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A Framework for Taxonomy and Evaluation of Self-Reconfigurable Robotic Systems

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ABSTRACT Self-reconfigurable robots have been proposed for a quite long period and in large numbers. However, there are very few systematic methodologies proposed to categorize and evaluate such kinds of robots. In this paper, we put forward a framework for taxonomy and evaluation (TAEV) of self-reconfigurable robots, based on the mechanism reconfigurability and the level of autonomy for reconfiguration. The mechanism reconfigurability of the robots is divided into two types: inter-reconfigurability and intra-reconfigurability which are quantified by the number of configurations and scale respectively. A combination of both the intra- and inter-reconfigurability feature is named as nested-reconfiguration. The levels of autonomy reconfigurability are ranging through different levels from manual teleoperation to fully autonomous systems. The evaluation metrics are introduced to quantify the level of autonomy and the sufficiency of self-reconfigurable robots. Detailed discussions on applications of the proposed framework are presented with real-robot examples.

INDEX TERMS Autonomy, autonomous systems, human-robot interaction, reconfigurability, reconfigurable robotics.

I. INTRODUCTION

Over the past decades, a noticeable tendency in robotics is that the research is more focused on developing robotic systems and solving issues in the context of unstructured environments instead of well-established environments. For the goal of navigating smoothly and executing missions in unstructured environments, developing fully autonomous and adaptive robots has been a hotspot in the robotics community and there have been significant efforts and developments in this area. Self-Reconfigurable (SR) robots are machines that can change their morphologies as per prescribed requirement or are adaptable to the environments with provided level of autonomy.

The need for reconfigurability regarding general reconfigurable systems (not necessarily a robot) is driven by three main factors, that is, multiability, evolvability, and survivability [1]. Similarly, we can conclude that the reconfigurability in robotics enables the functionalities of multiability, evolvability, and survivability of the robots (Fig. 1). The reconfigurability can generate different configurations, each of which is capable to handle a specific situation or deliver a particular function, such as grasping different objects or crossing over different terrains. The robotic system may change its morphology over time by reconfiguring the relative locations of its elements to adapt the environment. Reconfigurability can be a means for reinforcing survivability, can increase safety margins, and thus reduce the probability of failures. In the case of partial failures, reconfigurable robots can transform into a configuration by graceful degradation to maintain certain functionalities. The functionalities will result in an increase of the adaptability to external environments and robustness to failures, which are the primary development objectives for robot navigating in unstructured environments.

A. MOTIVATION

Although reconfigurability is useful and key for realizing adaptive and robust robotic systems, still the explicit

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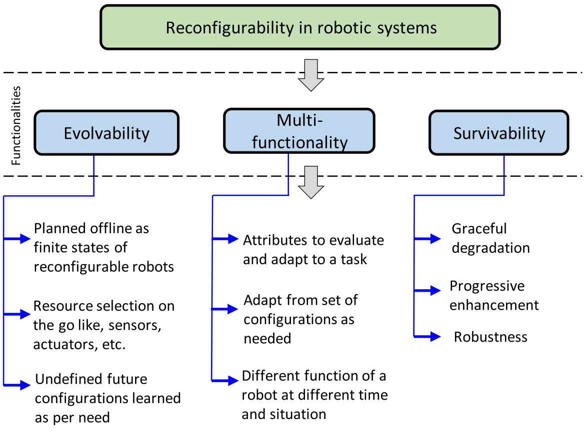

FIGURE 1. **The reconfigurability in robotics enables multi functionality, evolvability and survivability of the robot which lead to increase of adaptability and robustness.**

robot-specific definition of reconfigurability and taxonomy and evaluation system for it needed. Therefore, our overarching goal is to addressed following aspects:

1) Defining reconfigurability in the context of robotics;
2) Proposing a taxonomy and evaluation (TAEV)-framework for SR robots based on quantifying the reconfigurability and autonomy;
3) Proposing qualitative and quantitative ways for evaluating autonomous reconfigurability;
4) Evaluating the existing reconfigurable robots using the proposed TAEV-framework and also provide an on-line worksheet to evaluate it for other SR robots.

The rest of this paper is organized as follows: Section II the precedents on definition and classification are presented. Section III a framework for taxonomy and evaluation, i.e., TAEV-framework of self-reconfigurable robot is presented. The classification of self-reconfigurable robots based on the mechanism, i.e., inter-, intra- and nested-reconfigurability in Section IV. In the subsequent section (Section V), the autonomy of self-reconfigurable robots is qualitatively and quantitatively described. Section VI illustrates the application of the proposed taxonomy with real examples. Finally, Section VII concludes the paper.

II. RELATED PRIOR WORK

This section discusses the relevant work published to classify reconfigurable robots. A taxonomy for multi-robot systems based on computation, communication, and other capabilities are dealt in [2]. Swarm robots in comparison to reconfigurable robots may not be physically connected, and the distributed control mechanism guides the collective behavior. In this section, we present the related work on self-reconfigurable robots.

A. DEFINITION OF RECONFIGURABILITY AND SELF-RECONFIGURABLE ROBOTS

The term reconfigurability or reconfigurable or reconfiguration has been used in widespread domains. There have been a lot of works on discussing reconfigurability in the engineering design and product design communities [3]–[7]. The transformation design theory is studied and a framework is presented for reconfigurable systems in [8]. The common characteristics of reconfigurability in general systems were studied [1] where aerospace systems, planetary surface vehicles, and robots were exemplified [9], [10].

Reconfigurable systems are defined to be those that can reversibly achieve distinct configurations or states via alternating system form or function to achieve the desired outcome within acceptable reconfiguration time and cost [1]. Reconfigurable industrial robotic work cells were reviewed regarding the reconfigurability-associated performance criteria and means that measures the reconfigurability degree of such cells [11]. This work was dedicated to industrial robotic work cells and lacked a general perspective as well as detailed discussions.

Usually, self-reconfigurable robots are referred to as the modular robots whose components can autonomously organize into different configurations. Thus, the "Modular Self-Reconfigurable (MSR) robot" has been an idiomatic usage in the robotics community. For example, in [12], self-reconfigurable robots are treated equivalently to modular robots whose components can autonomously organize into different connected configurations. A *module* is defined as a fundamental unit of the modular robot where each module is an independent robot which can respond to the command. Whereas, *configuration* is a connected set of modules that act as a single identity or shaped robot. The survey and analysis of modular robots were reported in [13] and the methods and design principles of the coupling mechanism for connecting the different modules were reviewed in [14]. State of the art in the development of modular reconfigurable robot is surveyed in [15] and suggests future research directions. The mechanism to connect these modular units are reviewed in [14]. The self-reconfigurability in this paper is specifically self-assembly that can be defined as the reversible process where discrete entities bind to each other without being externally directed.

B. CLASSIFICATION OF SELF-RECONFIGURABLE ROBOTS

There have been a number of survey papers that reviewed a wide range of self-reconfigurable robots. The robots involved are usually correlated to robotic systems adapted modular design where modularity endows them reconfigurability. The classical tree-structured classifications of such Modular Self-Reconfigurable (MSR) robots were presented in some survey papers [16]–[18], which were usually based on the relative geometric arrangement of their modules/units. For example, the MSR robots are typically classified into architectural groups of lattice architectures and chain/tree architectures. A tree-structured of the taxonomy of modular self-reconfigurable robots is illustrated in Fig. 2.

To include more complex structures, a category is assigned as hybrid structures that mix both lattice and chain features [16]. Hybrid architectures take advantages of both

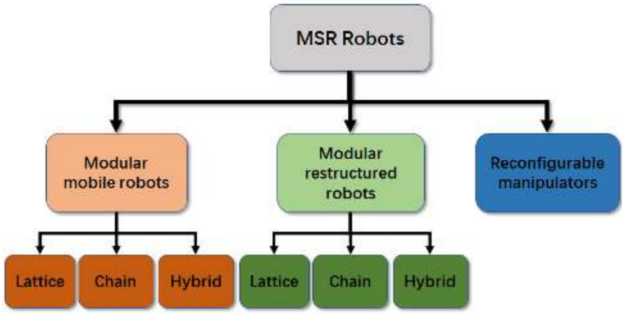

FIGURE 2. A tree-structured of the taxonomy of modular self-reconfigurable robots, categorizing the robots layer by layer where the upper layers embrace the subcategories at the lower layers.

the architectures. Mechanism and its control are designed for lattice reconfiguration and also allow to reach the target point in the space. Truss and free form are two additional structure-based categories [19]. If classified according to locomotion, the MSR robots can be divided into three categories: external, mobile and coordinated [19]. The lattice- and chain-based robotic systems are placed under coordinated subcategory because the majority of such systems are designed without wheels on individual units and hence mobility is realized only by the employment of coordination of robots. Another classification is based on the size of the robot, which can be a micro, mini, and macro.

Alternatively, the MSR robotic systems can be classified into deterministic and stochastic categories according to how units are reconfigured (moved) into place [17]. The deterministic reconfiguration has precise control over the structures whereas the stochastic type relies on units moving around using statistical processes [20]–[22]. The MSR robotic systems can also be classified as homogeneous and heterogeneous depending on the design uniformity of the modules.

The MSR robots have also been classified into the two categories in a tree structure: Mobile Configuration Change (MCC) and Whole Body Locomotion (WBL) [23]. These two categories were differentiated based on mobility patterns and reconfigurable properties of the robot. Moreover, the WBL could be classified into more subcategories based on the geometry, docking interface, and modality of reconfiguration. These subcategories are lattice architecture, chain or tree architecture, and a hybrid combination of both. Moreover, the lattice architecture was classified into three more bottomed subcategories, which are macro-sized robots, mini-sized robots, and transformable mechanisms. A most recent survey on MSR robots presented a tree-structured classification that categorizes MSR robots into modular mobile robots and modular restructured robots [24]. The former was further divided into joint-motion robots and joint-reconfiguration robots. The latter was divided into macro-sized reconfigurable manipulators and mini-sized reconfigurable robots. Furthermore, the fourth layer includes subcategories of the serial pattern, parallel pattern, chain architecture, lattice architecture, and hybrid architecture.

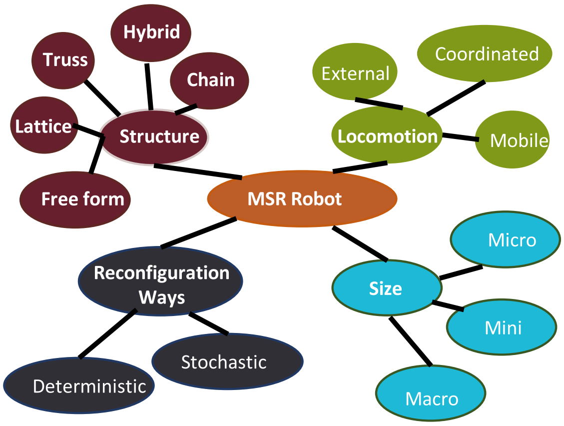

FIGURE 3. Classification of modular self-reconfigurable robots.

The categories/subcategories mentioned above can be reorganized and united in a neural-network-structured framework (which is illustrated in Fig. 3) [19]. However, a self-reconfigurable robot does not necessarily possess a modular design. It could be a self-contained robot which is capable of shifting into different configurations through specific mechanism design and motor actuation. Thus, there are still a large amount of self-reconfigurable robots not represented by the existing taxonomy systems. Moreover, these classifications only considered the structure of the self-reconfigurable robots but did not look into their autonomously reconfigurable capability as well as the evaluation.

C. AUTONOMY IN GENERAL ROBOTICS

The evaluation of robot autonomy has been proposed in automation and human-robot interaction fields where the autonomy was discussed as an engineering and psychological construct. The autonomy refers to a robot's ability to accommodate variations in its environment. According to [25], the autonomy level is often measured by relating the degree to which the environment can be varied to the mean time between failures and other factors indicative of robot performance. By integrating the definitions of autonomy found in literature, a specific definition was given to robots as follows [26]:

The extent to which a robot can sense the environment, plan based on that environment, and act upon that environment, with the intent of reaching some goal (either given to or created by the robot) without external control.

This definition shows that autonomy exists on a continuum scale with no autonomy to full autonomy. Autonomy evaluation and classification have mainly been carried out for unmanned systems. These evaluation methods mainly include but are not limited to the level-based method, axis-based method, table-based method, and formulation-based method. The level-based evaluation method is one of the most commonly used methods where the autonomy of a system is divided into several levels. Sheridan's level of autonomy was a ten-level evaluation method for the autonomy of automation systems [27]. NASA's Vehicle Systems Program High-altitude Long-range Sector (HALE Sector) formulated a streamlined autonomy evaluation (five levels) for their aircraft systems [28]. Beer et al. put forward ten levels of autonomy for Human-Robot Interaction (HRI) as well as five steps of guidelines for determining robot autonomy in HRI [26]. The axis-based methods can be divided further into double-axis and three-axis. The representative double-axis method was the Autonomous Control Level (ACL) method proposed by the US military [29] where one axis represents the autonomy level, and another axis represents the development era of the corresponding autonomy level. The typical three-axis method is the Autonomy Levels For Unmanned Systems (ALFUS) framework was proposed by Huang et al. [30]. The table-based method can provide more details in all respects than other means, for example, the lookup table presented in [31]. Furthermore, the evaluation methods have been extended in different ways such as combining fuzzy logic, adding considering aspects, and increasing the robotic systems scale [32].

Overview of the standards, performance metrics, testing and evaluation methodologies of autonomous systems and levels of autonomy for intelligent unmanned systems [33]. From another angle, these methods could be classified into two general categories, contextual and non-contextual. The most commonly referenced contextual model is the Autonomy Levels For Unmanned Systems (ALFUS) framework [30], based on which the autonomy is measured by mission complexity, environmental complexity, and human independence. In this case, the robot autonomy can be quantified based on the measure of robot performance in achieving a given task related to environment complexity, which requires to test a large number of tasks and environment configurations [34]. Differently, the non-contextual methodology provides a predictive measure of autonomous potential [33], requiring no prior knowledge of the environment and no extensive operational-level testing.

For autonomous robots, a general architecture was proposed twenty years ago, which was composed of three levels: functional level, execution level, and decision/planning level [35]. To remedy imperfection of this architecture, a two-tiered coupled layer architecture was proposed by featuring a tight coupling of the planner and executive in one layer (i.e., decision) [36]. The autonomy of surgical robots was reviewed regarding commercial use and research as well as the challenges faced in developing autonomous surgical robots [37]. Algorithm for forming the desired configuration with multiple modules based on isomorphism-based approach is proposed in [38]. The reliability analysis of the self reconfigurable system hardware architectures and the associated control systems failure modes and effect analysis (FMEA) analysis are presented [39]. Moreover the resilient robot concept is reviewed in [40].

The autonomy levels were first introduced into MSR robots in [24] where a cobweb evaluation model was proposed to evaluate the autonomy level of MSR robots. This model evaluates the hardware characteristics of individual modules that may affect the autonomy of the robot instead of reconfigurability-related characteristics which may or may not be purely hardware characteristics. Perception and intelligence factors are not accounted. Moreover, the model is dedicated to modular robotic systems, which cannot be directly applied to all self-reconfigurable robots. Addressing these gaps will be the focuses of our paper.

III. TAEV: TAXONOMY AND EVALUATION FRAMEWORK FOR RECONFIGURABLE ROBOTS

In this section, a taxonomy and evaluation system is proposed, named as TAEV framework for self-reconfigurable robots and based on the recognition of the mechanism and autonomy levels for reconfigurability of these robots. Autonomy is vital for evaluation, since having high level of mechanism reconfigurability achieved using manual intervention does not ensure higher reconfigurability index as in autonomy sense it cannot change shapes by itself.

In Section II, the term reconfigurability has been defined in a more general context. However *reconfigurability* differs from *modularity*.[1] In some scenarios, the reconfigurability of a robot is approximately equivalent to the adaptivity of the robot, meaning that a robot with highly reconfiguration ability is more likely adaptable to the environment or object that it encounters than the one with lower reconfigurability. Self-reconfigurable robotic systems feature reconfigurability compared to their fixed-morphology counterparts. However, the concept of reconfigurability has not been defined clearly and elaborated explicitly in robotics before. In this work, we define the *mechanism reconfigurability* of a robotic system as:

The extent/degree to which a self-reconfigurable robot or robotic systems can transform and evolve to another meaningful configuration with a certain degree of autonomy or human intervention.

The mechanism reconfigurability is twofold: intra-reconfigurability and inter-reconfigurability. Intra- reconfigurability for robots is referred as a system that is a single entity while having ability to change morphology without the assembly/disassembly. Whereas, inter-reconfigurability defines to what extent a robotic system can change its morphology through assembling or disassembling its robotic components. We realize that the reconfigurability of self-reconfigurable robots is not only determined by the mechanism reconfigurability but also by its autonomy level. Thus, the autonomy regarding reconfigurability must be considered in evaluating a self-reconfigurable robot. The general definition of autonomy given in the last section and is used to depict the autonomous capabilities of robots. Analogously,

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[1] Note that, modular/modularity as referred in Fig. 2, means that the robot is designed to be able to dock with other modules to form different configurations. Therefore, a modular robotic system should be self-reconfigurable or reconfigurable [13], [14]. Whereas a self-reconfigurable or reconfigurable robotic system might not be modular

a definition of *autonomous reconfigurability* is given as follows:

The extent to which a self-reconfigurable robot can sense its environment, plan its configuration based on that environment, and act to transform into specific configurations upon that environment with the intent of achieving some goal (either given by human or created by the robot itself).

Such a definition of autonomy reconfigurability integrates the concept of autonomy along with the features of sense, plan, and act. Autonomy reconfigurability ranges from no autonomy to full autonomy in terms of reconfigurability. The goal mentioned in the definition could be a final objective of a global aim (for example, traversing a forest) or temporary effort to overcome a local task (for example, grasping an object).

We realize that the classification of SR robots and their evaluation do not encompass the non-modular ones, neither the autonomy levels based on the analysis of previous literature discussed in Section II. We thus propose a triad system (as shown in Fig. 4) in which the X- and Y-axis represents the inter- and intra-reconfigurability respectively, and the Z-axis represents the autonomous reconfigurability. Any self-reconfigurable robot/robotic system pertains to one of the blocks, for example, the dark cube marked in Fig. 4.

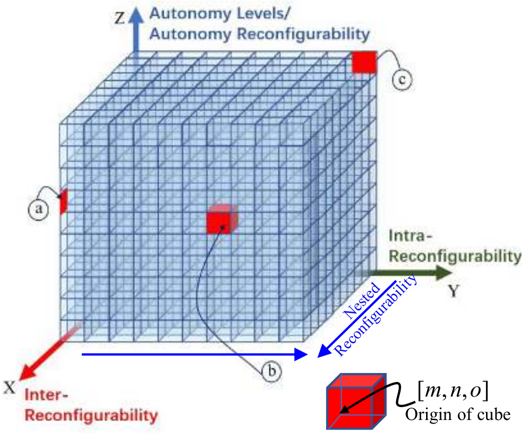


FIGURE 4. **Visual representation of the three axes of the proposed TAEV framework where ten categories are shown along each axis and each cube represents a category that a self-reconfigurable robot belongs to. Note that cube occupying XY-plane will have nested reconfigurability.**

For a given self-reconfigurable robot, the reconfigurability is quantified and indexed as follows:

$$\begin{aligned} V_{SR} &= (I_{INTER}, I_{INTRA}, I_{AUTO}) \\ I_{INTER} &\equiv m \in [0, \infty) \\ I_{INTRA} &\equiv n \in [0, \infty) \\ I_{AUTO} &\equiv o \in [0, 10] \end{aligned} \tag{1}$$

where V_{SR} is the index defined by I_{INTER}, I_{INTRA}, and I_{AUTO} denoting the inter-reconfigurability index, intra-reconfigurability index, and autonomy reconfigurability index, respectively. Note that the morphologies and the assembly/disassembly of the robotic system can go as high as possible and hence the higher limit is kept as infinity in (1). For example in [41], with twelve modules the possible number of inter-reconfiguration reported was 8182213. The elegant method using matrix based enumerating approach for the non isomorphic configurations of a reconfigurable modular robot system is shown in [42]. In this work the number of non-isomorphic configurations corresponding to the number of modules increases with exponential trend, i.e., (modules, non-isomorphic configurations) are as (4,7), (5,21), (6,60), (7,208), (8,704), and so on. Moreover, the algorithm to calculate the number of reconfiguration are given in [43]. The non-isomorphic configurations taken by modular and reconfigurable Rubik's snake robot are shown in [44] using the screw theory the kinematics is also presented.

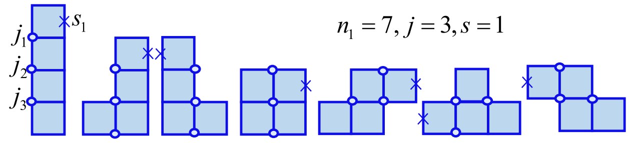
Taxonomy involves classification and naming of systems. In this work the combined features of intra- and inter-reconfigurability in robots is named as nested-reconfigurable robot. The nested reconfiguration, i.e., I_{NESTED} is equivalent to the number of morphologies, which is equal to the possible combination of inter- and intra-reconfigurability indexes of robotic modules within the robotic system. It is given by:

$$I_{NESTED} = \prod_{i=1}^{m} n_i, \quad i = \text{index of the module} \tag{2}$$

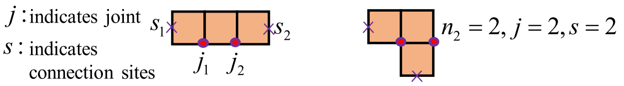
The nested reconfigurability can be easily identified in the plot (Figure 4) such that any cube occupying XY-plane will have nested reconfiguration which is combination of inter- and intra-reconfigurability. Indices $n_1, n_2, \ldots, n_m$ are the numbers of morphologies of the m modules, respectively. Index m represents the inter reconfigurability and o indicates the autonomy level. These are shown as the origin of the cube at (m, n and o). The autonomy level o defined quantitatively in section V-B as a rational number between the scale 0 to 10. The sides of the cube is of unit dimensions. Three situations are presented in Fig. 4: Case ⓐ represents the situation where the robot is only inter-reconfigurable and hence the cube lies in a XZ-plane as square; Case ⓑ highlights the situation when the robot is both inter- and intra- reconfigurable; while ⓒ depicts the situation where the robot is only intra-reconfigurable.

Figure 5a shows seven one-sided [45] intra reconfiguration shapes using Tetromino, which results in $n_1 = 7$ (Eq.1). Figure 5b shows the two one-sided intra reconfiguration shapes using Trimino, which results in $n_2 = 2$. Here the number of separate modules which are getting connected is two which results in $m = 2$. Therefore from Eq.1 product notation altogether there are 14 combination possible which is reflected by the nested reconfiguration states.

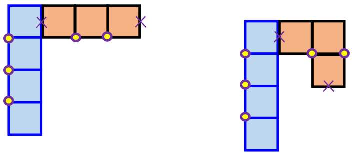
Note that I_{NESTED} index in our definition does not reflect upon the number of possible configurations or shapes that can occur after inter-reconfiguration and the difference due to connecting sites combinations. It only indicates the possible combinations between the different modules. Figure 5c shows the two states out of 14 possible combinations between



a) First module has seven one-sided shapes formed with Tetromino



b) Second module has two one-sided shapes formed with Trimino



c) Inter-reconfiguration using one of the shapes from Tetromino and Trimino

FIGURE 5. **Intra and Inter reconfiguration with Tetromino and Trimino shapes.**

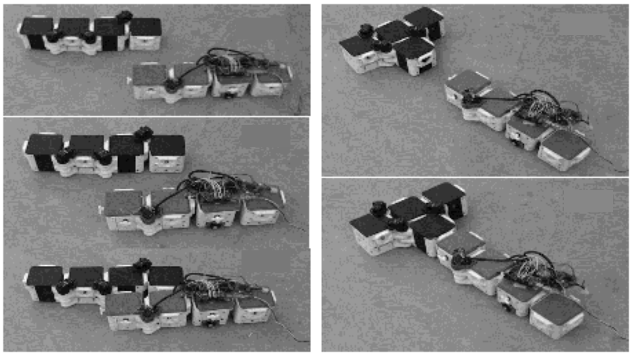


FIGURE 6. **Nested reconfiguration formation using two hTetros, i.e., Tetromino based platform [47]. Here two hTetro are not identical since having different docking arrangements.**

Tetromino and Trimino. Figure 6 shows the practical realization of nested reconfiguration using two hTetro robots [46] in its two formation based on inter and intra reconfiguration. In the following sections, the quantities on the three axes will be elaborated with detailed discussions and examples of real robots.

IV. MECHANISM RECONFIGURABILITY

In this section, we elaborate on the horizontal taxonomy plane, namely the mechanism reconfigurability, highlighting relevant mathematical models.

A. INTRA-RECONFIGURABILITY

The intra-reconfigurable robots are collections of components such as actuators, mechanical parts, power, sensors, controllers, etc. They act as single entities while having the ability to change their internal morphology without any assembly or disassembly externally. The Intra-reconfigurability index represents the number of configuration that the robot can transform into. A fixed morphology robot possesses a zero value of the index. One more morphology achieved through reconfiguration adds one point to the index. Fig. 7 presents a conceptual representation of intra-reconfigurable robots where the abstract object can change to six configurations (including the initial state)

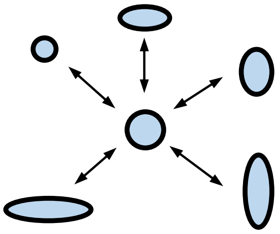


FIGURE 7. **Conceptual representation of the intra-reconfigurability where the object can change back and forth into each configurations (including the initial state) resulting it into finite state machine with six configurations.**

Intra-reconfigurability of SR robots has been generally centered on functional modules, namely locomotion/mobility systems, grippers/hands, and sensing. Most of the intra-reconfigurable mechanisms contribute to enhancing locomotion capabilities of the mobility systems. The reconfigurability enables the multi-modal locomotion where every transformed configuration corresponds to a specific locomotion mode. This kind of intra-reconfiguration usually refers to adaptive morphology [48]. The reconfiguration for locomotion makes a robot flexible for traversing over a variety of terrains and environments (land, air, and water). Examples include versatile amphibious robots capable of intra-reconfiguration between terrestrial and aquatic mechanisms [49] and reconfigurable walking mechanisms that produce a wide range of gait patterns [50]. The intra-reconfigurability can also enhance the manipulation capability through endowing robots the flexibility for a series of manipulation skills. For example, Wu et al. [51] proposed a metamorphic robotic hand whose intra-reconfigurable palm is capable of generating changeable topology to augment the dexterity and versatility of manipulation. Intra-reconfiguration for sensing enables a robot to adapt its sensor configuration to the environment or task at hand. A biomimetic predator-prey vision system is proposed based on a planarly self-reconfigurable robot [52]. The robot equipped with two cameras can mimic and apply the monocular and binocular vision mechanisms of predator and prey by changing its configurations. Recently the self-reconfigurable pavement sweeping robot named Panthera [53], [54] which can change its width based on pavement width and pedestrian density. The modularity and self-reconfigurable robot design are of high need in medical-assistive robots as well [55].

The most usual way to achieve the intra-reconfiguration is creating the relative motion of the linkages of the robot through DC motors play the role of revolute joints or prismatic joints. The joint motion drives the configuration evolution. A reconfigurable robot (RSTAR) can extend its height and width three-fold and move its center of mass both in the fore-aft and vertical directions [56]. Such intra-reconfigurations enable the robot to overcome extremely challenging obstacles, crawl over flexible and slippery surfaces and even climb vertically in a tube or between two walls. The Scorpio robot is an intra-reconfigurable quadruped that can reconfigure its legs from a default state for crawling to a wheel-like state for rolling [57]. An advanced version of Scorpio was proposed in [58] where the climbing mechanism was added through which the robot can climb through glass windows. The wheel-leg robots are platforms that their mobility systems can shift between wheels and legs through intra-reconfiguration [59], [60].

The origami robots are a recently emerging type of self-reconfigurable robots, which can shift from a folded state to an unfolded state just like the paper art, origami [61]–[63]. It is worth highlighting that the evaluation thought inherent in our proposition is that the reconfigurability of a robot is rated by the number of meaningful configurations, instead of by the articulated joints. Thus, the intra-reconfigurability index of a given origami robot may be equal to one, even though the reconfiguration between the folded state to unfolded state involves a large number of hinge or joint motions [64]. In contrast, a robot that can transform into two more configurations earns high rates if there are very few joints actuated during the transformation.

Emerging trends in robotics focuses on soft robotics that aims at utilizing the properties of materials to achieve different morphology (or reconfiguration) [65]–[67]. Growing robots are a category of soft robots that imitates biological growth [68] that achieve morphological evolution (or reconfiguration) through the incremental addition of material. A class of soft pneumatic robot was reported that it was capable of a basic form of this behavior, growing substantially in length from the tip [69]. It is important to note that in the TAEV evaluation system, the differences between the robots depend only on the reconfigurability and autonomy levels but not on the softness and material properties. Therefore, a soft reconfigurable robot may be evaluated as having the same reconfigurability as a rigid reconfigurable robot in the coordination system.

B. INTER-RECONFIGURABILITY

Other than the reconfiguration performing in the individual robot, a variety of specialized robots and complex structures can assemble together to form a new configuration. Fig. 8 presents a conceptual depiction of inter-reconfigurable robotic systems. The inter-reconfigurable robot consists of a congregation of modular robots able to form different morphologies through an ongoing assembly and disassembly process. Numerous inter-reconfigurable robots have been developed for various potential applications ranging from surveillance to space exploration and using different schemes for module docking and undocking, and all types of reconfiguration which includes manual, semi-autonomous, and fully autonomous. These modular robots could be either homogenous (Fig. 8a) or heterogeneous (Fig. 8b) intelligent components/agents.

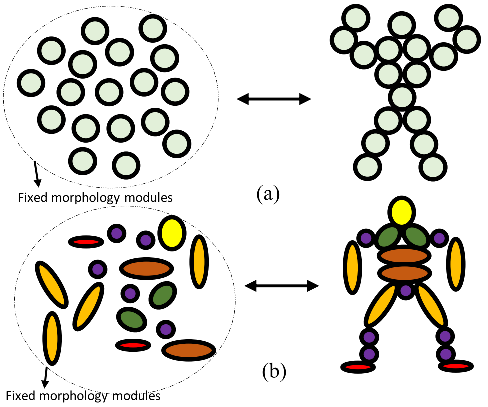


FIGURE 8. **Conceptual representation of the inter-reconfigurability (a) homogeneous robots. (b) heterogeneous robots where different colors indicate different robotic modules.**

Homogeneous modular robots possess a number of modules with the same design which form structures suitable to perform tasks. Due to their modularity, an advantage of such systems is that they are easy to scale up in size (and possibly function), by adding more units. Such robot systems features the capability of assembly and disassembly on macro- and micro- scales [70], wherein the individual robotic module maintains its morphology as constant when assembled in an aggregate structure. A commonly described disadvantage is limitations to functionality. Typically, these systems need more units to realize a given function than heterogeneous systems. There are a huge number of relevant examples such as CEBOT [71], Millibot [72], Crystalline [73], ATRON [74], SuperBot [75], Roombot [76], Soldercubes [77], SMORES [78], Molecubes [79] and many others. The modular matter called SoftCubes proposed in [80] uses identical or homogeneous serially connected modules with connecting parts made of soft stretchable elastomer for self-assembly and disassembly.

Alternatively, the robotic modules could be heterogeneous in the sense that hardware designs and adopted components are different between the modules. Each module performs specific functions, forming a topology that is suitable to perform the specific task. An advantage is versatility to design, compactness, and ability to add modules. A disadvantage is the increase of complexity in design, manufacturing, and simulation. For example, an architecture used modular robotic components for universal construction [81], which includes both active and passive components. A multi-robot team RIMRES (Reconfigurable Integrated Multi-robot Exploration System) was presented in [82]. The system is heterogeneous and consisted of a legged scout, a wheeled rover, and a number of immobile elements. All subsystems are equipped with common electromechanical interfaces, allowing to be integrated into an overall system for exploration missions in crater environments. The heterogeneity of self-reconfigurable multi-robot organisms consisting of four

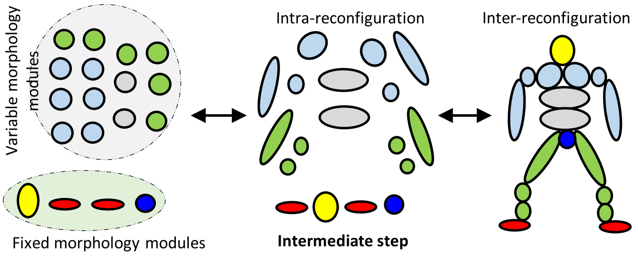


FIGURE 9. Conceptual representation of the nested-reconfigurability. The robotic system demonstrates both inter-reconfigurability and intra-reconfigurability.

heterogeneous platforms was discussed in terms of performance increasing and reliability [83]. The conclusion was drawn that physical constraints imposed on the system are the main factor for introducing and increasing the level of heterogeneity. The heterogeneous MSR robots were designed via a system called EDHMoR (Evolutionary Designer of Heterogeneous Modular Robots) [84] based on generative evolutionary algorithms, which made finding solutions easier. The reconfiguration planning of the heterogeneous SR robots, i.e., with non identical modules was presented in [85]. The reconfigurable design of SCARA robot by by adjusting the number of modules in the arm in order to meet more industrial needs is reported in [86]. The design of modular reconfigurable industrial robots were dealt with in [87], [88]. The robot consisting of separate revolute joints and link modules with different geometries were assembled manually. The different assembly configurations are analysed on the basis of the constraints, such as, workspace, payload, etc. The upper bound on the inter-reconfigurable formation for a given shape is discussed in [41], [89]. In [88], industrial-robot-specific key performance indicators (KPIs), like accuracy, speed and cost, were used to evaluate the reconfigurable robots.

In this paper, inter-reconfigurability is evaluated by considering the scale of the robotic system. The index quantifies the inter-reconfigurability by only calculating the number of the robotic modules involved in the whole robotic system. Therefore, given a homogeneous MSR robot and heterogeneous MSR robot, if their numbers of modules are the same, the values of the inter-reconfigurability index are the same.

C. NESTED RECONFIGURABILITY

The difference between intra-reconfigurability and inter-reconfigurability is that the former one involves single robotic modules and the latter one involves assembly or disassembly of more than two modules. Combining the advantages of the two kinds of reconfigurability results the nested reconfigurability as shown with its conceptual depiction in Fig. 9. The definition of nested reconfiguration is as below:

Nested reconfigurable robotic system is a set of modular robots with individual reconfiguration characteristics (intra-reconfigurability) that combine with other homogeneous or heterogeneous robot modules (inter-reconfigurability).

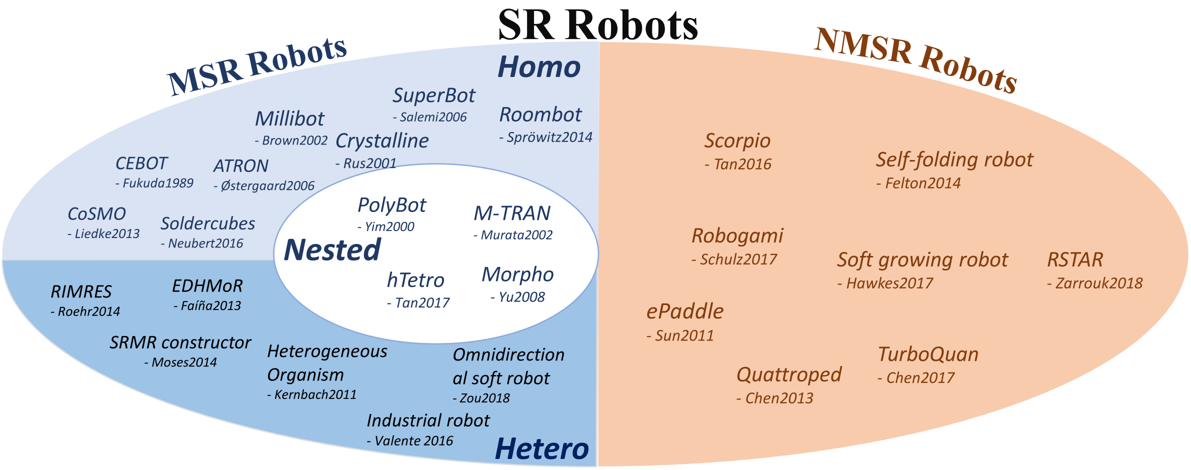
The concept of nested reconfiguration explicitly considers the ability of the modular components at the atomic level to internally transform their morphology. This can be seen in fact as a generalization of the self-deformation principle used in tensegrity-based cellular robots [90]. Here we can define a nested reconfigurable robotic system as a set of modular robots which have individual reconfigurable capability (intra-reconfigurability) and can combine with other homogeneous or heterogeneous robot modules (inter-reconfigurability). As shown in Fig. 8b, the heterogeneous inter-reconfiguration may achieve the same configuration as that of the nested-reconfiguration, even though the reconfigurability of individual robotic modules is different. On one hand, such systems are capable of generating more complex morphologies for performing specific tasks that are far from the capabilities of a single unit or to respond to programmable assembly requirements [47]. However, on the other hand, the two-level reconfiguration process in a nested reconfigurable robotic system implies several technical challenges in hardware design, planning algorithms, and control strategies. Fig. 10 is the Venn diagram that shows a number of representative MSR robotic systems and NMSR robots reported in literature. We can see that the conventional taxonomies only cover the left-hand side of the diagram. Whereas our taxonomy can also cover the right-hand side including some state-of-the-art robotic systems, such as the soft growing robot, self-folding robot, and robogami.

V. AUTONOMY OF RECONFIGURABLE ROBOTS

As reviewed previously, autonomy is a concept associated with automation and HRI traditionally and mostly. In our framework, while referring to the reconfigurability, we propose to integrate this notion into the taxonomy and evaluation system since the reconfigurability can be interpreted as the autonomous capability of reconfiguration. Assume that there is a reconfigurable robot which can shift to a number of configurations only with the manual control by humans. In this case, we consider that it has a high level of mechanism reconfigurability but will not consider it is with high reconfigurability (or self-reconfigurability specifically) in terms of autonomy sense because it cannot change shapes by itself. As pointed out in [24], the wordings of self-X, such as self-assembly, self-organization, and self-reproducing, embody certain degrees of the autonomy reconfigurability. There has been a huge amount of self-reconfigurable robots proposed and developed in robotics community. However, so far there are very few of them can be deployed in real applications. One of the main reasons is because of lacking autonomous capabilities in unstructured environments. Based on the precedent evaluation methods, here we propose to evaluate the autonomy reconfigurability level-based method and cobweb evaluation model which are qualitative and quantitative respectively.

A. EVALUATION METHOD-I OF AUTONOMY RECONFIGURABILITY

The autonomy level is evaluated by examining the involvement degree of reconfigurability in terms of autonomy in



MSR: Modular Self-reconfigurable robots

NMSR: Non-modular Self-reconfigurable robots

FIGURE 10. Venn diagram of selected MSR robotic systems and NMSR robots reported in literature.

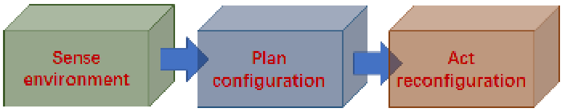


FIGURE 11. Three general steps involved in the autonomy reconfigurability.

three general steps (or called primitives, i.e., sensing, planning, and acting) when the reconfiguration is involving. As shown in Fig. 11, each domain were dealt specifically for self-reconfigurable robots in the literatures. The *sensing* aspects for self reconfigurable robots are dealt in [52], [91]–[94] with fault detection discussed in [95]. The comprehensive work dealing with the *planning* in self reconfigurable robots is reported in [96].

The autonomy reconfigurability is quantified by ten levels which are corresponding to ten categories of autonomy levels of reconfiguration. As indicated in Eq. (1), autonomy level takes a real values from zero to nine. the larger the number is, the higher will be the autonomy.

(i) *Manually teleoperated reconfiguration:* As the lowest level of autonomy reconfigurability, the human performs full aspects of the task including sensing the environment, monitoring the system, generating plans/options/goals, and implementation. Every step is decided by humans. In this case, the robot is just a tool provided to humans. The reconfigurable mechanism is provided to humans to select the configuration to be transformed to remotely. Since the robot has absolutely no autonomously reconfigurable capability, the index is equal to zero. It is worth noting that the robot with zero autonomy reconfigurability could be possibly a system with high degree of mechanism reconfigurability. Just like a Swiss army knife, it could be with many possible configurations but fully rely on manual operation. Another example is of the drain inspection quadruped wheeled robot reported in [97] that is manually reconfigured to its upside down position.

(ii) *Pre-defined configuration pattern:* The SR robot assists the human with implementing reconfigurations. However, sensing and planning is allocated to the human. For example, a human may tele-operate a robot, but the human may choose to prompt the robot to configure into a specifically pre-defined pattern to assist with some aspects of a task.

(iii) *Teleoperation assisted by reconfiguration:* Both the human and robot sense the environment. The SR robot assists the human with determining the reconfiguration options and suggests one, which human may or may not follow. The robot then executes the reconfiguration that the human chooses.

(iv) *Task intervention by reconfiguration:* All tasks are lead by human. Whereas, the robot senses the environment and judges to intervene with task in the way of reconfigurations. For instance, once the human operator commands the robot to navigate an obstacle too closely, the robot could reconfigure into a feasible pose automatically to avoid collision.

(v) *Reconfiguration decision support:* Both robot and human sense the environment and figure out a configuration plan. Whereas, the human selects the task and commands the robot to implement the reconfigurations. It is worth noting that the task intervention by reconfiguration is a local action, whereas the reconfiguration decision support is the global plan in a higher level.

(vi) *Shared control of reconfiguration with human initiative:* The SR robot senses the surrounding environment, develops configuration plans, and implements reconfigurations autonomously. Whereas, the human monitors the robot's progress and may intervene and influence the robot with new configuration plans in case that the robot is facing difficulties.

TABLE 1. **Autonomy level evaluation scale.**

Autonomy Reconfigurability	Level	Functions			Description
		Sense	Plan	Act	
Manual teleoperated reconfiguration	0	M	M	M	The task including sensing the environment and monitoring the system, generating plans/options/goals, and implementation are performed manually.
Pre-defined reconfiguration pattern	1	M/R	M/R	M/R	The human is assisted by the robot to determine the reconfiguration options. However, human carries sensing and planning. The robot then implements the reconfiguration that the human chooses.
Teleoperation assisted by reconfiguration	2	M/R	M/R	M/R	Human intervention is there in selecting the reconfiguration option suggested by the robot during operating it remotely.
Task intervention by reconfiguration	3	M/R	M/R	R	The robot senses the surrounding and decides to involve in the task in the way of reconfigurations.
Reconfiguration decision Support	4	M/R	R	R	Both the robot and human sense the environment and plan for reconfiguration. Whereas, the task is selected manually and command to implement it is given to robot.
Shared control of reconfiguration with human initiative	5	M/R	R	R	The robot does all aspects of the task. Whereas, the human may intervene and influence the robot's progress in reconfiguration.
Shared control of reconfiguration with robot initiative	6	M/R	M/R	R	The robot performs all part of assignment. In case the robot encounters difficulties, the manual intervention prompts for setting new configurations.
Supervisory control of reconfiguration	7	M/R	R	M/R	The robot performs all parts of the assignment, but manual override option is available in setting new configurations.
Executive control of reconfiguration	8	R	M/R	R	The human may give a set goal. The robot sense, plan and implement reconfiguration autonomously.
Fully autonomous reconfigurability	9	R	R	R	All aspects of the task are performed by the robot without any human intervention.
Collaborative reconfigurability	10	R	R	R	The robot not only can perform tasks on its own but also can collaborate and help human using reconfiguration.

M: Manual or human R:Robot, Sense: Sense environemnt, Plan: plan configuration, Act: Act or execute reconfiguration

(vii) *Shared control of reconfiguration with robot initiative:* The robot performs all aspects of the task (i.e., sense, plan, and act). Once the robot meets difficulties, it can prompt the human for assistance in setting new goals and reconfiguration plans.

(viii) *Supervisory control of reconfiguration:* The robot performs all aspects of the task (i.e., sense, plan, act). However, the human continuously monitors the robot and has over-ride capability to set a new configuration. Thus, the autonomy mode shifts to the shared control of decision support.

(ix) *Executive control of reconfiguration:* The human may give an abstract high level goal and the robot senses environment, sets configuration plan, and implements reconfiguration autonomously.

(x) *Fully autonomy reconfigurability:* At this level, the SR robot can fully adapt to the environment and cope with all aspects of the task while performing reconfigurations without any human intervention.

(xi) *Collaborative reconfigurability:* Conventionally, the full autonomy is highest level of autonomy. However, with its increasing pervasion, the robot should not only be able to perform tasks on its own, but also can collaborate and help human using reconfiguration naturally.

Given the levels of autonomy reconfigurability, which tier should a SR robot fall into is still unknown. A few guidelines are provided for determining what category a given self-reconfigurable robot belongs to.

Step 1 (Task/Object Identification): Firstly, we should identify what task or object is the robot encountering? The change of the environment, such as the terrain that the robot navigates, may require the robot to reconfigure its mobility system. Moreover, the autonomy reconfigurability of a robot is task-dependent. It may be able to reconfigure autonomously while doing a task. Whereas it may not be able to complete another different task with fully autonomous reconfiguration and needs human's assistance in determine and/or implement the reconfiguration strategy.

Step 2 (Necessary Configurations Identification): Secondly, we should identify what configurations and how many configurations needed for the robot in order to fulfill the task. The aspects of the task that the robot should perform requiring reconfiguration need to be identified.

Step 3 (Autonomous Reconfiguration Identification): Finally, we should identify what configurations the robot can shift to and how autonomous is the reconfiguration. Given the necessary configurations identified in Step 2, the robot's reconfigurability is compared. To what extent can the robot perform those reconfigurations that the task needs or the navigation around an object needs?

B. EVALUATION METHOD-II OF AUTONOMY RECONFIGURABILITY

Apart from the above level-based approach, we could have a more quantitative method for evaluating the autonomy reconfigurability based on the cobweb evaluation model which

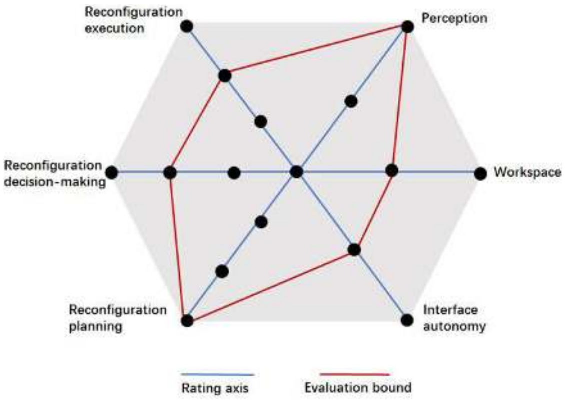


FIGURE 12. The cobweb evaluation model for evaluating the autonomy reconfigurability of self-reconfigurable robots, consisting of six performance indicators.

is shown in Fig. 12 As mentioned before, autonomy methods can be divided into contextual and non-contextual. The non-contextual methodology is desirable because this measure needs not to perform extensive operational-level testing beforehand. In addition, this autonomy-evaluating method enables the comparison across platforms without considering varying environmental factors. The hardware performance characteristics of the robotic module were chosen as the evaluation indicators in previously proposed evaluation method [24] where the hardware performance characteristics chosen are the module DOF, module attribute, interface autonomy, workspace type, and locomotion mode. Differently, our model adopts not only the hardware performance characteristics but also the capability in perception, planning and control for evaluating the autonomy of self-reconfigurable robots. The proposed cobweb evaluation model consists of six performance indicators, which are perception, workspace, interface autonomy, reconfiguration planning, reconfiguration decision-making, and reconfiguration execution, locating in a clockwise circle direction with equal intervals in the hexagon cobweb area.

Enlightened by the autonomy architecture proposed in [35], our model uses the execution and decision-making as two indicators for autonomy reconfigurability. In that paper, the functional level encapsulates the perception and action capabilities. Whereas in our model, the three indicators, i.e., perception, interface autonomy, and reconfiguration execution, are assigned to replace these two sets of functionalities. The reconfiguration execution includes all the functions that are required to perform the selected reconfiguration. The interface autonomy evaluates the autonomy degree of the attaching/assembly and detaching/disassembly capabilities of the inter-reconfigurable robots (i.e., modular robots). The workspace indicator evaluates the space reachability of the reconfiguration. The perception evaluates the sensing capability of the self-reconfigurable robot. This is not a direct factor related to reconfigurability but showing the potential of autonomous reconfiguration, in the sense that a robot which can is more likely to be able to perform reconfiguration autonomously than another with poorer perception capability. The grade description of the axes is as follows:

- ∗ The perception is classified into two grades $(0-2)$, where 0 denotes there is no sensor; 1 denotes medium sensing capability; 2 denotes full sensing capability.
- ∗ The workspace is classified into two grades $(0-2)$ where 0 denotes a point, 1 denotes that the reconfiguration can only happen in the 2D plane.
- ∗ The level of interface autonomy is represented by two grades $(0-2)$ where 0 denotes manual attaching or detaching; 1 denotes manual attaching and autonomous detaching; 2 denotes autonomous attaching and detaching. This indicator is a local evaluation factor for reconfigurability right happening on the interface.
- ∗ The reconfiguration planning is denoted in three grades $(0-3)$. This indicator evaluates the autonomy in planning aspect of reconfiguration. 0 denotes there is no planning capability in the robot; 1 denotes the robot provides support for planning strategy of reconfiguration; 2 denotes the robot leads to devise the planning strategy but the human monitor the process; 3 denotes the robot devises the planning strategy without any human intervention.
- ∗ The reconfiguration decision-making is denoted in three grades $(0-3)$ where 0 denotes that the decision made solely by humans; 1 denotes the robot provides advisory decision; 2 denotes the robot leads the decision-making but the human monitor the process; 3 denotes the robot makes the decision without any human intervention.
- ∗ The reconfiguration execution is denoted in three grades $(0-3)$. 0 denotes the execution made solely by humans; 1 denotes the robot provides supporting action for the execution; 2 denotes the robot leads the execution but the human monitor the process; 3 denotes the robot conducts the execution without any human intervention. After determining indicator values along all the axes, the autonomy reconfigurability I_{AUTO} can be calculated following the equation below:

$$I_{AUTO} = \frac{A_{ocp}}{A_{total}} \times 10 \tag{3}$$

where A_{ocp} is the occupied area by linking the indicator values of the specific self-reconfigurable robot, namely the area inside the red evaluation bound; A_{total} is the total area of the hexagon. The area occupied by the polygon inside was calculated using Equation 4.

$$A_{ocp} = \frac{sin(60^\circ)}{2}\left(\frac{G_P}{2}\times\frac{G_W}{2}+\frac{G_W}{2}\times\frac{G_{IA}}{2}+\frac{G_{IA}}{2}\times\frac{G_{RP}}{3}\right.$$
$$\left.+\frac{G_{RP}}{3}\times\frac{G_{RD}}{3}+\frac{G_{RD}}{3}\times\frac{G_{RE}}{3}+\frac{G_{RE}}{3}\times\frac{G_P}{2}\right) \tag{4}$$

where G_P is the grade assigned for a particular robot for its perception level, i.e., between (0-2). Similarly G_W, G_{IA}, G_{RP}, G_{RD} and G_{RE} are the grades for workspace, interface autonomy, reconfiguration planning, reconfiguration decision making and reconfiguration execution. For example, the evaluation bound shown in Fig. 12 has the autonomy level

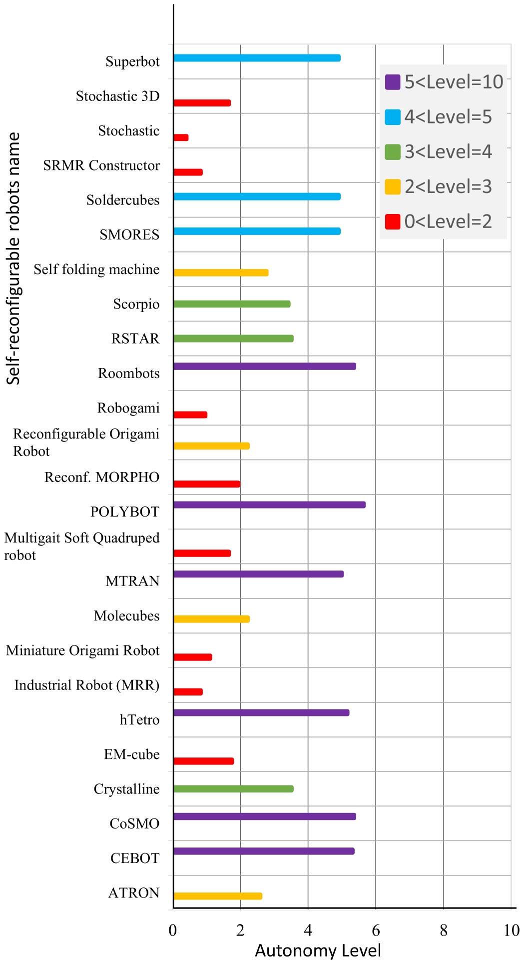


FIGURE 13. Autonomy levels evaluated of self-reconfigurable robots (References of the robots listed above are mentioned in Section VI-A).

calculated as per Equation (4) is 5.046. The evaluation of the autonomy level corresponding to the self reconfigurable robots name are illustrated in Fig. 13.[2] Note that in Fig. 13, the self-reconfigurable robots references are as ''Self folding machine'' [99], ''Reconfigurable origami robot'' [61], ''Soft-Cube'' [80], ''Miniature origami robot'' [100]. Note that the ''SoftCube'' [80], has very high inter-reconfigurability as more than 500 modules were shown to be serially connected which resulted in high achievable morphologies. It can be observed from the figure that the origami robots and soft quadruped robots reported in the literature have lowest index for autonomy as they are at present not equipped with the sensors and the planning, decision making and execution are done with manual intervention. For inter reconfigurable robots that change their shapes in 3D are also having lower level of autonomy as manual intervention is required and they are mostly lattice and mini sized robots. The reconfigurable robots manipulating in 2D workspace with their modules designed to carry specific task like cleaning, navigating through different terrains or cross sections are having higher levels of autonomy. The self reconfigurable robots shown in Fig. 13 equipped with modern mechatronics are not above the autonomy index value of six. We can think of examples taken from the Sci-Fi movies robots like in *Transformers* and *The Terminator* that can have highest level of reconfigurability as well as autonomy.

In the scope of our paper, the limitation of autonomous robots is associated with the autonomy of reconfigurability because it determines the adaptivity (to the environment) of the robot to some degree. In this point of view, increasing the level of autonomy reconfigurability will extend the limit of autonomous robots. The limitation with most of the autonomous robot is their adaption to the novel skills required with the change in the environment while ensuring the safety of human, robot, and environment. The robots are subject to mechanism adaptability which limits the workspace, manipulation, sensorimotor limitations etc. needed in an environment. To overcome it the fusion of sensory information with artificial intelligence (AI) techniques seems promising. However, at the same time not everything can be learned, because some problems are too complex for certain stage. For example humans do not learn writing sentences before learning words or integration before summation.

VI. USE CASES OF TAEV

In this section the TAEV of some reconfigurable robots reported in literature are presented. The insufficiency of self-reconfigurable robot is also discussed with respect to the taxonomy proposed.

A. ILLUSTRATIONS

Fig. 14 shows the visual representation of the three axes of the proposed TAEV taxonomy using the self reconfigurable robots examples. Note that the intra-reconfigurability of the modular robot, i.e., MTRAN-III, PolyBot-G3, Morpho, etc., are taken as the configuration that is taken by a single module which strictly depends upon the Degrees of Freedom (DOF) of single module instead of the available connecting faces with each module. However, a modular robot positioned at a single grid unit with less than two coupled DOF can not undergo self-reconfiguration on-grid. At least two coupled DOF spanning over two grid units are required, for example as in MTRAN [101]. RoomBot has three continuously rotatory degrees of freedom present in a single unit [76].

It is important to mention that for calculating the inter-, intra- reconfigurability in this work, the configurations shown with the physical robot reported in the literature is taken into account, instead of the simulation depictions. Although the robot may have the potential to connect with m-modules to get inter-reconfigurability as m. In that situation the coordinate of the cubes will shift to higher abscissa or ordinate value. The XZ-plane contains the inter-reconfigurable robots, mainly Crystalline [73], Superbot [75], Roombots [76], SMORES [78] and CEBOT [71]. The XZ-plane contains the robot with intra-reconfigurability are mainly Soft Quadruped [102], Origami robot [61] and the in-house developed robot

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[2] The worksheet for calculation of the autonomy indices in this paper can be found in the reference [98]

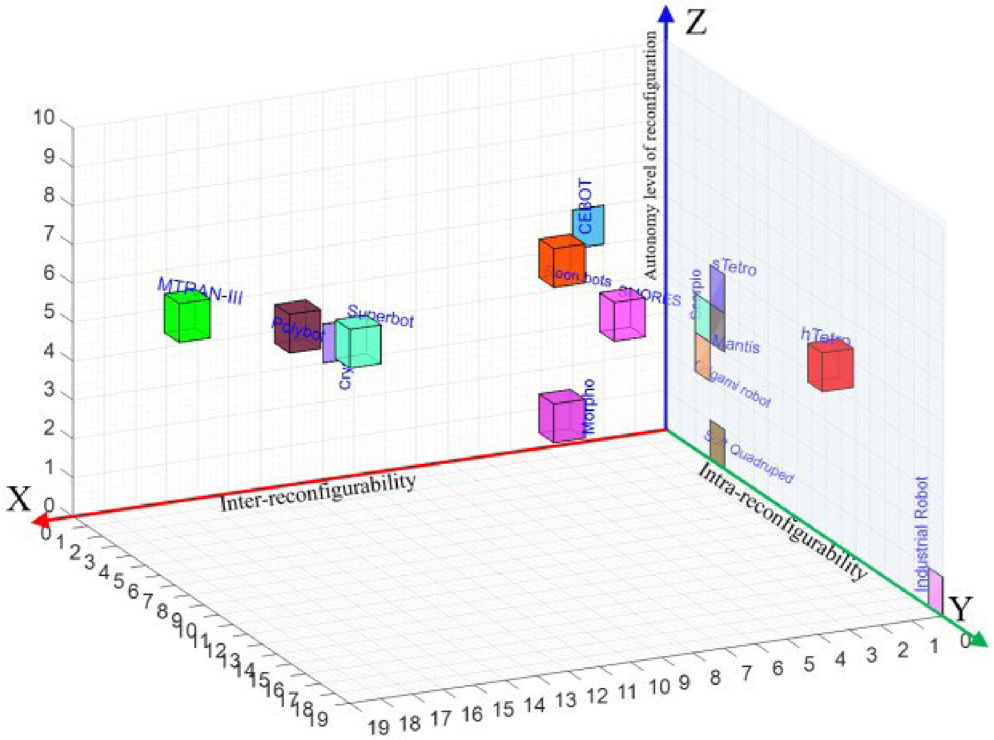


FIGURE 14. Visual representation of the three axes of the proposed TAEV of selected self-reconfigurable robots (note that the (*m*, *n*, *o*) as in Fig. 4 indices are evaluated as per the working configurations reported in published work for the respective SR robots). For autonomy level calculation of the above robots with their images, please refer [98].

Scorpio [57], Mantis [103] and sTetro [104]. The robots having both inter- and intra- reconfigurability are Morpho [90], hTetro [47], Polybot [93], MTRAN [105] and occupies the 3D spatial location in the TAEV plot. In SMORES [78] only two modules were shown to dock with each other which was considered in Fig. 14, but now it includes high-level planning, perception algorithms and modular hardware as reported in [106]. Modular industrial robot as reported in with six-DOF [87], [88] can have 18 feasible configuration [87] which is manually assembled while the sensors in the joint can detect the joint angles and torque. Hence, the taxonomy reported here will be useful to identify scope for further development and also as the performance indicator. There is still plenty of scope to design and develop the robots with the nested features with different levels of autonomy.

B. INSUFFICIENCIES IN SELF-RECONFIGURABLE ROBOTS

The reconfigurability of an SR robot would be restricted due to hardware limitation, especially in some conditions that require high adaptability and flexibility. The modular self reconfigurable robots are scalable. Thus the total functionality for a specific task will be of graceful degradation after the modules get cut or damaged or progressive enhancement where more advanced functionalities are gained with addition or attachment of modules. In any case, it is relatively easy to define the insufficiency and adequacy of the SR robot in context of task-dependent in a particular environment where specific reconfigurabilities need to be met. Some of the task-depended metrics are time for task completion, total energy consumed, percent of targets tracked, percentage of area covered, workspace, etc.

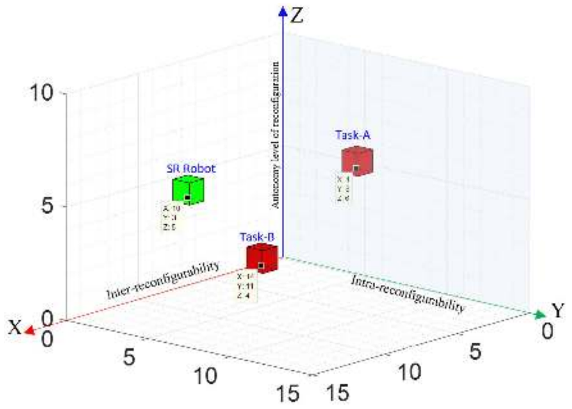
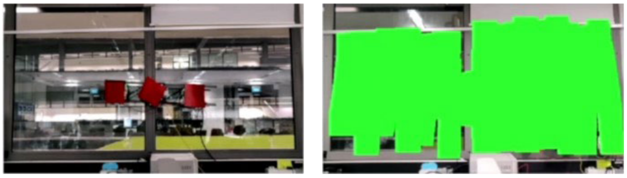


FIGURE 15. Demonstrated example of insufficiency using the proposed evaluation system.

Fig. 15 demonstrates two examples of insufficiency of SR robots using the proposed taxonomy/evaluation system. From the coordinate data, we can see that the inter-reconfigurability of the SR robot is sufficient for Task-A but insufficient for Task-B. Whereas the intra-reconfigurability of the robot is sufficient for both tasks. For the autonomy reconfigurability, Task-B could be satisfied because its index of autonomy level is lower than that of the robot, whereas Task A could not be satisfied since its required autonomy reconfigurability is higher than that of the robot.

a) Testbed to evaluate area coverage with fixed shape robot for windows cleaning

b) Area covered with fixed shape robot



c) Testbed to evaluate area coverage with reconfigurable window cleaning robot named Mantis

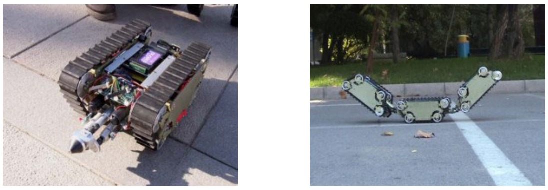
d) Area covered with Mantis

FIGURE 16. **Insufficiency of fixed morphology robot in cleaning windows task w.r.t., the reconfigurable robot Mantis [103].**

The practical example of the insufficiency is shown using the area coverage for windows cleaning task in Fig. 16 between a fixed morphology robot and the reconfigurable robot named Mantis [103]. Mantis has an innovative design with a capability of crossing over the vertical windows panel autonomously which results in nearly complete area coverage of the two windows panel in comparison to the half for fixed morphology robot. Here, the task of cleaning windows with the crossover of glass panels requires the TAEV index vector as [0,2,3] which is corresponding to $[m, n, o]$. Whereas, for the fixed shape robot, the TAEV index vector for glass façade cleaning is [0,0,0.8]; and for the intra-reconfigurable robot Mantis, the index vector is [0,3,3.47] which resulted in the successful completion of the given task of cleaning and crossing two panels on the glass façade.

Furthermore, Figure 17a shows the inter-reconfigurable robot JL-I designed for rough terrain. It has active spherical joints for docking with another module. The inter-reconfiguration which resulted in train configuration has enhanced the capabilities of pitch, yaw and roll movement of the module. Hence, for the single module robot JL-I, its TAEV index vector is [0,0,0.8], while the three-modules one with inter-reconfigurability is of [2,0,4.2]. Similarly, the proposed taxonomy was used for the hTetro which is a reconfigurable floor cleaning robot and is capable of efficient area coverage in 2-dimensions as discussed in [107], [108] is shown in Figure 17b. The energy based performance indicator for the hTetor was evaluated in [109]. The limitation of hTetro is that it can not access the stairs, which requires the reconfigurability in three-dimension. Motivated by this factor, sTetro (Figure 17c) [104] was in-house designed to navigate through stairs to overcome this limitation.

The proposed taxonomy model is used to evaluate the insufficiencies by scaling it up, i.e., by adding another dimension and grading it in the context of specific tasks, i.e., ‘‘task based performance index’’ or Key Performance Indicators (KPIs) like,



a) JL-I an inter-reconfigurable robot with enhanced motion and functionalities

b) hTetro an intra-reconfigurable robot in 2D-plane for cleaning task

c) sTetro an intra-reconfigurable robot in 3D stairs for cleaning task

FIGURE 17. **Examples for self-reconfigurable robots where JL-I [110] is inter-reconfigurable robot whereas hTetro [107], [108] and sTetro [104] are intra-reconfigurable robot used for cleaning floor and stairs.**

- Area coverage, Energy consumption,
- Computation costs,
- Graspability, i.e., the ability to grasp an object,
- Accuracy and repeatability, Reconnaissance ability,
- Task completion time durations,
- Speed and efficiency of transportation, cost, etc.

Hence, insufficiency is benchmarked with the specific task based performance indices or application in a given environment. It is also useful for the design trade-off studies. We have taken an example of floor cleaning environment by the robots and its performance index is area coverage, i.e, the percentage of floor area covered [111]. The average coverage area for hTetro which has intra-reconfigurability index of seven in a set of experiments was 94.56%, whereas the average coverage area of the fixed morphology robot with circular shape was only 80.52%. Similarly the area coverage for the Mantis is double than the fixed shaped robot that can only cover one glass panel only.

Design for Excellance (DFX) is also vital aspect for the design of self-reconfigurable robots where ‘X’ is a variable which can indicate several features like, manufacturability, power, variability, cost, yield, safety, etc. The DFX is another branch of study where the reconfigurable robots can be studied. Moreover some of the general safety features which may be adopted for long term working of these robots in a specific application are: a) SR robot should be encased properly so no objects can enter the module and cause damage or failure, b) Modules should be able to distinguish obstacles and mating or adjoining modules after reconfiguration to avoid self collision, c) Fail-safe connecting mechanisms, d)Fault tolerance and safety verification of control systems should be provided, etc. Note that the safety standards for the reconfigurable robots used for a specific applications needs extended committee to analyse and develop these standards.

VII. CONCLUSION

This article proposes taxonomy and evaluation framework for SR robots. Existing taxonomies and classifications are generally centered on MSR robots. Even though modularity is an efficient way of achieving reconfigurability and are extensively used to design of SR robots, it is not an indispensable and a necessary condition for realizing reconfiguration. To capture the broader spectrum of SR robots and robotic systems, the proposed framework encapsulates both modular and non-modular SR robots. We also discussed the deficiencies in the existing taxonomies regarding classification redundancy.

In summary, the proposed framework is for the taxonomy and evaluation of self reconfigurable robotic systems with three indices based on the definition of reconfigurability. The intra-reconfigurability and inter-reconfigurability which are two of the axes depict the reconfigurable capabilities at the mechanism level. The third axis represents the autonomy level for reconfiguration, which is coined as autonomy reconfigurability. The worksheet [98] is provided for evaluating the autonomy reconfigurability based on the six quantities proposed.

The highlights for the proposed taxonomy and evaluation (TAEV) method are as following:

1) A given self-reconfigurable robot or robotic systems can be allocated a unique index in the taxonomy space.
2) The SR robots can be assigned in the taxonomy space including both modular and non-modular systems (which are not covered by the previous taxonomies, for instance, the robotic origami).
3) The framework incorporates the autonomy reconfigurability where the autonomy levels are used to differentiate and evaluate SR robots.
4) Quantitative representation of inter- and intra reconfigurability along with its autonomy can be visualized using the proposed method. This is helpful in deciding the future development of SR robot and also useful for the design trade-off studies.
5) For including task based performance indicator several examples are discussed with practical applications of self-reconfigurable robots as maintenance robot.

The significance or veridicality of the design using quantitative means is beneficial. We believe reconfigurability is the essential and core factor in evaluating SR robots and robotic systems. The proposed taxonomy and evaluation framework could help robotics researchers to design, evaluate, and benchmark their SR robots. Since the tasks to be done by different robots are multifarious, we do not include specific applications into TAEV and only look at the robotic system itself since it is relatively self-contained. This framework will be instrumental in generating support tools, assessment approaches and discovery techniques to identify opportunities for future innovation.

TABLE 2. **Statistical index for calculating the Autonomy Index (AI) associated with the robots.**

Robots	**RP**	**DM**	**RE**	**P**	**RW**	**IA**	Area	AI
hTetro [108]	3	2	3	1	1	2	1.55	6
CEBOT [72]	3	2	2	1	1	2	1.38	5.3
POLYBOT [113]	2	2	2	1	2	2	1.46	5.6
MTRAN [106]	2	2	1	1	2	2	1.29	5
ATRON [75]	1	1	1	1	2	1	0.67	2.6
Roombots [77]	1	2	3	1	2	2	1.39	5.4
Soldercubes [78]	2	2	3	1	2	1	1.27	4.9
Crystalline [74]	2	1	2	1	2	1	0.91	3.5
Superbot [76]	2	2	3	1	2	1	1.27	4.9
SMORES [79]	2	2	3	1	2	1	1.27	4.9
RSTAR [57]	1	1	3	1	2	1	0.91	3.5
Scorpio [58]	1	2	3	1	1	1	0.89	3.4
Robogami [63]	0	0	2	1	1	0	0.25	0.9
SFM [100]	1	2	2	1	1	1	0.72	2.8
EM-cube [114]	1	1	1	1	1	1	0.45	1.8
CoSMO [115]	1	2	3	1	2	2	1.39	5.4
M.I. Robot [89]	0	0	0	1	2	0	0.21	0.8
Michie [116]	1	2	2	1	2	0	0.64	2.5
CkBot [117]	2	2	2	1	2	0	0.74	2.8
HyMod [118]	2	1	2	1	2	2	1.27	4.9
Modred [119]	2	2	2	1	2	1	1.11	4.2
SYMBRION [120]	2	2	3	2	1	1	1.38	5.3
Rebis [121]	1	1	2	0	2	0	0.14	0.5
Omni-Pi-tent [122]	1	1	0	1	2	1	0.55	2.1
Panthera [54]	3	2	2	1	0	0	0.73	2.4

RP: Reconfiguration planning, **DM**: Reconfiguration Decision making
P: perception, **RW**: Reconfiguration workspace
IA: Interface autonomy, Area: calculated as per Eq.4
AI: Autonomy index calculated as per Eq.3
M.I. robot: Modular industrial robot, SFM: Self folding machines

APPENDIX A: AUTONOMY INDEX TABLE

Table 2 lists robots presented in the literature and corresponding to them the indices for the factors, namely, reconfiguration planning (RP), Reconfiguration decision making (DM), Reconfiguration perception (P), Reconfiguration workspace (RW), and interface autonomy (IA) are listed. Then the area calculated using Eq. 4 and the autonomy index (AI) calculated using Eq. (3) are listed. Note that indices are correpsonding to the literature referred and each of the self-reconfigurable robot listed in Table 2 has capability to improve and hence can climb up in the ladder of autonomy and reconfiguration. The method proposed in this paper also provides the quantitative to compare several versions of the development and also hints on the area to focus on for improving the indices.

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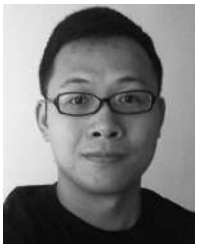

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