Towards Intelligent Sensor Evolution: A Holonic-Based System Architecture

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***Abstract*— Rapid developments of smart sensor technologies envisage a new era where information handling and knowledge sharing will play a crucial role. Traditional sensors were conceived as simple hardware transducers of physical quantities into measurable signals, eventually requiring an analogue/digital conversion to make data available for software applications. IEEE-1451 family of standards has added to mere transduction some architectural prescriptions to mainly address the issue of connection transparency, a desirable property virtually making any sensor a plug-and-play device. Our percept is that next generation smart sensor-based systems will have to face another challenge: the need to endow devices with the ability to process application-level bits of knowledge to best accomplish their informative goals. As a result, unexpected proactive and dialogue-oriented behaviors will have to be taken into account, thus reducing the gap between what we commonly refer to as smart sensors and intelligent agents. In order to support this view, a semantic-driven sensor-based system architecture is introduced and an example proof-of-concept case study is commented.**

Keywords - smart sensors, intelligent sensor, information processing, holonic modeling

I. INTRODUCTION

In the latest years, the impressive growth of pervasive and ubiquitous devices has entailed a profound evolution in the field of measurement systems. In fact, the mere transduction of physical quantities into analog or digital signals, do not live up to the complexity of modern society any more.

A number of commercial products endowed with "intelligent" functionalities are progressively replacing their old-generation competitors as it happens, for example, in mobile phones [1] or in industrial automotive applications [2].

The reasons fostering the adoption of smart technological solutions on a global scale are both technical and economical and can be enlisted as in [3]:

- reduction of the data communication with the main application processors for some preset functions with a specific value;
- lower system power consumption since some data is filtered and not all of the action needs to be done by the main processor;
- easier integration due to standard digital interface and pre-defined functions, avoiding developing all applications from raw data.

As a result, a large amount of legacy, incompatible, and often proprietary industrial solutions has sprung over years, sometimes producing specifications after upgraded to the rank of international standards (e.g., the ISO 11992-1 CAN bus [4] in the automotive industry).

When viewed through the lens of (artificial intelligence) AI, sensor "smartness" appears to stay in-between merely transduction and complex post-processing, with the boundary left undetermined. Yet, it is difficult to state with certainty to what extent IEEE-1451 compliant sensors can be considered as intelligent agents since they share aspects related to the measurement field with others related to information processing.

In any case, information processing brings forth the need of a reference model for the correct understanding of the obtained measures. Hence, especially in distributed settings like wireless sensor networks (WSN), the share of local ontologies [5] necessary to refine and control the global observed phenomenon, become a key point to address.

Our percept is that next generation smart sensor-based systems will have to face this challenge: endowing devices with the intelligence necessary to communicate with peers and humans to best accomplish their informative goals. The paper is devoted to provide a prospective view on this aspect. The remainder of the paper is as follows. Section II overviews the recent trends in the evolution of smart sensor technologies towards solutions with an increasing level of intelligence embedded; Section III introduces the employed sensor-based communication model; Section IV investigates a possible case study; Section V reports on early implementations and future perspectives; Section VI concludes the work.

II. RELATED WORK

As addressed in [6], there is a language gap between practitioners in the two fields of measurements and AI.

In our view, an oversimplified classification may be considering the first group as focusing on the statistical aspects [7] and the second on the semantics of the measured data [5]. In this perspective, lessening the distance between the two groups would mean narrowing the gap between the measurements of physical phenomena and their interpretation models.

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At the very core of any sensor, there is a transduction action permitting the transformation of measurands into electrical/optical outputs. These are more suitable for both data analysis and the activation of high-level processes for data presentation [8].

Once arrived at the electrical/optical stage, an analogue/digital (A/D) converter determines the passage from the physical world to the computational world. In fact, from a computational intelligence (CI) perspective, A/D or D/A conversions can be revisited and generalized in the framework of fuzzy sets and granular computing [8]. In other terms, after the A/D conversion process, digitalized measurement values become containers of information granules that need to be given sense by means of some computational task.

According to this view, smart sensors can be considered as a first attempt to bridge the gap between measurements and information processing since they are purposely conceived as hardware/software transducers able to bring the measured physical signal to an application target level.

IEEE has played a pivotal role in the smart sensors standardization process through the IEEE-1451 family of transducer interface standards [9]. In particular, the IEEE-1451 addresses mainly the significant engineering aspect of connection transparency. The aim is to aid transducer manufacturers in developing smart devices that can be interfaced to networks, systems, and instruments in a plug-and-play fashion.

However, smart sensors are not conceived to offer support in high-level information processing needs such as, for example, the possibility to host self-correction on board, performing data integration and fusion, managing local alarms to reduce the network and the host load. Henceforth, a new family of intelligent sensor capable to deal with the increasing complexity of modern applications is required to go beyond architectural prescriptions defined by the IEEE-1451 standards.

As of the latest couple of years, a new class of devices referred to as ‘intelligent sensor hubs’ is attracting the focus of the market and the academia. These can be viewed as sensor platforms endowed with a microcontroller unit that pre-process and aggregate external sensor data. An example of this new sensor generation is the MMA9550L motion sensing platform from Freescale company, housing a 14-bit 3-axis accelerometer together with a 32-bit CPU, I2C, SPI and other GPIOs. The low-power and small size enable applications in mobile phones, portables devices and also medical and industrial applications.

The enhancement of sensor platforms with a microcontroller unit derives from the need to overcome the limits of traditional smart sensor technologies, which cannot be customized to any specific application context since the embedded logic is fixed. However, the bare availability of a microprocessor does not suffice to provide an intelligent framework alone. Sensory data, in fact, have to be processed in accordance to an ontology shared with the potential end-users of the information processing task.

Typical limitations related to application-level tasks such as (to cite a few) effective customization, data fusion and self-calibration require to employ some kind of ‘software intelligence’ currently not addressed by the available standards. Consequently, it seems that the concept of sensor is broadening in the direction of AI [10] and intelligent agents [11]. For this reason, there has been a growing debate in the last couple of years on the appropriateness of using the term “smart sensor” when referring to functionalities typical of intelligent information processing [12].

Intelligent information processing brings sensory data at a higher level where the problems of suitable data interpretation models. At this stage, research on sensors inevitably floods into AI: at this level, transductions continue to occur but at the ontological level thus posing the relevant problem of sense disambiguation [13].

It is useful to stress that sense disambiguation is considered one of the most relevant and difficult problems in AI [14]. Semantics is prone to ambiguity because there can be multiple interpretation models (ontologies) and a reference knowledge [15] crafted by domain experts may not be always available. To correctly interpret sensory data, disambiguation strategies have to be pursued and some recent works begin to focus on that with reference to sensor-based applications [16] [17].

When the positive outcome of the disambiguation procedure in charge of an agent is hindered by the unavailability of sufficient local knowledge, one solution is requesting for help to an external source. A dialogue is then instantiated between the querying agent and one or more respondents (whatever humans or machines), thus producing a ‘conversational’ [18] behavior.

Communication protocols and architectures have been extensively studied in the field of multi-agent systems (MAS) [19] [20] and human-machine interaction (HMI) [21] [22]. Basing on these studies, a semantic-driven dialogue-oriented system architecture to use in sensor networks for knowledge sharing and information processing is introduced in this paper. Capitalizing on the experience gained in the fields of smart sensors research and CI, we are confident that the proposed architecture provides a preliminary step in the direction of next-generation intelligent sensor-based systems.

III. PROPOSED SYSTEM

In [23], a modeling approach for processing information at multiple granularity levels was presented. This approach grounds on the concept of “holon”, introduced by Arthur Koestler in late 60s [24]. Such concept is at the very core of our proposal; for this reason, it is useful recalling briefly the basic properties of holons and holonic systems.

A. Holons and Holonic Systems Architecture

In CI, holons and holonic systems can be considered as a recent evolution of agents and MAS [25]. In particular, holon is a recursive agent [26] with peculiar computational aspects such as self-modularity and self-organization.

Self-nested hierarchies of holons are properly called holarchies: with respect to MAS, they account for a more general concept of agent organization comprising multiple nested granularity levels. At the base of a holarchy, atomic holons are found, i.e., holons that cannot be further decomposed according to the problem context. Fig. 1 depicts an agent-based representation of a holarchy.

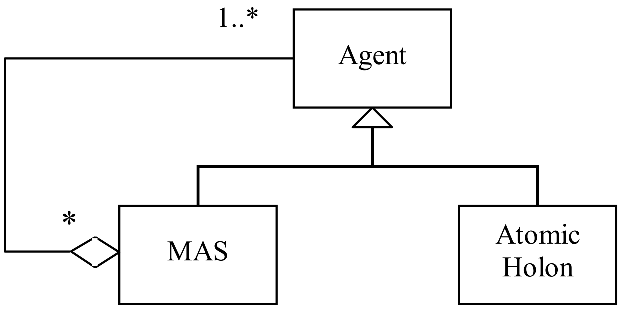

Figure 1. Architectural agent-based representation of a holonic system (slightly adapted from [27]).

It is noteworthy that holons and holarchies, due to holon intrinsic recursiveness, can be considered as two faces of the same coin viewed at two adjacent granularity levels [28]. Consequently, holon encapsulates in a single concept that of system of arbitrary complexity thus overcoming the part/whole and abstraction/enrichment dichotomy [29] that traditionally impedes Reductionist approaches [30]. As a result, the holonic view is highly suitable for modeling complex problems under a multi-granularity levels holistic [31] perspective.

B. *Holonic Intelligent Sensor Information Processing model*

The same recursive concept of holon encompassing multi-level agent-based architectures can be used to setup an information processing framework for dealing with data interpretation at an arbitrary semantic granularity.

In [13], a holonic model for processing sensor data at multiple granularity levels was introduced. Each level accounts for a different scale of information granules (in the Zadeh's sense [32]) that can be represented by means of linguistic descriptions (whatever fuzzy [33] or categorical), i.e., ultimately by words [34].

The information processing model can be implemented as a composition of two layered parts:

- the holonic transduction layer (HTL) and
- the holonic ontological layer (HOL)

The HTL is the computational layer. It consists in the implementation of the transduction functions necessary to functionally map a measured input signal into an output digital value.

The HOL is the agent-based layer. HOL is engineered as to respond to user query by claiming information from the subordinate HTL or from other agents listening to the bus. In this sense, it encompasses the features of interface and broker agents in hierarchical MAS architectures [35]. It is useful noticing that the querying user can be another intelligent sensor or a human as well. In this last case, system dialogue takes the form of human-computer interaction [22].

HOL works in strict cooperation with HTL. For example, HOL may account for the concepts of 'ppm' and 'ammonia' and answers the query about 'what is the concentration of ammonia' by calling the transduction function Ppm(*ammonia*), which outputs the part-per-million concentration of NH_3 at a given sampling time *k*.

It could happen that the queried intelligent sensor is not able to compute ammonia directly with an acceptable accuracy, because of its high cross-sensitivity. In this case, intelligent sensor equipped with low-cost ammonia detector could ask other sensors to share their data to infer on the presence and accurate concentration of ammonia basing on some computational inference mechanism as the ones presented in [36][37].

Fig. 2 depicts a hypothetical setup made of the five intelligent sensors in Table 1, each one endowed with a basic traditional sensor. By means of the computational techniques presented in [36] and [37], an intelligent sensor can answer the query about the concentration of ammonia by instantiating a dialogue with the other peers connected to the bus.

TABLE I. INTELLIGENT SENSORS EMPLOYED FOR THE HYPOTHETICAL SETUP DISPLAYED IN FIG. 2.

Intelligent Sensor id	***Basic sensor employed in HTL***	***Principal monitored Quantities in HOL***	***Basic sensor cross-sensitivity***
IS1	LM335	temperature	low
IS2	TGS2602	air contaminants	high
IS3	TGS2180	humidity	low
IS4	MQ136	sulfur dioxide	high
IS5	MQ131	ozone	high

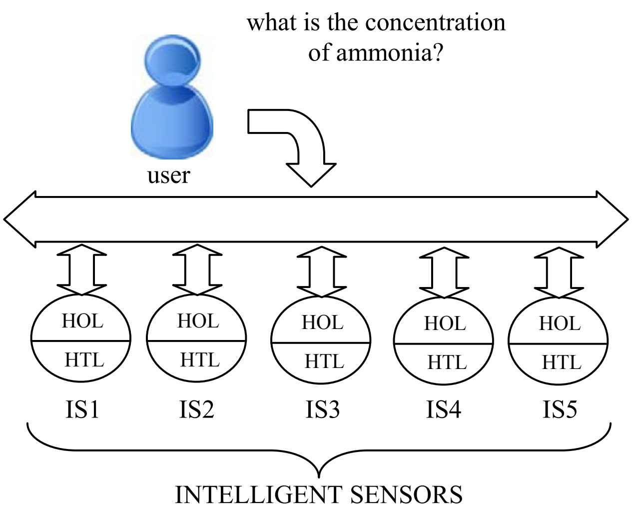

Figure 2. Holonic intelligent sensor example setup. The five intelligent sensors of Table 1 have to work in cooperation to minimize the effect of high-cross-sensitivity and properly respond to user query. Ammonia is not directly measured by any of the employed HTLs, however, it can be inferred by applying CI techniques, i.e., by instantiating a dialogue among intelligent sensors.

C. System Knowledge Organization and Properties

As shown by early works on sensor-equipped mobile robots in 80s [38], the problem of organizing and traversing different granularity levels according to both enrichment or abstraction criteria is a central issue from the system engineer's point of view.

In more recent years, the aspect of knowledge granularity has been intensively studied in the framework of granular computing (GrC) [39] and now seems to offspring in the field of holonic systems [28].

According to Pedrycz's view [40], GrC as opposed to numeric computing (which is data-oriented), is knowledge-oriented and accounts for a new way of dealing with information processing in a unified way. Since knowledge is basically made of information granules, information granulation operates on the granule scale thus defining a sort of pyramid of information processing where low levels account for ground data and higher level for symbolic abstraction.

In the holonic semantic model presented in [41], all the holons at the same level (representing one or more sub-holarchies) share the same ontology. The holons at the lowest level receive data from the real world using a set of sensors. Furthermore, these holons can handle various actuators to operate in the real world. On the other hand, all the holons at the higher levels receive data from the holons at the neighboring lower level. In sum, holarchy represents system knowledge across different granularity levels, spanning from the sensors/actuators level to the context-dependent problem conceptualization.

D. A Holonic Smart Sensor-Based System Proposal

By coupling the information processing model with the holonic architecture previously reported, a system is obtained where architectural and semantic recursion is operated by means of communication acts among system agents (the interested reader can refer to [42] for a formal specification of agents' communication acts). As a result, a dialogue-oriented system using intelligent sensors as intelligent agents can be modeled.

The employed ontology sharing mechanism is entirely based on communication acts among holons. Communication is a fundamental issue at least for reasons of two orders:

- It allows for representing bits of local information according to a distributed multi-level model of the observed system (refer to [13] for an example holarchy managing multi-level knowledge organization in low-cost gas sensor setups);
- It permits the extraction of inference rules from the environment where the holarchy dwells by means of recently developed computational techniques [43].

The proposed system is portrayed in Fig. 3. The querying user depicted in Fig. 2 becomes the agent managing the HOL while the above mentioned HTL becomes a recursive encapsulation of (holonic) intelligent sensors representing the knowledge objects to use in the information processing task.

As the figure shows, the system is built around the dialogue between HOL and HTL at any possible granularity level. At the maximum possible abstraction level there is, generally, a human user (acting in charge of the HOL) who queries the subordinate HTL (representing the automated part of the system).

The novelty of the model is that traditional user/system dichotomy has disappeared in favor of a holistic view: the user (human or machine) is now part of the model.

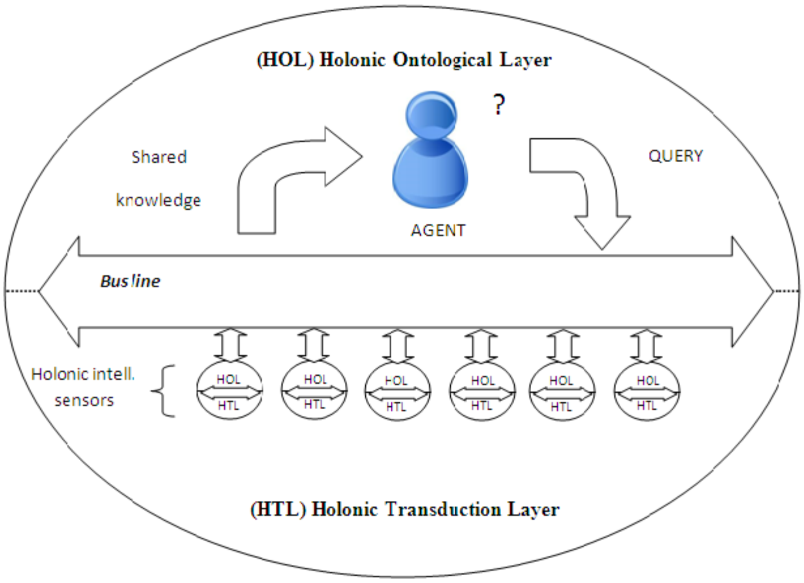

Figure 3. Conceptual model of a holonic intelligent sensor-based system. Since the model is recursive, the image accounts for a generic granular representation level.

IV. Example Case Study

In this Section, a possible application of the proposed intelligent sensor-based system model is discussed. Proof-of-concept case study is the indoor monitoring of various air quality parameters by means of low-cost oxide-based resistive sensors. Due to their cheap manufacturing process, these sensors are prone to show imprecise and inaccurate responses being sensitive to multiple contaminants at once [44]. Furthermore, their output changes significantly with temperature and humidity.

Suppose to consider three low-cost sensors: TGS2602 (air contaminants), MQ131 (ozone and mono-nitrogen oxides) and MQ136 (sulfur dioxide). As shown in [16], this triplet is sufficient to discriminate among CO, NH_3 and SO_2 presence, if appropriate sensor response disambiguation techniques are applied. Additionally, LM335 and TGS2180 can be used for temperature and humidity calibration.

A. General holonic architecture

The reference communication bus architecture is the one presented in Fig. 2. Five holons account for one measured parameter each. One additional holon instead acts as representative for the human user interested in interfacing the system.

In general, it happens that a relevant pattern to monitor is the result of a composition of distributed events (i.e., parameter values involving at least two holons at the same time). In this case, one holon queries the other on the supposedly occurring pattern. If the queried holon verifies that its local parameters are consistent with the warning raised by its paired unit, a proper action is triggered. In general, the more complex the pattern, the more the rounds of communication acts to check pattern verification.

In the following, two example use cases are commented to provide an overview of the possible communication acts exchanged among the hosts connected to the bus. The two examples have been chosen to depict the flexibility of the holonic-based architecture where communication acts can be triggered both from high-level holons (e.g., human user) or low-level holons (local sensors).

B. Use case 1: temperature and humidity self-calibration

In this use case, the action is triggered by the human user (super-holon) asking for the instantaneous concentration of ammonia. User performs her request by means of the PC connected to the LAN bus.

The queried holon (the one with MQ131 connected), according to its datasheet, is highly dependent on temperature and humidity. For this reason, to accurately fulfill its request, it calls the two holons of temperature and relative humidity to receive their data. Once that this information has been obtained, the MQ131 holon is able to calibrate its output and responds to user query with a text string like this:

```
%ANSWER TO QUERY FROM 192.168.8.137/Human%
    Ammonia is    8 ppm
    measured @    8.44 AM UTC+1
    with          temperature = 19°C
                  relative humidity = 65%
    in            AeFLab computer science laboratory
    accuracy      high
```

If, for example, the temperature holon were off-line, the MQ131 holon would continue providing a response, but with lower accuracy. In this latter case, the output string could be like the following:

```
%ANSWER TO QUERY FROM 192.168.8.137/Human%
    Ammonia is    8 +/-5 ppm
    measured @    8.44 AM UTC+1
    with          relative humidity = 65%
    in            AeFLab computer science laboratory
    accuracy      low  - -> could not find temperature
                            information
```

C. Use case 2:detecting a gas

In this use case, the action is triggered by one holon locally detecting a transition from one state to another. The holon looks up its local knowledge base (KB). KB stores all patterns the system consider as important to monitor. For example, as shown in [16], the following pattern accounts for NH_3 presence:

$$\text{MQ131} < \theta \text{ AND TGS2602} > \theta \text{ AND MQ136} < \theta$$

being θ an empirically tuned threshold value.

If MQ136 holon begins to sense local values such that the logical state MQ136 $< \theta$ is true, then it raises a query to TGS2602 and MQ131 holons to know their current logical states. If both the two queried holons confirm the NH_3 pattern, then a warning is raised to the PC holon to inform high-level holon (human user).

V. Implementations and Future Works

A test-bed implementation of the previously described holonic architecture is currently under way.

All holons are supposed to communicate their data by means of an Ethernet bus and inform one other about their services (e.g., measuring ammonia or CO) by means of a shared repository accessible via a Web-service interface.

Holons connected to the bus are hosted by the following devices:

- For the HTL, low-cost Linux-based RISC devices for continuous data acquisition and local parameter monitoring have been used. With reference to the overall system holarchy, all these units are responsible for hardware/software transductions by converting physical-level signals into digital parameters.

- For the HOL: one PC hosting complex data processing and visualization. This unit is responsible for extracting coherent IF THEN patterns from the sampled data sent by the HTL. After such process, the HTL is informed of the extracted patterns and can use them either for triggering user-defined actions (such as local alarms) or for knowledge exploration.

Each Linux-based RISC device is equipped with one of the three gas sensors reported in Fig. 2, plus a humidity and temperature sensor to host self-calibration on board. Software on-board has been written in C language to perform data acquisition, compression, storage and publishing. On each device, an ever running task constantly analyze real-time data arriving from all input channels to check if one of the monitored patterns verifies (or is about to verify). In this case, an action is triggered to the high-level holon (for example, a mail is sent to the system administrator if the temperature surpasses 25°C).

The PC station has been equipped with a Java-based data analysis framework realized by the Holsys company. In particular, the framework called H-GIS (Holonic-Granularity Inference System) implements the computational technique presented in [36][43] allowing one to extract inference rules from sampled data.

At the moment, employed acquisition devices write the sampled data into excel files, which are submitted in batch to H-GIS for knowledge extraction. In this setup, H-GIS is the true only agent of the architecture capable of exposing a high-level interface to an external user. In the long run, we aim at endowing each Linux-based RISC device with the same 'intelligence' of the PC hosting the inference system.

One pending issue is to find a suitable communication protocol to use for distributed information sharing in holonic-based systems. According to this objective, our schedule is to evaluate the opportunity of using standard ontology language (such as the Semantic Sensor Network ontology [46]) and rule description language in agent message exchange on bus. Figure 4 reports on the experimental system architecture.

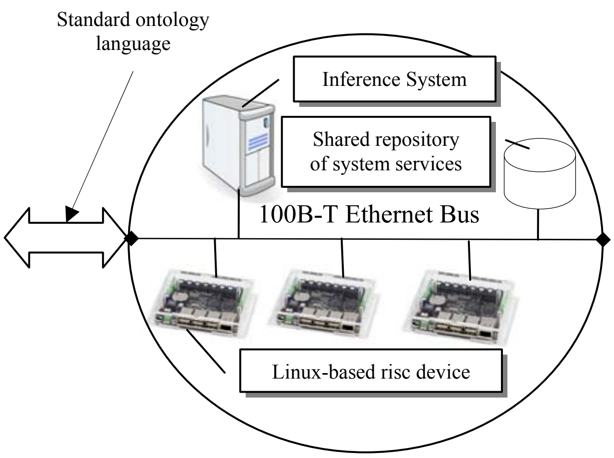

Figure 4. Test-bed architecture for holon hosting.

VI. CONCLUSION

When operational contexts are complex, cluttered and ambiguous, in addition to the relevant features of connection transparency and pre-processing functions, it is useful to endow smart devices also with the ability to interpret data thus showing an intelligent behavior towards the application layer and the human user.

With this objective, a semantic-driven dialogue-oriented system architecture to use in sensor networks for knowledge sharing and information processing has been introduced. The architecture has its backbone in a bus dwelling all holon communication.

Due to intrinsic holon properties, information can be organized according to a multi-level representation. This means that the same request can be answered differently (dependently on the operational context) since it ingenerates communication acts aimed at responding with the maximum possible accuracy level permitted by the current knowledge available. As a result, a communication among holons is instantiated at multiple semantic granularity levels.

One significant aspect that has been skipped here is the reverse engineering effort that has to be carried out in order to identify the possible utterances and consequently the meaningful context-sensitive queries. Furthermore, a proper communication protocol among holons has to be found to leverage real-world implementations. Future works will concentrate on such language-oriented aspect that still need to be formalized and properly tested.

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