Towards an Evaluation Framework for Autonomous Systems

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***Abstract*—Despite the active and proficuous research in autonomous and self-adaptive systems of the last years, an evaluation framework to assess abilities related to adaption and to provide guidance to make a system smarter is still missing. In this paper, we perform the first steps towards an evaluation framework for autonomous systems to (i) make an assessment of a system from the perspective of its capacity to adapt and learn over time to handle new and unexpected conditions, (ii) explore and identify the possible pathways of improvement of the smart abilities (e.g., decisional autonomy, adaptability, perception, interaction, etc.) of a system, (iii) make a re-assessment when the improvement has been performed.**

***Index Terms*—Evaluation framework, Autonomous systems, Self-Adaptation.**

I. Introduction

In the last years, we observed active and proficuous research in autonomous and self-adaptive systems (SASs). The SEAMS community produced two roadmaps to summarize the state-of-the-art, for identifying critical challenges [1] and essential topics of self-adaptation [2]. There have been also survey papers aiming at identifying the underlying research gaps and elaborating on the corresponding challenges of SASs [3]. The work in [3] also provides a taxonomy of self-adaptation, including the object to adapt, realization issues, temporal characteristics, and interaction concerns. The work in [4] presents another taxonomy of self-adaptation and a survey on engineering SASs. The work in [5] reviews the state of the art on self-adaptivity from the computer science and cybernetics points of view. The work in [6] proposes a classification of self-adaptation patterns that support self-adaptation at the component and system levels. A recent work [7] also investigates how the concept of uncertainty is perceived in the community and how it is currently handled in the engineering of self-adaptive systems. Finally, a recent book presents the basic principles, engineering foundations, and applications of SASs [8].

However, to the best of our knowledge, no existing paper provides an evaluation framework to assess abilities related to adaptation and to provide guidance to developers and engineers to make a system smarter, in the spirit of making it more autonomous. In fact, figuring out how to concretely operate to make a system smarter is not obvious, since it involves various system's abilities like decisional autonomy, adaptability, perception, interaction with other systems and humans. By analyzing famous evaluation frameworks, such as the Capability Maturity Model Integration (CMMI)[1], we realized that an evaluation framework needs to cover various abilities together with a clear identification of various levels for each of these abilities.

In this paper, we aim at making the first steps towards providing an evaluation framework to help developers and engineers to assess system's abilities related to adaptation and smartness. The evaluation framework is called LENS - evaLuation framEwork for autoNomous Systems - and it can be used, e.g., for (i) making an assessment of a system under the lens of abilities related to adaptation and smartness, (ii) identifying the possible directions of improvement, and (iii) making a re-assessment when the improvement has been performed. This would permit to define key performance indicators (KPIs) to measure improvements in making systems smarter. Our idea is to develop LENS by exploiting the Multi-annual Robotic Roadmap [9] for robotic systems, since this roadmap identifies various abilities of autonomous robotics and

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[1] https://cmmiinstitute.com/

defines levels for each of them.

The paper is organized as follows. Section II surveys the state of the art in evaluation frameworks for adaptation. Section III introduces the Multi-Annual Roadmap for Robotics in Europe, since LENS exploits it. Section IV presents LENS, the evaluation framework we contribute in this paper. Section V discusses the results of this paper and concludes with final remarks and directions for future works.

II. Literature review in evaluation framework for adaptation

Existing taxonomies, e.g. [3], [4], identify concepts behind adaptation, however, they cannot be used as evaluation frameworks. In the literature we can find works focusing on a specific system's ability, such as adaptability, and they provide metrics for measuring them [10]–[15]. Being focused on a specific metric, these works miss a holistic view, and, moreover, metrics are defined for specific development phases, e.g. architecture development.

To further investigate the state of the art in evaluation frameworks for system adaptive abilities, and be sure not to omit existing relevant evaluation frameworks, we systematically analyzed related literature. Specifically, we searched for suitable publications in the *IEEE Xplore*, *ACM*, and *Scopus* digital libraries. As the search string, we used the following:

> *(Adaptive System(s)* ***OR*** *Autonomous System(s))* ***AND*** *(Evaluation Framework* ***OR*** *Measurement Framework* ***OR*** *Assessment Framework).*

The search was performed by considering publications title, abstract, and keywords, in the time period from 2012 to 2022. As a result, we got 32 papers from Scopus, 5 papers from IEEE Xplore, and 2 papers from ACM. However, the subsequent screening of publications and duplicates removal showed that the set of papers from Scopus already included papers obtained by querying the other libraries. Thus, the evaluation has been performed on a total of **32** unique papers. The inclusion and exclusion criteria we defined to identify the set of potentially relevant papers are given in Table I. A replication package for the SLR is provided in [16].

Eventually, only a few papers (i.e., [17]–[24]) fulfilled the criteria and were evaluated. In [17], the authors present *ReSonAte*, a dynamic risk estimation framework for autonomous systems. The probabilities of unsafe conditions or failures are computed from runtime observations about the state of the system and environment, besides safety requirements, design time assumptions, and past failures. Similarly, the work in [18] aims at dynamically exploiting IoT data to support the risk awareness of Connected and Autonomous Vehicles (CAV), thus enabling faster reactions and better decision-making for a safer mobility. The proposed framework exploits multiple risk profiles to support users in better understanding risks and appropriately adapting to various situations. Differently from [17] and [18], where risk refers to the probability and severity of undesirable events, in [19] the risk is intended as a barrier to the implementation of autonomous systems or as the consequences of the use of such systems. The authors provide a risk assessment framework, which is intended to evaluate the different levels of autonomy a system can show, and the risk faced when implementing each of these levels. In [20], the authors propose a model-based resilience assessment framework, which exploits a resilience ontology to guarantee a transparent and up-to-date modeling and quantification of the system risk and reliability metrics. The work in [21] presents an evaluation framework of performance limitations that combines safety analysis and sensor attack simulation. In [22], the authors propose a conceptual framework, i.e., a metamodel, to support early design decisions for systematically deriving Safety Supervisors (SSV) for autonomous systems. From an engineering perspective, the framework allows one to arrive at an evidence-based decision about which algorithms to choose for the further development of a safety monitor, by conducting what-if analyses and comparing different meaningful combinations of available solutions. In [23], the authors target the need for development organizations of capabilities, processes, and tools required to achieve the needed readiness for designing Autonomous Machine Systems (AMS). To this aim, by means of semi-structured interviews and based on the literature, they identify a set of factors affecting the organizational readiness to design AMS. Lastly, [24] reports a framework for evaluating the robustness of autonomy of Unmanned Aircraft Systems (UAS), namely, the ability of autonomous systems to continue operation in the presence of faults or safely shut down.

Inclusion criteria
1. Peer-reviewed papers published in journals, conferences, and workshops.
2. Papers presenting an evaluation framework.
Exclusion criteria
1. Papers not written in English.
2. Short papers, posters and tutorials ($<$ 3 pages).
3. Conference Proceedings.

TABLE I: Inclusion and Exclusion Criteria

In conclusion, to the best of our knowledge, there exists no generic framework for the assessment of adaptive abilities of autonomous systems.

III. Multi-Annual Roadmap For Robotics in Europe

Similarly for robotics roadmaps defined for other continents and countries[2], the Multi-Annual Roadmap for robotics in Europe (MAR) [9] provides a high-level strategic overview of the robotics community and its objectives and identifies challenges and opportunities available for robotics. Even though MAR focuses on robotics, it is suitable to be generalized and it provides a detailed technical guide to analyze medium to long term research and innovation goals. We consider this aspect as a unique characteristic that we did not find in other roadmaps and, in general, in other documents.

More precisely, MAR identifies a set of robot abilities, which provide a way of characterizing the whole system performance. Moreover, each ability has a series of ability levels, which provide a progressive characterization of what any robotic system might do. These are the abilities of a robot to perform the following actions:

- *Adaptability*: to adapt itself to various scenarios, environments, and conditions.
- *Cognitive Ability*: to interpret a task, human commands, and environment, as well as, work interactively with humans, so to efficiently and effectively execute the task potentially under uncertainty.
- *Configurability*: to be (re-)configured or self-(re-)configured to perform a task.
- *Decisional Autonomy*: to act autonomously (degree of autonomy).
- *Dependability*: to perform its given mission without errors.
- *Interaction Ability*: to interact both cognitively and physically either with users, operators or other systems around it, including other robots.
- *Perception Ability*: to perceive its environment.
- *Manipulation Ability*: to handle objects.
- *Motion Ability*: to move.

Each ability captures one specific aspect of the operation and behavior of a robot system. MAR is focusing on robotics, which is, indeed, a special kind of autonomous system. Moreover, the different system abilities are defined in a way that is independent of any particular robot configuration or market domain [9].

[2] Australia: https://roboausnet.com.au/robotics-roadmap/, US: https://www.nowpublishers.com/article/DownloadSummary/ROB-066

IV. The LENS Evaluation Framework

To define LENS, we exploited the various surveys and books in the field [1]–[4], [8] and we further performed a literature review, as discussed in Section II. In particular, we found very useful to exploit the Multi-Annual Roadmap for robotics in Europe (MAR), which is described in Section III. Therefore, the MAR document has been an important starting point for defining LENS. However, since the MAR document is very focused on robotics, there is the need of carefully analyze it to remove the robotics specific aspects and to generalize to autonomous systems. Subsequently, LENS can be customized to other domains or class of systems, according to their peculiarities. For instance, a specific and important class of medical devices is that of Programmable Electronic Medical Systems (PEMS) [25]. PEMS is an interesting class of systems since exhibit a DOA (degree of autonomy), but they do not have manipulations and motion abilities. Therefore, a customization of LENS to PEMS would require to (i) remove the manipulation and motion abilities, (ii) remove sub-abilities that do not apply to PEMS, such as sub-abilities in the interaction, perception, and cognitive abilities that require motion, (iii) tune the name and the definition of the levels, as well as the name of abilities when it is important in order to better fit into the PEMS class of systems. Indeed, other domains or class of systems would require different customization of the LENS framework. We would like to highlight that besides of removing abilities and sub-abilities and customizing the names and definitions, there could be the need of adding extra abilities, such as explainability and ethics, which are increasingly important aspects for the trustworthiness of autonomous and adaptive systems.

In Section IV-A, we discuss the abilities of LENS and in Section IV-B we describe the steps that should be followed to use the LENS framework.

A. Abilities in LENS

For space reasons, we cannot describe in details each ability of the LENS framework and the levels of each ability. We instead focus on two specific abilities that are good representative of the framework.

Table II reports the adaptability ability of LENS with its levels. Adaptability is defined as the ability of the system to adapt itself to different work scenarios, different environments, and conditions. Adaptation may take place over long or short time scales, and it may relate to local control systems or actions, to the whole system, or to interaction. Instead, Table III shows the description

Level	Name	Description
0	No Adaptation	The system does not alter its operating behavior in response to experience gained over time.
1	Recognition of the need for adaptation	The system recognizes the need for parameter/component/task adaptation. The system identifies the problem but does not yet know how to correct it.
2	Adaptation of individual components/parameters/tasks	The system alters individual parameters/components/tasks in any part of the system based on assessments of performance **local to the module** on which the parameter operates.
3	Process chain adaptation / Multiple parameters adaptation	The system alters several parameters/components/tasks based on the aggregate performance of **a set of interconnected or closely coupled modules**.
4	Communicated component/parameter adaptation	The process of adaptation is carried out between multiple independent agents. The adaptation is communicated between agents and applied individually within each agent. Agents can be both real and simulated, and of different types.

TABLE II: Adaptability ability

Level	Name	Description
0	No Action Ability	Systems are defined by having some level of action on the environment. This level remains for compatibility.
1	Defined action	The system executes fully pre-defined actions as a sequence of sub-actions. This sequence can repeat until stopped by an operator or other system event.
2	Decision based action	The system is able to alter its course of action based on perceptions or system events. It is able to select between a set of pre-defined actions based on its decisional autonomy ability.
3	Sense driven action	The system is able to modulate its action in proportion to parameters derived from its perceptions. The perceptions are used to drive the selection of pre-defined actions or the parameters of pre-defined actions.
4	Optimized action	The system is able to alter the sub-task sequence it applies to the execution of a task in response to perceptions or a need to optimize a defined task parameter.
5	Knowledge driven action	The system is able to utilize knowledge gained from perceptions of the environment including objects within it, to inform actions or sequences of action. Knowledge is gained either by accumulation over time or through the embedding of knowledge from external sources, including user inputs that associate properties with perceptions.
6	Plan driven action	The system is able to use accumulated information about tasks to inform its plans for action.
7	Dynamic planning	The system is able to monitor its actions and alter its plans in response to its assessment of success.
8	Task action suggestions	The system is able to suggest tasks that contribute to the goals of a specific mission.
9	Mission proposals	The system is able to propose missions that align with high-level objectives.

TABLE III: Cognitive ability - Action sub-ability

of the levels of the action sub-ability of the cognitive ability in LENS. The cognitive ability is defined as the ability to interpret the task and environment such that tasks can be effectively and efficiently executed even where there exists environmental and/or task uncertainty. In this context, the action sub-ability concerns the ability of the system to act purposefully within its environment and the degree to which it is able to carry out actions and plan those actions.

These tables might be exploited, by following the process described in Section IV-B, to assess a system according to the two abilities. When performing the assessment, the evaluation committee should assign to each level one of the following values:

- *Not applicable - white*: this is the default value and it is assigned when the level is still too low for the application domain and, thus, a higher level must be present for all the systems in that domain.
- *Satisfied - green*: when the level is completely satisfied. We also require the evaluation committee to justify the value.
- *Improvable (low effort) - yellow*: when the system can be improved for (better) satisfying the level. The effort for realizing the improvement is low. We also require the evaluation committee to identify the direction of improvements needed for reaching that level.
- *Improvable (high effort) - orange*: when the system can be improved for (better) satisfying the level. The effort for realizing the improvement is high. We also require the evaluation committee to identify the direction of improvements needed for reaching that level.
- *Unable - light-gray*: when the system is not able to own the ability at that level, cannot be improved to reach this level of ability, or the improvement is out of scope. This can be due to several reasons: the system configuration, its goals, the lack of other abilities, etc.

To better show how an evaluation summary looks like, we can focus on the PEMS class of systems mentioned above. With an illustrative purpose, Table IV shows how

Ability	Levels														
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Configurability															
	○	○	○	○	○										
Adaptability															
	○	○	○	○	○										
Dependability															
	○	○	○	○	○	○	○	○							
Autonomy															
	○	○	○	○	○	○	○	○	○	○	○	○			
Interaction (Int)															
Human-system Int	○	○	○	○	○	○	○	○	○						
Human-system Int feedback	○	○	○	○	○										
System to system Int	○	○	○	○	○	○	○								
Human-system Int safety	○	○	○	○	○	○									
Human-system Int safety - context	○	○	○												
Perception															
Perception	○	○	○	○	○	○	○	○	○						
Object recognition	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Scene perception	○	○	○	○	○	○	○								
Cognitive															
Action	○	○	○	○	○	○	○	○	○	○					
Interpretive	○	○	○	○	○	○	○	○	○	○					
Envisioning	○	○	○	○	○										
Acquired knowledge	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Reasoning	○	○	○	○	○	○	○	○	○						
Human interaction	○	○	○	○	○	○	○	○							

TABLE IV: LENS evaluation summary for PEMS. When evaluating a concrete PEMS, each circle should be colored according to the color code given in Section IV-A and by following the process steps listed in Section IV-B.

the outcome summary of an evaluation of a potential PEMS should be.

The overall evaluation will be reported in a summary report as well as filled tables with the details of the evaluation for each ability and level.

It is important to highlight that the evaluation values do not take into account the return-on-investment (ROI) for performing a specific improvement of the system. The aim is just to make a rough estimation of the effort to be made to improve the system. We expect that making a proper evaluation of the ROI for a specific improvement requires different profiles and competencies, and it is out of the scope of LENS. Instead, LENS aims at providing the context to enable informed decisions on go/no-go improvements.

B. Steps to perform evaluation of autonomous systems

The activities that should be performed to evaluate autonomous systems with LENS are described in the following.

Phase 0 – Presentation: Preparation before starting the evaluation. This is an informal step with the main purpose of bringing all important stakeholders on-board. They form the evaluation committee.

Phase 1 – Analysis: First, (1) LENS itself is presented, along with (2) the autonomous system to be evaluated, (3) the context in which the system is supposed to operate, and (4) the business goals of the system. Then, the autonomous system is evaluated under each dimension. For each ability, the evaluation committee will perform the following steps:

(5) it assesses the system and assigns a color to the values of the ability, by focusing only on *Not applicable*, *Satisfied*, and *Unable* values;

(6) it provides examples explaining the given assessment;

(7) it assesses the system and assigns a color to the values of the ability, by focusing only on *Improvable (low effort)* and *Improvable (high effort)* values;

(8) it provides recommendations for potential extensions of the system.

Phase 2 – Reporting the evaluation results, along with recommendations for potential extensions of the autonomous system, are presented by the evaluation committee and documented in a report.

V. Conclusions and Future Work

In this paper, we describe the first steps towards an evaluation framework, called LENS, for investigating possible pathways for making autonomous systems smarter. The framework includes a set of abilities and levels for each of these abilities. To define LENS we exploited the large literature in the field [1]–[4], [8] and the roadmap for robotics in Europe (MAR) [9]. Indeed, since the MAR is focused in robotics it requires a serious and deep customization to the autonomous systems domain in general. However, its use has been very valuable, since it identifies various abilities organized in different levels. Therefore, the MAR document represents a precious starting point for the definition of the LENS framework.

We foreseen various pathways for future work. First, we will provide a complete description of the LENS framework, and, to better understand the details of the evaluation framework, we plan to customize it to the PEMS class of systems. In fact, in the near future, there will be an increasing need of smarter PEMS. Moreover, we have the required knowledge in this class of systems, and we have access to systems on which to experiment the LENS framework, such as the MVM mechanical ventilator developed during the COVID-19 pandemic [26], [27].

Second, we plan to support the LENS framework with a tool, which will enable designers in evaluating systems to assess abilities related to adaptation and to guide them in making their system smarter.

Third, we will investigate how to extend LENS with a support (in terms of metrics and/or KPIs) for a quantitative evaluation that takes into account also the return-on-investment of performing a specific improvement. This will also include an analysis of risks of performing the improvements, similarly to what performed in some of the works surveyed in Section II.

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