and Shankar Chakraborty (2011)	Industrial robot	Robot Selection	pick-and-place	WPM, TOPSIS and GRA
Mahdi Nasrollahi et al. (2020)	Industrial robot	Robot Selection	Industry use	FBWM-PROMETHEE
Rahmath Ulla Baig et al. (2020)	Industrial robot	Robot Selection	Industry use	AHP
Goswami, et al (2021)	Industrial robot	Robot Selection	Industry use	TOPSIS-ARAS and COPRAS-ARAS
Ankit Kumar and Manoj Kumar (2019)	Robot arm	Material Selection	Industry use	AHP
Mahmood Shahrabi (2014)	Industrial robot	Robot Selection	Industry use	FAHP and FTOPSIS
Radu Eugen Breaza et al. (2017)	Industrial robot	Robot Selection	Milling operation	AHP
Yi-Xi Xue et al. (2016)	Industrial robot	Robot Selection	Industry use	HTL-QUALIFLEX
Hu-Chen Liu et al. (2014)	Industrial robot	Robot Selection	Industry use	ITL-TOPSIS
Ertugrul Karsak et al. (2012)	Industrial robot	Robot Selection	Industry use	Fuzzy linear regression

Cinzia Amici et al. (2020)	Mini-Parallel Kinematic Machines	Robot Selection	Industry and medical use	Survey of all tools
Patrick Taillandier et al. (2011)	Mobile robot	new exploration strategies	rescue	PROMETHEE
Xinkai Zuo et al. (2020)	Mobile robot	Autonomous exploration	Indoor	RAGV Graphs
Nicola Basilico and Francesco Amigoni (2011)	Mobile robot	exploit exploration strategies	search and rescue scenarios	MCDM
Fuli Zhou et al. (2018)	Mobile robot	Robot Selection	Hospital pharmacy	Fuzzy extended VIKOR

Green Robotics as a problem of MCDM

To demonstrate MCDM nature of Green Robotics, two numerical examples – design of two educational purpose line follower mobile robots are presented in this paper. The considered robots have more applications in teaching, laboratories and competitions. They simulate rescuing of victims in a hostile environment. The line follower robot has to move along a line (white or black) on a surface. The educational robots considered in numerical examples 1 and 2 are detailed in Fig. 1 and 2 respectively.

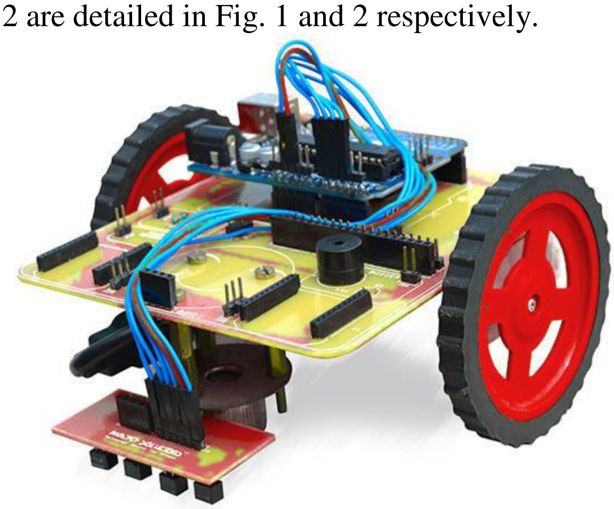

Fig. 1 Mobile robot in numerical example 1

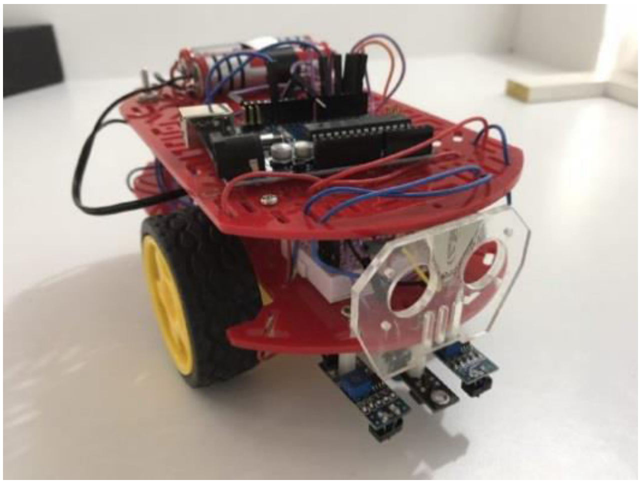

Fig. 2 Educational mobile robot in numerical example 2 (Alves Filho et al. 2018)

Main components required to build a mobile robot are: chassis, robot controller, actuators and sensors. Chassis is a structural member which gives shape and size of the robot. Controller performs data processing and monitoring activities. Electric motors are used for driving the wheels. Reflectance sensors are used for identifying an aimed path. Batteries are used as an energy source for the robot. Other supportive parts serve their purpose. The required number of wheels, sensors, motors and other parts are depending upon design of the robot. In educational mobile robot design, there is no risk for the people working in the robot environment. Also there is no need for high performance characteristics for an educational robot. So, only energy, environment, educational and financial aspects are considered in this study. The objectives of the robot design are (1) Eco-friendly nature – the robot parts are to be made of low hazardous materials and their disposals are to be in safe and proper ways; Certification of robot components – Adherence to International Standards is taken as representative of this objective. (2) Energy saving – low electric power consumption by the battery; (3) Low cost –cost of the robot and its parts are to be low; (4) Serves the purpose – the robot needs to satisfy all requirements of its use in teaching, laboratories and competitions. Scope for green computing – programming is taken as representative of this objective. In the problem solved in this research work, these four objectives are considered as Criteria and the robot's parts are considered as attributes. Fig. 3 shows the overall structure of the numerical example 1 considered.

Problem Goal: Green and sustainable design of line-follower educational mobile robot
Criteria / Objectives:
1. Robot Cost
2. Energy consumption
3. Certification of robot components – Adherence to International Standards
4. Scope for Green computing – Learning

Attributes:
1. Wires - Energy saver / Ordinary
2. Input/ Output Devices- Energy saver / Ordinary
3. Wheels – Plastic / Metal
4. Tyres – Rubber / Eco-friendly
5. Sensors –LED / Ultrasonic, Energy saver / Ordinary
6. Chassis – Acrylic / Metal
7. Controller – Arduino / Microcontroller
8. Software / Programming – Arduino programming/ Microcontroller code
9. Batteries - Energy saver / Ordinary
10. Motors – DC stepper / DC Geared
11. Motor driver board- Energy saver / Ordinary
12. Battery connectors – Plastic / Metal
13. Battery holder– Plastic / Metal
14. Fastening screws– Plastic / Metal

Fig. 3 Overall structure of MCDM problem (numerical example 1)

Research Tools

Two numerical examples – design of educational mobile robots were solved in this work. The problems were solved in MCDM approach. A hybrid method, ISM-ANP is employed to crack the problems. ISM is a very popular approach (Shashank Kumar et al. 2021). Warfield (1974) proposed it initially and then it has many variants and improved versions. ISM is used by many researchers successfully to find relationships between attributes of a problem. For a real world problem, more number of attributes is available. To solve the problem, examining only one attribute will not help. All attributes' behavior and their indirect and direct relationships will help to find the best solution. So ISM is used to get collective information about attributes' relationship. The merits of ISM are: (1) it has a systematic approach. So with help of a computer, it is possible to compare and analyze all possible solutions using all relationships of attributes and transitive rule. (2) ISM is very efficient. Using transitive rule, 50% – 80% of relational queries can be reduced. (3) It helps and records the outcomes of group discussions on complex issues. (4) The user does not need any knowledge about ISM. Just by knowing about the problem and answering computer generated queries, the user can develop ISM model for the problem. (5) ISM generates a structured model and a graphical picture about original situation of a problem. So it is easily understandable by anybody. (6) ISM encourages the user to think more about all possible attributes, situations and solutions for a problem. (7) Quality of interpersonal and interdisciplinary communication among the participants is improved. Participants can concentrate more on specific issue at a time. (8) It is a good learning tool to know about an in-depth understanding and significance of a list of

attributes and their relationships by the user. (9) It helps to frame certain policy decisions for a problem in view of specific objectives.
ANP is an improved version of AHP. It was proposed by Saaty in 1996. AHP is generally utilized for ranking factors which are possessing bi-directional relations (Shashank Kumar et al. 2021). AHP is the best for the factors having linear relations. But for network structure, AHP cannot be utilized. ANP has a benefit over AHP. ANP prioritize a set of factors based on dependency, unidirectional, independency and bidirectional relations (Chen et al. 2019). ANP is a popular method to create a network for a structured model (Vasanthakumar et al. 2017). Any link can be generated among all attributes of a problem. There is no restriction for a decision-maker to model complexity and diversity of attributes. So he/she can think naturally and usually, and get the best solution for a problem using ANP. In ANP, there is no restriction on number of attributes, their relationships and solution choices of a problem. So, without simplifying the problem, directly it can be solved by ANP. ANP has applications in all fields. Few of them are supply-chains, scheduling, path-finding, resource allocating, marketing, etc.

Research methodology

In this research study, green mobile robot design was demonstrated using a hybrid MCDM methodology. In phase-1, ISM is used to identify a hierarchical structure or interrelationship between attributes. Fig. 4 shows ISM for mobile robot design. In phase-2, ANP method is used to identify the importance of the attributes and their best choice of selection. ANP methodology is shown in Fig. 5.

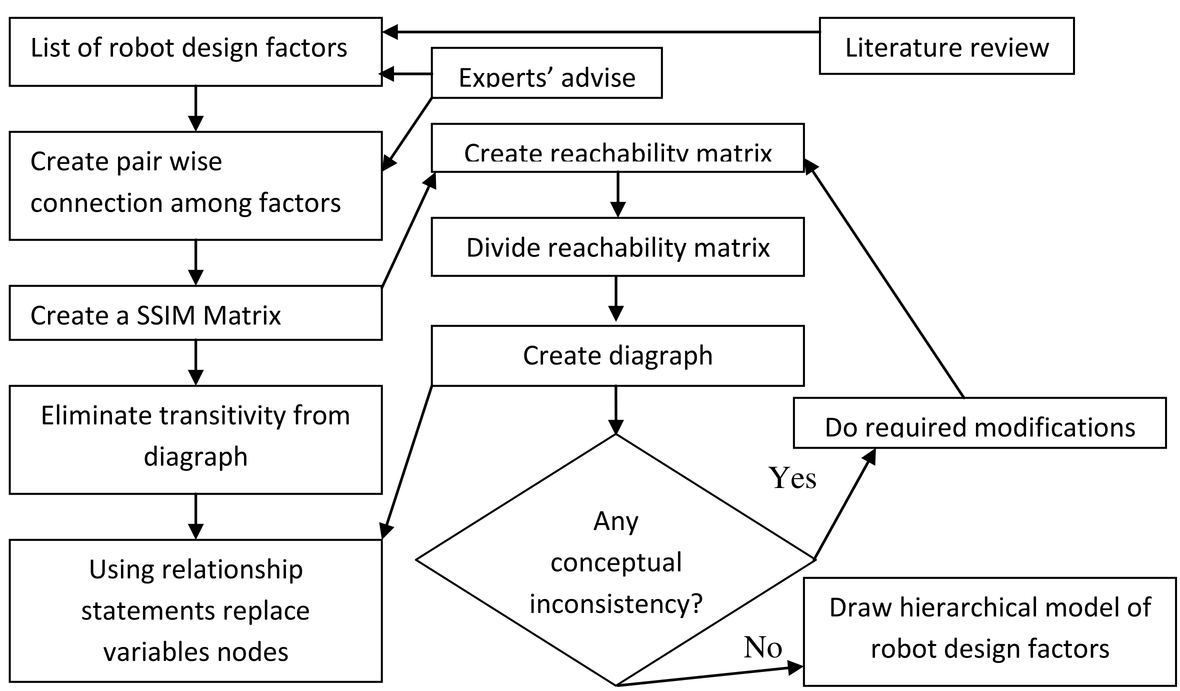

Fig. 4 ISM for Mobile robot design

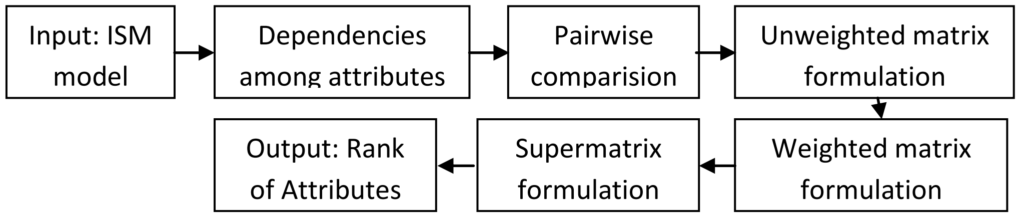

Fig. 5 ANP Procedure

Phase-1: ISM

ISM is used to identify all relationships between the attributes of green robot design. It also helps to draw the hierarchical structure of the attributes. Step by step procedure of ISM approach is detailed below:

Step-1: It identifies all attributes of the robot design. It also identifies interactions between them.

Step-2: It finds relationship among all the attributes.

Step-3: It establishes Structural Self-Interaction Matrix (SSIM) with a help of attributes' relationship. SSIM matrix is detailed below:

$$W = \begin{array}{c} \\ c_1 \\ c_2 \\ \vdots \\ c_m \end{array} \begin{array}{c} \begin{array}{cccc} c_1 & c_2 & \dots & c_n \end{array} \\ \begin{bmatrix} 0 & \sigma_{12} & \cdots & \sigma_{1n} \\ \sigma_{21} & 0 & \cdots & \sigma_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{m1} & \sigma_{m2} & \cdots & 0 \end{bmatrix} \end{array} \tag{1}$$

Where C_i indicates i^{th} factors. S_{ij} signifies interrelationship between i^{th} and j^{th} factors. SSIM is represented by the symbol W. SSIM matrix is completed with the below mentioned symbols:

"V" indicates the link between attributes 'i' and 'j' ('i' helps to reach 'j')

"A" indicates the link between attributes 'j' and 'i' ('j' helps to reach 'i')

"X" indicates bidirectional relationship between attributes 'i' and 'j'

"O" indicates no link between attributes 'i' and 'j'

In general, based on experts' opinion, links are determined. Suppose, there is a difference of experts' opinion in finding the linkages among two attributes, only crucial attributes' links are considered. This method is used up to get approval from all the experts.

Step-4: An Initial Reachability Matrix (IRM) is prepared by substituting binary numbers (0 and 1) for the symbols 'V', 'A', 'X' and 'O' based on the below mentioned rules:

Rule-1: If 'V' is in (i, j) of SSIM, then it is replaced by '1' and (j, i) of SSIM is replaced by '0'

Rule-2: If 'A' is in (i, j) of SSIM, then it is replaced by '0' and (j, i) of SSIM is replaced by '1'

Rule-3: If 'X' in (i, j) of SSIM, then it is replaced by '1' and (j, i) of SSIM is replaced by '1'

Rule-1: If 'O' in (i, j) of SSIM, then it is replaced by '0' and (j, i) of SSIM is replaced by '0'

Step-5: Use transitivity concept – If 'Attribute 1' is linked with 'Attribute 2' and 'Attribute 2' is linked with 'Attribute 3', then 'Attribute 1' is linked with 'Attribute 3'. Inferences due to multiple indirect linkages are disappeared using this concept. Final Reachability Matrix (FRM) is prepared in this way.

Step-6: Level partitions are performed using FRM, Reachability Set (RS) and Antecedent Set (AS). The Intersection Set (IS) is found by comparing RS and AS. By comparing IS and RS, if an attribute is in both sets, then it occupies top level in an ISM hierarchy model. Attributes occupying top level are disconnected from others. They are put in top level. They are removed in both RS and IS. Then other attributes compared to identify next level. This process is continued up to allotting all attributes.
Step-7: A digraph is drawn using the FRM. Here, top-level attributes are placed in top position. Below them, next level attributes are placed. Then third-level attributes are placed. At last, fourth-level attributes are placed.
Step-8: Find dependence and driving powers of each attribute. Then attributes are separated in four categories using a MICMAC analysis.

Phase-2: ANP

In ANP, a pair-wise or super matrix is established. It represents importance of one factor when compared to others. Consider a system with 'n' number of factors. C_p represents component of p. p =1, 2 …N. N_p represents e_{h1} $e_{h2\ldots}$ e_{hNh1}. Then the super matrix (A) is generated as below:

$$A = \begin{array}{cc} & \begin{array}{cccc} c_1 & c_2 & \cdots & c_n \\ e_{11}\cdots e_{1n_1} & e_{21}\cdots e_{2n_2} & & e_{n1}\cdots e_{nn_N} \end{array} \\ \begin{array}{cc} c_1 & \begin{array}{c} e_{11} \\ \vdots \\ e_{1n_1} \end{array} \\ c_2 & \begin{array}{c} e_{21} \\ \vdots \\ e_{2n_2} \end{array} \\ & \\ c_n & \begin{array}{c} e_{n1} \\ \vdots \\ e_{nn_N} \end{array} \end{array} & \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ A_{n1} & A_{n2} & \cdots & A_{nn} \end{bmatrix} \end{array} \quad (2)$$

A pair-wise assessment is done to create a priority-vector. It indicates that impact of one factor over another factor. Its value is zero, when a factor has no effect on another factor. Now the super matrix 'A' is simplified as below:

$$A = \begin{bmatrix} I & A_{12} & 0 \\ A_{21} & 0 & 0 \\ 0 & A_{32} & I \end{bmatrix} \quad (3)$$

'I' is an identity matrix. A_{12}, A_{21} and A_{32} are factors' influencing values. Cesaro sum rule is used to find overall influencing value of the factors. Now the supermatrix is converted to limiting powers as below:

$$A^{\infty} = \lim_{k \to \infty} (1/N) a_j^k$$

Supermatrix is converged as a unique-limit column vector:

$$A^{\infty} = A^{\infty} \times e^T$$

Supermatrix is further simplified. A simplified stochastic matrix's limit-priorities are found from Principal Eigen value. A hierarchy with three stages for $q_i = 1, A^{\infty}$ is detailed below:

$$A^{\infty} = \lim_{k \to \infty} \begin{pmatrix} 0 & 0 & 0 \\ A_{22}^{k} A_{21} & A_{22}^{k} & 0 \\ A_{32} \sum_{p=0}^{k-2} A_{22}^{p} & A_{32} \sum_{p=0}^{k-1} A_{22}^{p} & I \end{pmatrix}$$

If, $|A_{22}| < 1$ infers that $(A_{22})^{k} \to 0$, as $k \to \infty$, so:

$$A^{\infty} = \lim_{k \to \infty} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ A_{32}(I - A_{32})^{-1} A_{21} & A_{32}(I - A_{22})^{-1} & I \end{pmatrix} \tag{4}$$

Results and Discussion

Analysis of Results

This research study was performed in two phases. Phase-1 is ISM modeling. Phase-2 is prioritization using ANP method. In phase-1, data was collected using questionnaires as per requirements of ISM. Brief information was given in the questionnaires which were sent to get response from various researchers working in mobile robotics field. In phase-2, relative weights among all attributes were identified through another set of questionnaires. As per ANP standard rule, relative weight of each attribute was found.

Phase-1: ISM Modeling

Step-1: Identification of all objectives and attributes for green mobile robot design was performed.

Step-2: Pairwise comparison was prepared based on Experts' opinions. The relationship among all attributes was established. Tables 2 and 3 show attributes, their choices, and their weights in numerical examples 1 and 2 respectively.

Step-3: SSIM matrix was established using Equation 1(Table 4).

Step-4: IRM was prepared from SSIM matrix.

Step-5: FRM was prepared from IRM matrix using transitivity rule (Table 5).

Step-6: Attributes were listed in different levels using RS, AS and IS sets (Table 6).

Step-7: ISM hierarchy model was developed using attributes' level. Relationship between attributes is shown by connection arrow. ISM model of green mobile robot design is shown in Fig. 6. To identify dependent attributes and independent attributes, a MICMAC analysis was performed. Based on dependent power and driving power, the attributes were divided into four clusters (Fig. 7). Attributes which have same range of dependent power and driving power were grouped in same cluster. But the priority to be given for an attribute is not identified in ISM. ANP is used for prioritizing attributes. So ISM is the input to ANP procedure.

Phase-2: ANP

Step-8: ISM was taken as input to ANP. MICMAC analysis results were used for making ANP model. Independent attributes were not compared with other attributes. Energy saver connection wires, I/O devices, Metal wheels, Eco-friendly tyres, Metal battery connector, holder and fasteners are selected. Only dependent attributes were considered as per Table 7 for numerical example 1. Alternatives were found by considering choices of battery, controller, software, sensor, motor and motor driver board. Table 8 was considered for numerical example 2. Using FRM and attributes relationship, a pairwise comparison was established in Super Decision software. ANP models for examples 1 and 2 are shown in Fig. 8 and 9.

Step-9: Based on Experts' opinion, relative weights of the attributes were found as per Equation 2. An unweighted supermatrix was prepared.

Step-10: Weighted supermatrix was prepared as per alternatives comparison using Equation 3.

Step-11: Limited supermatrix was prepared using Equation 4 (Table 9).

Step-12: Now raw columns of limited supermatrix give priorities of attributes (Tables 10 and 11).

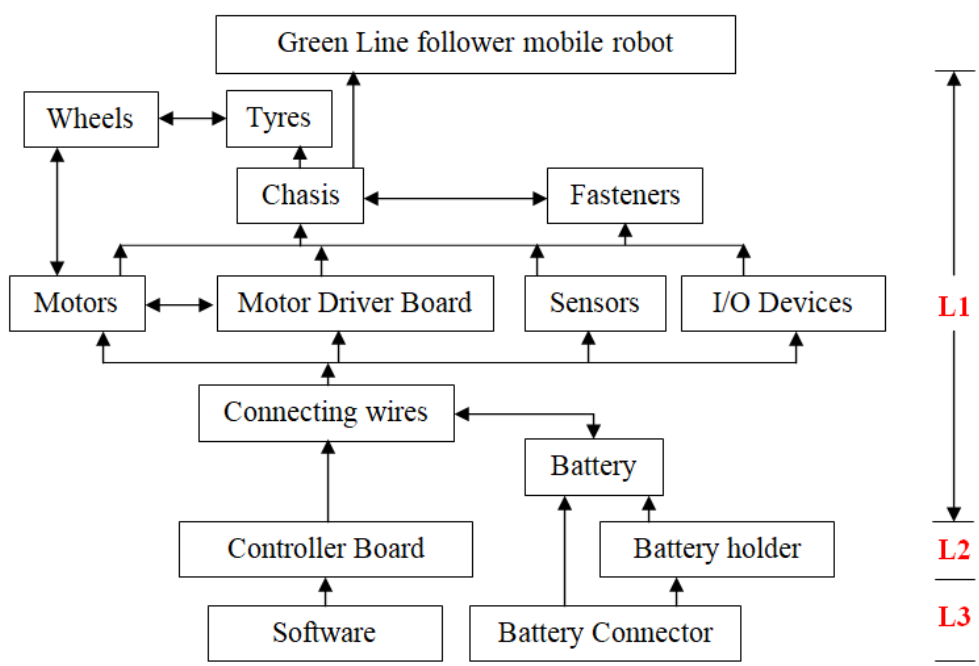

Fig. 6 Model giving the relationships among robot components based on ISM (numerical example 1)

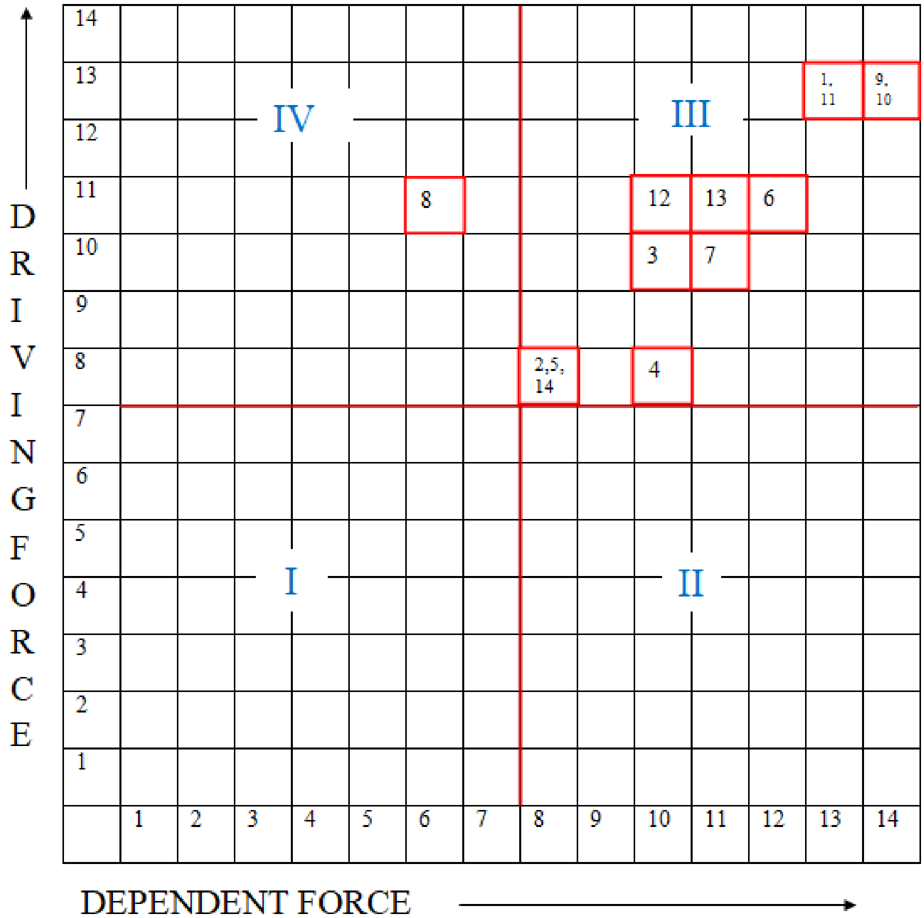

Fig. 7 MICMAC analysis (numerical example 1)

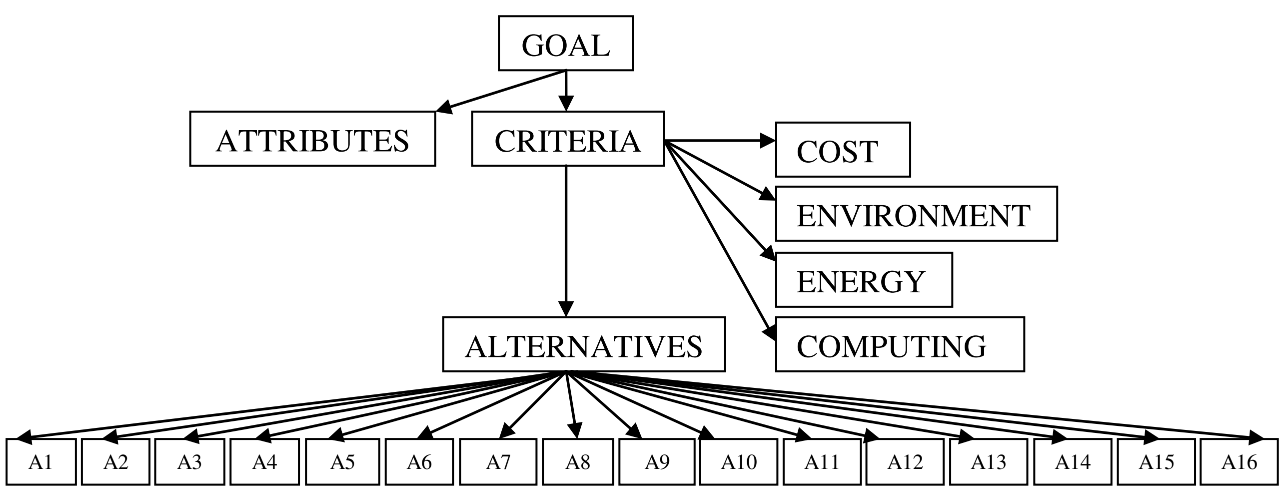

Fig. 8 ANP model (numerical example 1)

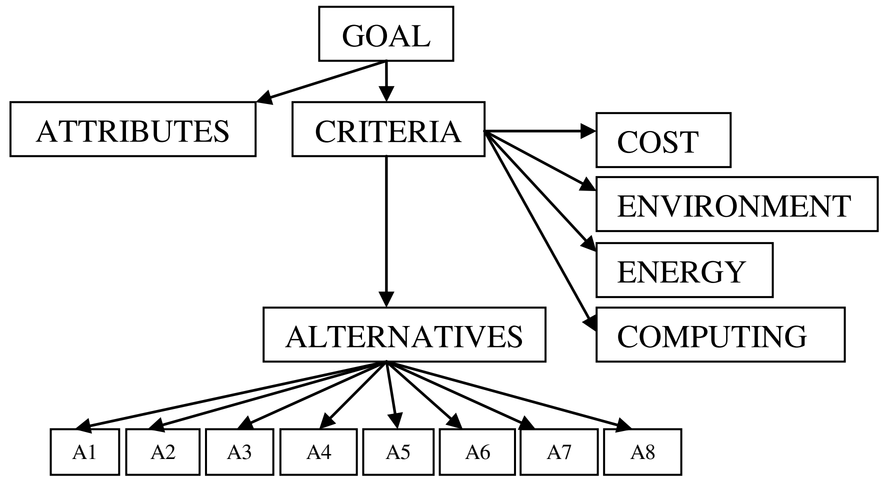

Fig. 9 ANP model (numerical example 2)

Table 2 Attributes, their choices, and their weights in numerical example 1

Attributes		Choices	Criteria			
No.	Name		Cost ($)-Approximate	Energy (W)-Average	Environment (1-5 scale)	Learning (1-5 scale)
1	Connection wires	ordinary	2	0.1	1	1
		Energy saver	3	0.05	2	2
2	I/O devices	ordinary	3	0.2	1	1
		Energy saver	5	0.1	2	2
3	Wheels	Metal	2	0	2	2
		Plastic	1	0	1	1
4	Tyres	Rubber	2	0	1	1
		Eco-friendly	1	0	4	2
5	sensors	Infrared	4	0.1	3	2
		Ultrasonic	5	0.2	1	4
6	chasis	Metal	5	0	3	2
		Acrylic	6	0	1	1
7	controller	Arduino UNO	22	0.5	3	4
		Microcontroller	8	1.0	1	2
8	software	Arduino programming	0	0.5	3	4
		Microcontroller code	0	0.7	1	2
9	battery	LiPo/Li-ion	60	60	4	4
		ordinary	10	100	2	2
10	motors	DC motor geared type	5	0.72	4	3
		DC Stepper	40	1.18	2	4
11	Motor driver board	L298N board	5	0.3	3	3
		Stepper motor board	2	0.5	2	4

12	Battery connectors	Metal	2	0.01	2	2
		Plastic	2	0.01	1	1
13	Battery holder	Metal	4	0	2	2
		Plastic	2	0	1	1
14	Fastening items	Metal	1	0	2	2
		Plastic	1	0	1	1

Table 3 Attributes, their choices, and their weights in numerical example 2 (Alves Filho et al., 2018)

Attributes		Choices	Criteria			
No.	Name		Cost ($)-Approximate	Energy (W)-Average	Environment (1-5 scale)	Learning (1-5 scale)
1	Arduino	ordinary	11900	0.5	2	2
2	Sensor	Analog	10,00	0.12	2	1
		Digital	6,30	0.10	1	2
3	Motor	DC	39,00	0.72	1	2
		Step	79,00	1.18	2	1
4	Chasis	Acrylic	42,00	0	1	2
		Metal	11900	0	1	1

Table 4 SSIM matrix (numerical example 1)

Attribute No.	14	13	12	11	10	9	8	7	6	5	4	3	2	1
1	O	O	O	X	X	X	O	X	O	X	O	O	X	X
2	O	O	O	X	O	O	X	X	O	X	O	O	X	
3	X	O	O	O	X	O	O	O	X	O	X	X		
4	O	O	O	O	X	O	O	O	A	O	X			
5	O	O	O	X	O	O	X	X	O	X				
6	X	X	X	O	X	X	O	O	X					
7	O	O	O	X	O	X	X	X						
8	O	O	O	V	V	V	X							
9	O	X	X	X	X	X								
10	O	O	O	X	X									
11	O	O	O	X										
12	O	X	X											
13	X	X												
14	X													

V = $i \rightarrow j$; A = $j \rightarrow i$; X = $i \leftrightarrow j$; O = $i \not\leftrightarrow j$

Table 5 FRM Matrix (numerical example 1)

Attribute No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Driving force
1	1	1	1*	1*	1	1*	1	1*	1	1	1	1*	1*	0	13
2	1	1	0	0	1	0	1	1	1*	1*	1	0	0	0	8
3	1*	0	1	1	0	1	0	0	1*	1	1*	1*	1*	1	10
4	1*	0	1	1	0	1*	0	0	1*	1	1*	0	0	1*	8
5	1	1	0	0	1	0	1	1	1*	1*	1	0	0	0	8
6	1*	0	1	1	0	1	1*	0	1	1	1*	1	1	1	11
7	1	1	0	0	1	1*	1	1	1	1*	1	0	1*	0	10
8	1*	1	0	0	1	1*	1	1	1	1	1	1*	1*	0	11
9	1	1*	1*	1*	1*	1	1	0	1	1	1	1	1	1*	13
10	1	1*	1	1	1*	1	1*	0	1	1	1	1*	1*	1*	13
11	1	1	1*	1*	1	1*	1	1*	1	1	1	1*	1*	0	13
12	1*	0	1*	1*	0	1	1*	0	1	1*	1*	1	1	1*	11
13	1*	0	1*	1*	0	1	1*	0	1	1*	1*	1	1	1	11
14	0	0	1	1*	0	1	0	0	1*	1*	0	1*	1	1	8
Dependent force	13	8	10	10	8	12	11	6	14	14	13	10	11	8	148

Table 6 Level partitions of Attributes (numerical example 1)

Attribute no.	Reachability set	Antecedent set	Intersection	Level/ iteration
1	1,2,3,4,5,6,7,8,9,10,11,12,13	1,2,3,4,5,6,7,8,9,10,11,12,13	1,2,3,4,5,6,7,8,9,10,11,12,13	I
2	1,2,5,7,8,9,10,11	1,2,5,7,8,9,10,11	1,2,5,7,8,9,10,11	I
3	1,3,4,6,9,10,11,12,13,14	1,3,4,6,9,10,11,12,13,14	1,3,4,6,9,10,11,12,13,14	I
4	1,3,4,6,9,10,11,14	1,3,4,6,9,10,11,14	1,3,4,6,9,10,11,14	I
5	1,2,5,7,8,9,10,11	1,2,5,7,8,9,10,11	1,2,5,7,8,9,10,11	I
6	1,3,4,6,7,9,10,11,12,13,14	1,3,4,6,7,9,10,11,12,13,14	1,3,4,6,7,9,10,11,12,13,14	I
7	1,2,5,6,7,8,9,10,11,13	1,2,5,6,7,8,9,10,11,12,13	1,2,5,6,7,8,9,10,11,13	II
8	1,2,5,6,7,8,9,10,11,12,13	1,2,5,7,8,11	1,2,5,7,8,11	III
9	1,2,3,4,5,6,7,9,10,11,12,13,14	1,2,3,4,5,6,7,9,10,11,12,13,14	1,2,3,4,5,6,7,9,10,11,12,13,14	I
10	1,2,3,4,5,6,7,9,10,11,12,13,14	1,2,3,4,5,6,7,9,10,11,12,13,14	1,2,3,4,5,6,7,9,10,11,12,13,14	I
11	1,2,3,4,5,6,7,8,9,10,11,12,13	1,2,3,4,5,6,7,8,9,10,11,12,13	1,2,3,4,5,6,7,8,9,10,11,12,13	I
12	1,3,4,6,7,9,10,11,12,13,14	1,3,6,8,9,10,11,12,13,14	1,3,6,9,10,11,12,13,14	III
13	1,3,4,6,7,9,10,11,12,13,14	1,3,6,7,8,9,10,11,12,13,14	1,3,6,7,9,10,11,12,13,14	II
14	3,4,6,9,10,12,13,14	3,4,6,9,10,12,13,14	3,4,6,9,10,12,13,14	I

Table 7 Alternatives selection by ANP (numerical example 1)

Alternatives	Attributes (varying)				CRITERIA			
	Sensor	Controller	Motor	Battery	COST ($)	ENERGY (W)	ENVIRONMENT	LEARNING
A1	IR	Arduino	DC Geared	LiPo	119	62.28	39	37
A2	IR	Arduino	DC Geared	ordinary	69	102.28	37	35
A3	IR	Arduino	DC Stepper	LiPo	151	62.94	36	34
A4	IR	Arduino	DC Stepper	ordinary	101	102.94	34	32
A5	IR	Microcontroller	DC Stepper	ordinary	87	103.64	30	28
A6	IR	Microcontroller	DC Stepper	LiPo	137	63.64	32	30
A7	IR	Microcontroller	DC Geared	ordinary	55	102.98	33	31
A8	IR	Microcontroller	DC Geared	LiPo	105	62.98	35	33
A9	Ultrasonic	Arduino	DC Geared	LiPo	120	62.38	37	39
A10	Ultrasonic	Arduino	DC Geared	ordinary	70	102.38	35	37
A11	Ultrasonic	Arduino	DC Stepper	LiPo	152	63.04	34	36
A12	Ultrasonic	Arduino	DC Stepper	ordinary	112	103.04	32	34
A13	Ultrasonic	Microcontroller	DC Stepper	ordinary	88	103.74	28	30
A14	Ultrasonic	Microcontroller	DC Stepper	LiPo	138	63.74	30	32
A15	Ultrasonic	Microcontroller	DC Geared	ordinary	56	103.08	31	33
A16	Ultrasonic	Microcontroller	DC Geared	LiPo	106	63.08	33	35

Table 8 Alternatives selection by ANP in numerical example 2 (Alves Filho et al. 2018)

Alternatives	Attributes (varying)			CRITERIA			
	Sensor	Motor	Chasis	COST ($)	ENERGY (W)	ENVIRONMENT	LEARNING
A1	Analog	DC	Acrylic	259,00	2,19	2	3
A2	Analog	DC	Metal	367,00	2,19	2	2
A3	Analog	Step	Acrylic	339,00	3,11	3	2
A4	Analog	Step	Metal	447,00	3,11	3	1
A5	Digital	DC	Acrylic	251,60	2,14	1	4
A6	Digital	DC	Metal	359,60	2,14	1	3
A7	Digital	Step	Acrylic	331,60	3,06	2	3
A8	Digital	Step	Metal	439,60	3,06	2	2

Table 10 Priorities of Alternatives by ANP (numerical example 1)

Alternatives	Limiting value	Priority Rank
A1	0.016623	1
A2	0.015967	2
A9	0.015852	3
A3	0.014899	4
A10	0.014713	5
A11	0.013842	6
A4	0.0138	7
A12	0.013443	8
A8	0.011542	9
A7	0.011501	10
A16	0.011124	11
A15	0.010203	12
A6	0.010039	13
A14	0.009172	14
A5	0.008931	15
A13	0.008349	16

Table 11 Priorities of Alternatives (numerical example 2)

Alternatives	ANP		Priority Rank in Alves Filho et al. (2018)
	Limiting value	Priority Rank	
A1	0.021224	5	1
A2	0.019526	7	2
A3	0.03401	2	1
A4	0.034574	1	2
A5	0.020349	6	1
A6	0.017291	8	2
A7	0.026852	3	2
A8	0.026173	4	2

Discussions

Numerical example 1

This numerical example is to design a green educational line-follower mobile robot. Based on experts' opinion four criteria, 14 attributes and 16 alternative solutions were selected. Also relationships among them were established. Using ISM approach, they were placed in three levels. Top level (Level 1) attributes are wheels, tyres, chassis, fasteners, motors, motor driver board, sensors, I/O devices, connecting wires and battery. Intermediate level (Level 2) attributes are controller board and battery holder. Bottom level (Level 3) attributes are software and battery connector. The influence of level 1 attributes is low. The influence of level 2 and 3 attributes are medium and high respectively.

Based on the driving and dependent powers, attributes were divided in four clusters. There is no attribute in cluster 1 (Autonomous) – low driving and dependent powers. Attributes in cluster 1 have low impact on the system and they can be handled easily. Also there is no attribute in cluster 2 (Dependent) – low driving power and high dependent power. So there is no highly depending attribute. Attribute 8 – software is in cluster 4 (Independent) – high driving power and low dependent power. Attributes listed in this cluster are highly influencing performance of the system. So a high attention is to be given to them. Robot software needs high attention from the robot designers. All other attributes are in cluster 3 (linkage) – high driving and dependent powers. The attributes listed in this cluster are unstable. So they have to be chosen carefully. 16 alternatives were analyzed by ANP. The priorities of alternatives ranked by ANP are A1>A2>A9>A3>A10>A11>A4>A12>A8>A7>A16>A15>A6>A14>A5>A13. Alternative one (A1) got rank 1. So it can be considered by the robot designer.

Numerical example 2

Alve Filgo et. al (2018) detailed a green robot design problem. They considered an educational line follower mobile robot as in Fig. 2. They tried to solve this problem using a multi-objective optimization approach. Tables 3 shows attributes, their choices, and their weights. Robot controller, sensor, motor and chassis are considered. Robot controller is Arduino board. Choices for selecting sensor are analog and digital. Choices for selecting motor are DC motor and Stepper motor. Acrylic or metal chassis is to be selected. So, there are eight alternatives. They were analyzed by ANP. The priorities of alternatives ranked by ANP are A4>A3>A7>A8>A1>A5>A2>A6. Alternative one (A4) got rank 1. So it can be considered by the robot designer. Fig. 9 details ANP model for this problem.

Managerial implications

This research work is carried out to help robot designers to select the best components of mobile robot. Four important criteria namely cost, green design (eco-friendly), energy saving and green computing were considered in this study. In numerical example 1, if the designer considers all four criteria, then alternative A1 is the best choice. So it can be selected. If a designer considers only green computing, then ranks of alternatives are A9>A1,A10,A11>A2,A3,A12,A16>A4>A8,A14,A15>A13>A6,A7>A5. So, alternative A9 is the best option. If a designer considers only cost, then ranks of alternatives are A11>A3>A14>A6>A9>A1,A8,A12,A16>A4>A5>A13>A10>A2>A15>A7. So, alternative A11 is the best option. If a designer considers only eco-friendly nature, then ranks of alternatives are A1>A2,A3,A9>A4,A8,A10,A11>A16,A7,A12>A6>A14,A15>A5>A13. So, alternative A1 is the best option. If a designer considers only energy saving, then ranks of alternatives are A2,A4,A5,A7,A10,A12,A13,A15>A1,A3,A6,A8,A9,A11,A14,A16. So, alternatives A2,A4,A5,A7,A10,A12,A13,A15 are best options.

In numerical example 2, if the designer considers all four criteria, then alternative A4 is the best choice. If a designer considers only green computing, then alternative A5 is the best option. If a designer considers only cost, then alternatives A4 and A8 are the best options. If a designer consider only eco-friendly nature, then alternative A3 and A4 are the best options. If a designer considers only energy saving, then alternatives A3, A4, A7 and A8 are the best options.

This research study- unique contribution

This is the first study tried to do green design of two educational line follower mobile robots in a MCDM approach. In numerical example 1, based on experts' opinion, four criteria, 14 attributes and 16 alternative solutions were selected. Also relationships among them were established. This study used a hybrid MCDM approach, ISM-ANP. Using ISM approach, attributes were placed in three levels. Based on the driving and dependent powers, attributes were grouped in four clusters. Attribute needs more attention was identified. Robot software needs high attention from the robot designers. All other attributes need careful decision making. Since, they were listed in more unstable nature cluster. 16 alternatives were analyzed by ANP. The priorities of alternatives ranked by ANP were found. Four important criteria namely cost, green design (eco-friendly), energy saving and green computing were analyzed by ANP. If a designer considers all four criteria, then the best alternative A1 was suggested by ANP. If a designer considers only one criterion, then the best alternative was also suggested by ANP. In numerical example 2, ANP analyzed 8 alternatives. The results are compared with a literature (Alve Filho et. al, 2018) results. So, the methodology utilized in this research study is distinctive and has few merits when compared to others.

Conclusions and Future works

This work discusses characteristics of green design and development of mobile robot in sustainability aspect. It details the relationship between the environment and robotics. It focuses all important criteria for green design of mobile robots. Cost reduction and increased autonomy are also benefits of the proposed strategies. It is found that there is no specific standard to design and evaluation of green robotics. Important metrics to evaluate different perspectives were considered in this work. In case of educational mobile robots, they are mainly used in schools and colleges for teaching and doing experiments. Also they are used in various competitions. So a huge quantity of mobile robots is fabricated. Main problems with mobile robot design are (1) designers are not using standard parts. Further they are making necessary parts themselves. (2) Components are not designed and manufactured in the aspect of environment preservation. (3) Green materials are not selected. (4) Energy saving aspect is not considered. (5) Batteries are not manufactured in eco-friendly nature. Lot of issues related to batteries used in robots. They are not reusable. Also they are not disposed properly in the environment. Millions of batteries are discarded. So they cause pollution. (6) Electromechanical parts of the robot cause more damage to the environment. Size of robot components may be small. But, a huge quantity of robot parts like sensors and actuators are discarded without proper treatments. They cause pollution. So, production of robot components and batteries is to be based on green initiatives and standards. Then only, they will help the environment.

This work dealt green robotics as a problem of MCDM. Contradictive objectives such as cost reduction, energy saving, eco-friendly and green computing were considered in the numerical problems of green design of educational mobile robots. A decision maker will need more number of choices for his/her selection. So a hybrid MCDM approach, ISM-ANP was utilized to solve the problem. The proposed methodology detailed about four important criteria, 14 attributes and 16 alternative solutions (numerical example 1). ISM gave details about relationship among the attributes, their importance and classification in three levels.

MICMAC analysis classified the attributes in four clusters. From that, the attributes need more attention and careful decision making were identified. ANP detailed the priorities of the alternative solutions.

Worldwide acceptable common standards and certifications are to be established in green robotics. Robot designers need to follow them from starting to end process of robot making. Mainly in selection techniques, mechanisms and components for robot design, careful decision making is needed. All important criteria such as low energy consumption, low cost, low pollution, green computing, high efficiency, green supply chain, green manufacturing are to be considered. This work had a discussion about green mobile robot design in various aspects. Surely this work will be very useful for robot designers.

Future works

Other MCDM techniques can be used to solve the problems. This research work can be extended to stationary industrial robots. Further this problem can be solved in a multi-objective optimization approach. Optimization techniques such as MOPSO, MOGA, MOACO, etc can be used to crack the problem.

Annexure 1 and 2

Data sets used in Numerical examples 1 and 2 are given.

Declarations:

Authors' contributions:

V. Sathiya- Concept Development, Data collection, Problem solving, Manuscript preparation
M. Chinnadurai – Problem solving and Manuscript editing
S. Ramabalan – Manuscript preparation and Manuscript editing

Funding: This research was not supported by any agency

Availability of data and material: Literature Data and materials used in this research work are adequately mentioned in the necessary places. (data transparency)
Data presented in Annexure 1 and 2 can be used by any researcher.

Code availability: Super Decision software was used in this study. (software application or custom code)

Compliance with ethical standard

Conflict of interest: The authors declare that they have no conflict of interests.

References

Abbas Mardani, Ahmad Jusoh, Khalil MD Nor, Zainab Khalifah, Norhayati Zakwan, Alireza Valipour (2015) Multiple criteria decision-making techniques and their applications – a review of the literature from 2000 to 2014. Econ Res-Ekon Istraž 28(1):516-571. https://doi.org/10.1080/1331677X.2015.1075139

Alves Filho SE, S T de L Sá, Burlamaqui AMF, Aroca RV, Gonçalves LMG (2018) Green Robotics: Concepts, Challenges, and Strategies. IEEE Lat Am Trans 16(4): 1042-1050. https://doi.org/10.1109/TLA.2018.8362135

Ankit Kumar, Manoj Kumar (2019) Implementation of Analytic Hierarchy Process (AHP) as a decision-making tool for selection of materials for the robot arm. Int J Appl Eng Res 14(11):2727-2733. Link: https://www.ripublication.com/ijaer19/ijaerv14n11_27.pdf

Asadi S, Hussin ARC, Dahlan HM (2018) Toward Green IT adoption: from managerial perspective. Int J Bus Inf Sys 29(1):106–125. https://doi.org/10.1504/IJBIS.2018.094002

Cinzia Amici, Nicola Pellegrini, Monica Tiboni (2020) The robot selection problem for mini-parallel kinematic machines: a task-driven approach to the selection attributes identification. Micromachines 11:711. https://doi.org/10.3390/mi11080711

Cusack P, Perrett T (2006) The EU ROHS directive and its implications for the plastics industry. Plast Addit Compd 8(3):46–49. https://doi.org/10.1016/S1464-391X(06)70584-0

Dawes M (2015) An introduction to ISO 14000. Link: http://ems.asn.au/about/iso14000/

Ertugrul Karsak E, Zeynep Sener, Mehtap Dursun (2012) Robot selection using a fuzzy regression-based decision – making approach. Int J Prod Res 50(23):6826-6834. https://doi.org/10.1080/00207543.2011.627886

Fuli Zhou, Xu Wang, Mark Goh (2018) Fuzzy extended VIKOR-based mobile robot selection model for hospital pharmacy. Int J Adv Robot Sys July-August, 1–11. https://doi.org/10.1177/1729881418787315

GEC, (2015) EPEAT criteria. Link: https://www.epeat.net/about-epeat

Goswami SS, Behera DK, Afzal A, Razak Kaladgi A, Khan SA, Rajendran P, Subbiah R, Asif M (2021) Analysis of a robot selection problem using two newly developed hybrid MCDM models of TOPSIS-ARAS and COPRAS-ARAS. Symmetry 13:1331. https://doi.org/10.3390/sym13081331

Hu-Chen Liu, Ming-Lun Ren, Jing Wu, Qing-Lian Lin (2014) An interval 2-tuple linguistic MCDM method for robot evaluation and selection. Int J Prod Res 52(10):2867-2880. https://doi.org/10.1080/00207543.2013.854939

Jacob Nielsen, Henrik Hautop Lund (2005) Modular robotics as a tool for education and entertainment. Comput Human Behav 24(2):156-166. https://doi.org/10.1016/j.chb.2007.01.011

Mahmood Shahrabi (2014) Identification and selection of robot using FAHP and FTOPSIS hybrid model. Int J Mod Eng Sci 3(1):16-28. Link: http://www.modernscientificpress.com/Journals/ViewArticle.aspx?tRyrbufkjak1a0wD6Ne03otpj1JtUffJd6CZE+WncpCYje1U8jxPGOj97a6LfpAF

Mahdi Nasrollahi, Javaneh Ramezani, Mahmoud Sadraei (2020) A FBWM-PROMETHEE approach for industrial robot selection. Heliyon 6:e03859. https://doi.org/10.1016/j.heliyon.2020.e03859

Mehdi Keshavarz Ghorabaee (2016) Developing an MCDM method for robot selection with interval type-2 fuzzy sets. Robot Comput Integr Manuf 37:221-232. https://doi.org/10.1016/j.rcim.2015.04.007

Manjunatheshwara KJ, Vinodh S (2018) Grey-based decision-making method for sustainable material selection of tablet device enclosure. Clean Techn Environ Policy 20:2345–2356. https://doi.org/10.1007/s10098-018-1610-7

Ming-Lang Tseng, Md Shamimul Islam, Noorliza Karia, Firdaus Ahmad Fauzi, Samina Afrin A (2019) Literature review on green supply chain management: Trends and future challenges. Resour Conserv Recycl 141:145-162. https://doi.org/10.1016/j.resconrec.2018.10.009

Molla A, Cooper V, Pittayachawan S (2011) The green IT readiness (G-readiness) of organisations: an exploratory analysis of a construct and instrument. Commun Assoc Inf Sys 29(1):67–96. https://doi.org/10.17705/1CAIS.02904

Mohd Javaid, Abid Haleem, Ravi Pratap Singh, Rajiv Suman (2021) Substantial capabilities of robotics in enhancing industry 4.0 implementation. Cogn Robot 1:58-75. https://doi.org/10.1016/j.cogr.2021.06.001

Neşe Yalçin, Nuşin Uncu (2019) Applying EDAS as an applicable MCDM method for industrial robot selection. Sigma J Eng & Nat Sci 37(3):779-796. Link: https://eds.yildiz.edu.tr/AjaxTool/GetArticleByPublishedArticleId?PublishedArticleId=3876

Nicola Basilico, Francesco Amigoni (2011) Defining effective exploration strategies for search and rescue applications with Multi-Criteria Decision Making. 2011 IEEE International Conference on Robotics and Automation, 15 August 2011.

Patrick Taillandier, Serge Stinckwich (2011) Using the PROMETHEE multi-criteria decision making method to define new exploration strategies for rescue robots. IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR), Kyoto, Japan. 321 – 326.

Paul Moubarak, Pinhas Ben-Tzvi (2012) Modular and reconfigurable mobile robotics. Robot Auton Sys 60(12):1648-1663. https://doi.org/10.1016/j.robot.2012.09.002

Radu Eugen Breaza, Octavian Bologaa, Sever Gabriel Racz (2017) Selecting industrial robots for milling applications using AHP. Procedia Comput Sci 122:346–353. https://doi.org/10.1016/j.procs.2017.11.379

Rahmath Ulla Baig, Shaik Dawood, Mohamed Mansour, Tarik Tawfeek (2020) Identifying and prioritising future robot control research with multi-criteria decision-making. Trans Famena 44(3). https://doi.org/10.21278/TOF.44302

Rudén C, Hansson SO (2010) Registration, evaluation, and authorization of chemicals (REACH) is but the first step-how far will it take us? Six further steps to improve the European chemicals legislation. Environ health perspect 118(1):6–10. https://doi.org/10.1289/ehp.0901157

Sathiya V, Chinnadurai M (2019) Evolutionary algorithms-based multi-objective optimal mobile robot trajectory planning. Robotica 37(08):1-20. https://doi.org/10.1017/S026357471800156X

Sathiya V, Chinnadurai M, Ramabalan S, Appolloni A (2021) Mobile robots and evolutionary optimization algorithms for green supply chain management in a used-car resale company. Environ Dev Sustain 23:9110–9138. https://doi.org/10.1007/s10668-020-01015-2

Shahla Asadi, Ab Razak Che Hussin, Halina Mohamed Dahlan (2017) Organizational research in the field of Green IT: A systematic literature review from 2007 to 2016. Telemat Inform 34(7):1191-1249. https://doi.org/10.1016/j.tele.2017.05.009

Shahla Asadi, Elaheh Yadegaridehkordi, Mehrbakhsh Nilashi, Sarminah Samad (2019) Green information technology adoption: a systematic literature review. J soft comput dec sup sys 6(3):8-17. Link: https://jscdss.com/index.php/files/article/view/194/pdf_223

Shashank Kumar, Rakesh D, Raut, Kirti Nayal, Sascha Kraus, Vinay Surendra Yadav, Balkrishna E Narkhede (2021) To identify industry 4.0 and circular economy adoption

barriers in the agriculture supply chain by using ISM-ANP. J Clean Prod 293:126023. https://doi.org/10.1016/j.jclepro.2021.126023
Sivakumar TB, Hasan Hussain S, Kanmani A, Anand Babu MH (2021) Surveillance robot for health care applications using IoT and wireless sensor network. Mater Today proc. https://doi.org/10.1016/j.matpr.2021.01.170
Sri Fatiany Abdul Kader Jailani, Lili Marziana Abdullah (2017) Systematic literature review on green it practice and executional factors. Int J Supply Chain Manag 6(2):147-154. http://ojs.excelingtech.co.uk/index.php/IJSCM/article/view/1486
Thoo Ai Chin, Huam Hon Tat, Zuraidah Sulaiman (2015) Green supply chain management, environmental collaboration and sustainability performance. Procedia CIRP 26:695-699. https://doi.org/10.1016/j.procir.2014.07.035
Varun Chodha, Rohit Dubey, Raman Kumar, Sehijpal Singh, Swapandeep Kaur (2021) Selection of industrial arc welding robot with TOPSIS and Entropy MCDM techniques. Mater Today proc. https://doi.org/10.1016/j.matpr.2021.04.487
Vasanthakumar C, Vinodh S, Vishal AW (2017) Application of analytical network process for analysis of product design characteristics of lean remanufacturing system: a case study. Clean Techn Environ Policy 19: 971–990. https://doi.org/10.1007/s10098-016-1293-x
Vijay Manikrao Athawale, Shankar Chakraborty (2011) A comparative study on the ranking performance of some multi-criteria decision-making methods for industrial robot selection. Int J Ind Eng Comput 2:831–850. https://doi.org/10.5267/j.ijiec.2011.05.002
Xiao W, Yang J, Fang H, Zhuang J, Ku Y, Zhang X (2020) Development of an automatic sorting robot for construction and demolition waste. Clean Techn Environ Policy 22:1829–1841. https://doi.org/10.1007/s10098-020-01922-y
Xinkai Zuo, Fan Yang, Yifan Liang, Zhou Gang, Fei Su, Haihong Zhu, Lin Li (2020) An improved autonomous exploration framework for indoor mobile robotics using reduced approximated generalized voronoi graphs. ISPRS Ann Photogramm Remote Sens Spat Inf Sci 5(1) XXIV ISPRS Congress (2020 edition). https://doi.org/10.5194/isprs-annals-V-1-2020-351-2020
Yi-Xi Xue, Jian-Xin You, Xufeng Zhao, Hu-Chen Liu (2016) An integrated linguistic MCDM approach for robot evaluation and selection with incomplete weight information. Int J Prod Res 54(18):5452-5467. https://doi.org/10.1080/00207543.2016.1146418
Yıldızbaşi A, Ozturk C, Efendioglu D, Bulkan S (2020) Assessing the social sustainable supply chain indicators using an integrated fuzzy multi-criteria decision-making methods: A case study of Turkey. Environ Develop Sustain 23:4285–4320. https://doi.org/10.1007/s10668-020-00774-2
Yoshiaki Itoh, Toru Yamazaki, Hun-ok Lim, Kenichi Takemura (2016) Robot development project with humanand eco-friendly smart materials. Robomech J 3(21). https://doi.org/10.1186/s40648-016-0060-4
Yu Peng, Nan Wang, Yuting Diao, Haipeng MI (2019) Swarm robotics platform for intelligent interaction. Virtual Real Intell Hardw 1(3):316-329. https://doi.org/10.3724/SP.J.2096-5796.2019.0019

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- graphicalabstract.docx
- Annexure1Example1.xlsx
- Annexure2Example2.xlsx