An Autonomy Viability Assessment Matrix for Agent-based Autonomous Systems

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***Abstract*—In autonomous systems research, it is unlikely to find two or more autonomy models that have significant match, especially when they represent different domains. Consequently, different concepts and approaches are utilized to construct the autonomy models. These two issues among others pose the difficulty of creating a general matrix or methodology to assess a broad class of autonomy models. In this paper, we propose a novel method to assess and evaluate the viability of agent-based autonomous systems' models. We use an Autonomy Viability Assessment Matrix (AVAM) that consists of three attributes and eleven criteria in the autonomy viability assessment. We apply the matrix on seven autonomy models. We present the assessment result of the AVAM which confirms its ability to assess a broad class of autonomy models.**

Keywords—software agent; autonomous system; autonomy assessment; situation awareness assessment

I. Introduction

An autonomous system is a self-directed system to achieve its goals. It works without external control, behaves based on algorithms, according to strategies and governs by rules. Autonomous systems aim to eliminate risks, enhance performance and reduce costs that plague non-autonomous systems [1]. Collier [2] defined an autonomous system via its ability to modify its behavior based on its observations to increase its viability in order to enhance its survival. Autonomous systems have been developed for environments that are inaccessible or unsafe for humans to work [2], [3]. Additionally, they are used to reduce human cognitive load in analysis, control and reasoning tasks [4]. Figure 1 shows an example of an autonomous system's architecture of a robot.

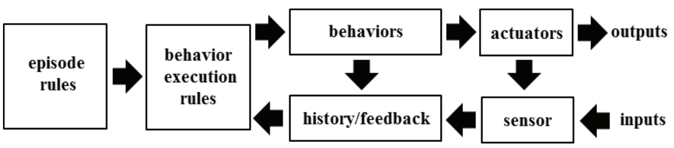

Fig. 1. Behavior execution architecture of a robot (modified from [5])

Autonomy assessment is the process of measuring and validating the quality of autonomy in a system. In general, autonomy assessment is performed based on measuring a human's and a system's interactions degree, reliability measures, human standpoint measures, decision choice quality, usability and etcetera. There are a number of proposed methodologies and matrixes in the literature to assess or validate the autonomous system's ability regarding: (1) human robot interaction assessment, e.g., [6], (2) situation awareness assessment, e.g., SAGAT of [7], [8] and [9], (3) autonomy viability assessment e.g., [10], [11] and [12], and (4) human preference of autonomy, e.g., [13] and [14].

However, there is no methodology or matrix that is general enough to assess a broad class of autonomy models. This is because of the variations in the dependencies of each work. Consequently, there is no general autonomy model that can be a base for others' assessment. As examples, Reed [15] validated his work via a simulated fighter aircraft; Roehr and Shi [16] validated their work via robot simulation; Zieba et al. [12] developed their own performance assessment matrix to validate their work; Bush et al. [17] validated their work via natural disaster recovery simulation; Cote et al. [18], validated their work via robot simulation; Rajabzadeh [19] validated his work via smart grid simulation; and Petersen [20] developed a Task Effectiveness (TE) performance matrix to assess the validity of her work.

In this paper, we propose an Autonomy Viability Assessment Matrix (AVAM) for assessing agent-based autonomy models'. The AVAM consists of three attributes that are represented by eleven criteria. We then apply the matrix on seven autonomy models and successfully obtain their assessment scores. The rest of the paper is organized as follows: The following section reviews the related literature, Section III presents the AVAM, Section IV presents the AVAM assessment results and section V presents the conclusion of the work.

II. Literature Review

Different autonomy approaches and models are proposed in the literature and each of which is built based on some arguments and offers solutions that resolve specific autonomy issues [1], [16] [21], [22]. Still, many researchers acknowledge the fact that autonomous systems might act undesirably due to different circumstances which might be beyond their control [16], [23], [24], [25].

Software agent and adjustable autonomy are two core concepts that enrich the autonomous system research. Software agent concept opens the door for new research topics including agents' autonomy, freedom and responsibility. Researchers argue that agents are retrospectively responsible for their actions. For a given time, if an agent has the intention to do an action and performs the action based on self-obligation, then the agent is responsible for doing the action. Agents' decisions of actions might involve predefined conditions, motivations and emotions that are constrained by their autonomy boundaries. Autonomous agents with uncertainties need humans' assistance to perform successful actions. The adjustable autonomy concept provides the merit of humans and agents sharing control of an autonomous system. It further facilitates the autonomy assessment because of its qualitative and quantification features.

A. Autonomy Assessment Methodologies

The autonomy assessment in the literature considers quantitative and qualitative measures. Quantitative assessment contributes a number of measurement metrics. It helps to trace process flow and identify deficiencies that need to be fine-tuned [19]. However, the meaning of the results is hard to understand [12]. Consequently, a qualitative assessment is an important methodology, especially, in complex autonomous systems or reactive automation that are difficult to be quantitatively measured. Subsequently, there are two main methodologies to assess autonomy:

- Expert Assessment: It is mainly qualitative assessment that focuses more on the system's development aspects of an autonomy model. An expert assesses the autonomy requirements of a system and their specifications according to some guidelines. The requirements might include goal, interaction, usability, autonomy distribution organization, environment, agents and situation awareness requirements [4]. For example, the United State army considers the capabilities of observation, perception, situation awareness and decision-making in the autonomy assessment.

- Performance Assessment: This is a widely used autonomy assessment methodology especially in robotics and unmanned systems. The performance assessment implies a qualitative or quantitative assessment for a workable or a simulated autonomous system. It is achieved via implementing measurement metrics to verify and validate the autonomy of the system based on its performance. The measurement metrics consider two dimensions: (a) performance: independency from human, successfulness and consistency, (b) complexity: of the environment and the goal achievement. Examples are [6], [16] and [26].

B. Autonomy Assessment Criteria

There are many representations and different criteria used in the literature to describe the quality of autonomy [6]. There is no general term or specific matrix that can be used in the autonomy assessment process. The commonly used notions in autonomy assessment are viability, effectiveness, efficiency and resilience of the autonomous system. These notions are loosely defined terms in the autonomy literature. Consequently, their attributes are defined according to their autonomous systems. Nevertheless, their aim is to ensure an achievement of common objectives which mainly enhance the usability, reliability and flexibility of autonomous systems.

Insaurralde and Lane [4] defined autonomy usability as the ability of an autonomous system to successfully perform actions without human intervention. Usable autonomy entails reduction of human workload via adopting flexible autonomy and considers users' preferences [13], [27]. Consequently, it entails reducing the disturbances of the autonomy distribution and adjustment [12].

Roehr and Shi [16] aimed to maximize overall system autonomy, team-work performance and ensure better performance in achieving the goal. They considered, in the autonomy assessment, the attributes of efficiency and reliability that are measured according to the following criteria: (1) the cost of losing, damaging or replacing the autonomous system; (2) the interactions constraints e.g., cost and numbers; and (3) the successfulness of the performance.

Miller and Parasuraman [10] defined viable autonomy for UAV system via autonomy usability and flexibility attributes. They measure autonomy flexibility according to autonomy distribution for human-agent interactive decisions (i.e., internal and external autonomy adjustment) and situation awareness capability of the system. They measure usability according to the criteria of human's mental workload, user satisfaction and overall system performance. Consequently, Parasuraman et al. [11] defined viability of an autonomous system via its ability of mental workload, situation awareness and reliability attributes. They showed that reliability as the only consideration for an autonomy attribute is not sufficient. There are other critical demands to the autonomous systems that need to be fulfilled.

Zieba et al. [12] considered resilience in measuring adjustable autonomy quality. The resilience measurement considers the attributes of efficiency, adaptability, stability and interaction capabilities. Mostafa et al. [9] adapted system's ability of situation awareness as a key factor of autonomy assessment measure.

Durand et al. [28] proposed to assess autonomy via measuring performance consistency. They identify inconsistencies' sources in Unmanned Aerial Vehicle (UAV) via the physical parts, the algorithms and the approximations. Sellner et al. [23] focused on enhancing human operators' ability in controlling robots sliding autonomy. They addressed that humans' responses are the bottleneck of system's responses' speed compared with other autonomous entities.

C. *Autonomy Assessment Techniques and Tools*

There are different autonomy assessment techniques and tools in the literature. We present the following examples of agent-based assessment techniques and tools.

Huber [29] proposed a flexible model of autonomy for a BDI agent. The agent is designed to exhibit different autonomy levels based on situations. The autonomy is measured based on the agent's internalization of the external influences across its internal structure of beliefs, desires, intentions, and capabilities. The agent autonomy level dignifies its ability to filter the negative influences. Huber claimed that autonomy is represented via agent's goal directedness and planning capabilities and defined absolute autonomy as an infinite level of autonomy. In addition, autonomy is not a single property of the agent; it rather considers the internal and external conditions. Huber's aim is to ensure that the agent's autonomy adjustability does not compromise its integrity. Figure 2 shows the effect of the external influences on the agent's autonomy.

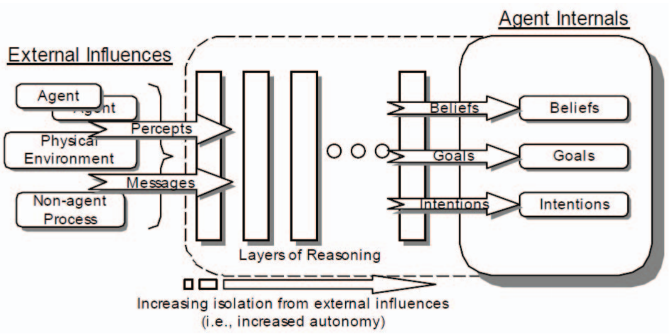

Fig. 2. Huber's [29] BDI agent with explicit autonomy model

Sierra and Schorlemmer [24] proposed a distributed mechanism to block or ostracize agents that violate certain norms. They experimented a cooperative norm scenario in which two options are possible; cooperate or defect. An agent's utility increases when it cooperates with cooperative agent and vice versa. The violator agents are categorized into unrestricted, semi-restricted and ostracized based on their violation records. The mechanism significantly reduces norm violations among the agents' community and increases their compliance to the cooperation norm.

Wallace and Henry [30] proposed a self-assessment mechanism to SOAR agent autonomy distribution. The self-assessment relies on policies that work as a constraint model of an agent's behavior. The self-assessment includes building hierarchal execution model that represents the agent's behavior to trace the goals and actions performed by the agent. The intended actions are validated via the execution model according to the prescribed policies in order to be either executed or prevented.

Insaurralde and Lane [4] proposed a measurement metric for Unmanned Marine Vehicle (UMV) autonomous capability assessment. The assessment objective is to configure the satisfactory autonomy degree or level for the UMV system. Insaurralde and Lane suggested two measurement metrics to assess autonomy: Degree of Autonomy (DoA) which is a real number, the value of which indicates the amount of autonomy that the system has and Level of Autonomy (LoA) which is a natural number that indicates the grade of operations that are autonomously performed (see Figure 3). They defined autonomy measurement via the usability of an autonomous system with or without human intervention. They proposed the following framework for autonomous UMV system's autonomy assessment:

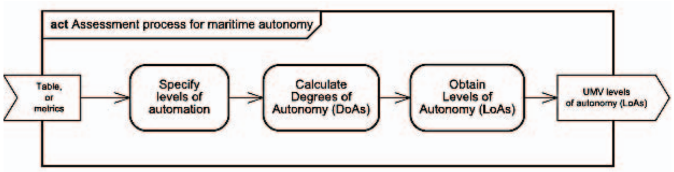

Fig. 3. The assessment process of system's autonomy [4]

Situation Awareness Assessment (SAA) is another technique that measures and validates the performance of a process, procedure or mental ability of a system [9], [31]. SAA privileges are frequently used in computer science, especially in computer automation aspects [31]. It investigates the flow points in a system that might cause or caused risk or failure [7], [8].

Bosse et al. [32] defined SAA as, "*a quantitative evaluation of the situation that has to do with the notions of judgment, appraisal, and relevance*." The notion of SAA has been widely accepted by researchers, applied to different fields and in different domains [27], [32]. Many different approaches that perform assessment operation for other techniques or systems are proposed in the literature [31], [33]. Mostly, however, situation awareness assessment techniques in the literature are deployed to achieve the following objectives:

- Performance-based assessment: This approach concerns with systems' performance assessment. The performance-based assessment is an independent technique that studies the appropriateness of decision-making in actions. An issue of this measure is that a high-level assessment does not guarantee optimal performance due to decision-making constraints [33]. Knowing that, the essential reason of delivering high-level assessment is to enhance the decision-making ability [7], [8].

- Situation-based assessment: In this approach, SAA is implicitly integrated within the system components [27]. It assists an operator to clarify a situation [34]. Then it suggests possible actions for the situation and the operator discretionally selects an action among them to act on situations.

- Simulation-based assessment: This approach is similar to the performance-based assessment but induces a system's processes without interfering in its activities. The measure focuses on tracing and understanding the data and its manipulations that causes triggering actions [33], [34].

- Subjective assessment: The subjective assessment uses third party observer to numerically represent the assessment (e.g., checklist approach). This observer might feed the observations as input to the system in another round of operation [31], [32].

A significant outcome is the Situation Awareness Global Assessment Technique (SAGAT) proposed by Endsley [7] to measure the situation awareness level of a system. The aim of SAGAT is to assist a pilot of an air fighter to maintain high-level of performance during a mission to enhance his/her decision-making quality and the cockpit's performance. Naderpour and Lu [27] adopted the SAGAT model in technological disaster avoidance system.

Scholtz et al. [33] proposed a SAA technique for human-robot interface. They adopt the SAGAT style method in the assessment performance. The technique is used in a vehicle-based robotic autonomous system to evaluate the supervisory interface of human-robot interaction (HRI). The practical objective of the research is to make a human supervisor aware if the vehicle is in trouble and needs assistance. The interface provides the supervisor with information about the vehicle, the environment and the route. The supervisor is timely notified about the system's attitude (normal, cautionary or hazardous) to do the required, if any. The research result shows that the situation awareness level is correlated with the workload and the time.

Gehrke [35] proposed six criteria for assessing the situation awareness of autonomous systems based on Endsley's [7] SAA model and suggested methods to fulfill the proposed criteria. Gehrke claimed that only entities with high reasoning capabilities such as humans and agents can show SA ability. Ontology is proposed as a solution for improving perception ability and to share and reason the knowledge of contexts. Gehrke however, only reviewed the features and the limitations of the existing situation awareness approaches and suggested a set of requirements as situation awareness quality criteria, but without the mechanisms and processes to achieve them.

III. The Autonomy Assessment Matrix

As we deliberated in the previous sections, there are many opinions and diverse understanding of what autonomous agent and autonomy are. As a result, different approaches are proposed to resolve some of the autonomy problems. There is no general formula that can assess a wide range of autonomy models and provides rough estimation to the autonomy viability quality of their corresponding autonomous systems.

In this section, we present an Autonomy Viability Assessment Matrix (AVAM) as a general matrix for autonomy models' assessment. The AVAM investigates the existence of a viable autonomy model for the dynamic environment constraints based on the attributes of usability, reliability and flexibility. The autonomy usability assessment attribute is concerned with the (1) autonomy model success in a dynamic environment, (2) application complexity, (3) domain independency, (4) user preference and (5) user workload. The autonomy reliability assessment's attribute concerns with the (1) external control ability and (2) system disturbance reduction. Finally, the autonomy flexibility assessment attribute is concerned with (1) internal control ability, (2) autonomy measurement dynamism, (3) autonomy distribution ability and (4) situation awareness capability. The autonomy assessment attributes and their criteria are extracted from different resources including [10], [11], [12], [13] and [14]. Table 2.4 details the AVAM that we proposed.

TABLE I. The Autonomy viability assessment matrix

Attribute	*Definition*	*Criterion*
Usability	The autonomy model satisfies human user needs.	The autonomy model of an agent is said to be usable if: 1. It is successfully applicable in a dynamic environment. 2. It is easy to apply and not complex. 3. It is domain independent. 4. It fulfills users' preferences. 5. It is capable of reducing users' workload.
Reliability	The autonomy model minimizes the risk of failure and manifests trustable and confident autonomy.	The autonomy model of an agent is said to be reliable if: 6. It has an authority (human) that controls its autonomy. 7. It is resistant to the disturbances of the autonomy distribution and adjustment.
Flexibility	The autonomy model is directed to enhance agents' autonomy in a system.	The autonomy model of an agent is said to be flexible if: 8. It allows the agent to initiatively reason its autonomy (i.e. internally adjusting the autonomy). 9. It has explicit and dynamic autonomy measurement mechanism. 10. It has efficient autonomy distribution and adjustment mechanisms that distribute and adjust the autonomy down to the action level. 11. It has situation awareness capabilities.

We evaluate each of the autonomy viability attributes' criteria with one when it is present and zero when it is absent and assume that the criteria have equal weights. The overall number of the criteria is 11. If a criterion of a viability attribute is found to be satisfied, it is considered and the overall model autonomy viability score is incremented by one. The final score is assigned over 11 based on the assessment results and converted to percentage using the following formula:

$$\nu_m = \left(\frac{\sum_{i=1}^{n} c_i}{n}\right) * 100$$

where ν is an autonomy viability percentage of an autonomy model m, c is the criterion score of 1 if it is satisfactory or zero if it is not, i is the criterion index and n is the total number of assessed criteria.

IV. Testing And Results

We consider autonomy models from different domains including: domain specific, robotics and unmanned systems to validate the generality of the assessment matrix. We test the AVAM on seven sample autonomy models: (1) Reed [15], (2) Roehr and Shi [16], (3) Zieba et al. [12], (4) Bush et al. [17], (5) Cote et al. [18], (6) Rajabzadeh [19] and (7) Petersen [20]. The test methodology is presented in the following steps:

Step1: Search autonomy model samples.

Step2: Gather the available resources/references for each of the samples.

Step3: Adopt the samples with rich resources and filters out the samples that have poor resources.

Step4: Perform a comprehensive study of each sample.

Step5: Identify the autonomy viability attributes for each of the samples.

Step6: Identify the criteria of each of the autonomy viability attributes.

Step7: Evaluate the quality of each criterion for each sample.

Step8: Estimate the final autonomy viability score.

We apply the above steps on the seven mentioned autonomy models. According to the AVAM evaluation results, the autonomy models of Roehr and Shi [16] and Zieba et al. [12] have the higher score of 63.6% and the model of Bush et al. [17] has the lowest score of 36.3. In Table 2, we present the assessment results of the seven autonomy models.

TABLE II. THE AUTONOMY VIABILITY ASSESSMENT RESULTS

Autonomy Model		*Autonomy Viability Attributes*			*Score (%)*
No.	*Reference*	*Usability*	*Reliability*	*Flexibility*	
1	Reed [15]	(2), (3)	(6)	(8), (10)	45.4
2	Roehr & Shi [16]	(2), (3), (4)	(6), (7)	(8), (9)	63.6
3	Zieba et al. [12]	(3), (5)	(6), (7)	(8),(9),(10)	63.6
4	Bush et al. [17]	(5)	(6)	(8),(9)	36.3
5	Cote et al. [18]	(2), (3)	(6)	(9), (10)	45.4
6	Rajabzadeh [19]	(2), (3), (5)	(6)	(8), (9)	54.5
7	Petersen [20]	(2), (3), (5)	(6)	(8), (10)	54.5

The overall assessment results are presented in Figure 4. It reveals that there are two research gaps in the assessed sample of autonomy models. The first research gap is in applying the proposed models in a real-world application of dynamic environment (i.e. criterion 1). The second research gap is the absence of situation awareness mechanisms that improve the overall system's autonomous performance (i.e. criterion 11). Only one model among the seven models considered user preference in its autonomy model design (i.e. criterion 4).

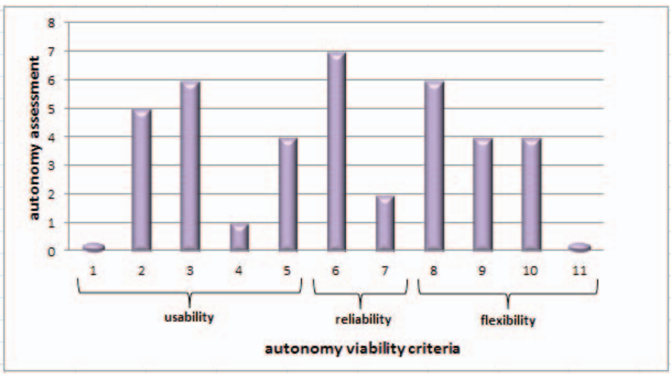

Fig. 4. The overall autonomy assessment results

On the other hand, six of the seven models are domain dependent (i.e. criterion 3) which manifest usable autonomy models. Consequently, the agents initiatively reason on their autonomy in six models (i.e. criterion 8) which manifest flexible autonomy models. Finally, human control is presented in all the seven models (i.e. criterion 6).

V. CONCLUSION

We conclude that formulating autonomy model that is viable for dynamic environment constraints is a challenging process. The literature offers many different autonomy models to overcome some of the autonomy challenges. However, there is no specific model or algorithm that yields an ideal viable autonomy.

In this paper, we present an Autonomy Viability Assessment Matrix (AVAM) to assess agent-based autonomy models. The AVAM matrix consists of three attributes and 11 criteria. We test the matrix on seven autonomy models and the test results confirm the ability of the matrix to assess a broad class of autonomy models. It is able to identify two research gaps that can be further studied.

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