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On the Role of Perception and Apperception in Ubiquitous and Pervasive Environments

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Abstract

Building on top of classic work on the perception of natural systems this paper addresses the role played by such quality in environments where change is the rule rather than the exception. As in natural systems, perception in software systems takes two major forms: sensory perception and awareness (also known as apperception). For each of these forms we introduce semi-formal models that allow us to discuss and characterize perception and apperception failures in software systems evolving in environments subjected to rapid and sudden changes—such as those typical of ubiquitous and pervasive computing. Our models also provide us with two partial orders to compare such software systems with one another as well as with reference environments. When those environments evolve or change, or when the software themselves evolve after their environments, the above partial orders may be used to compute new environmental fits and different strategic fits and gain insight on the degree of resilience achieved through the current adaptation steps.

Keywords: Software engineering, Evolvability, Resilience, Robustness, Pervasive environments, Ubiquitous environments

1. Introduction

When changes take place due e.g. to mobility or system evolution, it becomes important to guarantee robustness throughout system adaptations, that is the ability to match dynamically changing assumptions about the system and its deployment environments. Such property is often referred to as *resilience*, namely the ability to maintain one's (functional and non-functional) identity in spite of changes both exogenous (i.e. either environment- or user-specific) and endogenous (that is, pertaining to internal assets or resulting from dynamic adaptations) [1, 2]. Resilience finds its origins in the classic concept of Aristotelian entelechy, namely the ability to pursue completion (that is, one's

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optimal behavior) by continuously re-adjusting one's functions and structure so as to retain an optimal or healthy state whatever chain of events may take place [3].

This work focuses on two necessary conditions to resilience, namely sensory perception and awareness (also known as apperception).

- Perception represents a sort of "physical layer[1]" providing a system's higher adaptation layers with a view to a set of figures (originating within and without the system boundaries) that it can sense and whose changes it can be alerted from within a reasonable amount of time and with a certain degree of accuracy. In Sect. 2 we discuss perception in evolvable software systems (ESS), we identify three "sub-layers" necessary to support perception services, and provide a semi-formal model to reason about perception capability of ESS in highly changing environments such as those typical of ubiquitous and pervasive computing. Section 2 also discusses perception failures defined after the above-mentioned sub-layers.

- A second necessary condition to resilience is the matter of Sect. 3, in which we introduce and discuss apperception. Apperception is a higher-level form of consciousness that corresponds to a system's ability to make "effective use" of the contextual figures perceived currently or in the past. "Effective" here refers to the ability to operate control in the higher-level adaptation processes. Apperception includes the capability to construct theories about the current and related past situations [4] with which to drive system evolution. Section 3 also introduces an apperception model based on Boulding's general system's theory [5]. Apperception failures are also briefly discussed.

A major consequence of the models introduced in Sect. 2 and Sect. 3 is the fact that they provide us with two partial orders to compare evolvable software systems with one another as well as with reference deployment environments. When those environments evolve or change due to e.g. mobility, or when the software themselves evolve after their environments, the above partial orders may be used to compute new environmental fits and different strategic fits and gain insight on the degree of resilience achieved through the current adaptation. Our vision on how this may be put to use is given in Sect. 4, which also concludes this work providing the reader with a view to the current work in progress that is meant to extend our results to the higher-level "layers" of system evolution.

2. Perception

The problem of a system's ability to perceive events and properties of their surrounding environment is probably as old as humanity itself. Among the many who addressed it in the past we count luminaries such as Aristotle and Plato, Descartes and Leibniz, de La Mettrie and Herbart—to name but a few. More recently this problem has been cleverly studied e.g. by Block [6] and Lycan [7]. In what follows we build on top of these giants with the specific difference of addressing a peculiar class of systems, namely adaptive software systems. In this specific framework perception is interpreted simply as a precondition to becoming aware of the context and situations a system is set to operate into. In turn, this awareness (also known as apperception [8]) will be discussed in next section as a precondition to being able to exhibit and sustain resilience through the analysis of the current and past scenarios and the synthesis of theories with which to drive adaptations.

2.1. Perception Layers

As observed by many authors, a system endowed with the ability to perceive possesses (at least) the following three qualities:

1. First, the system comprises a number of "sensors" enabling to register *raw facts*. This is called "phenomenal consciousness" or (P-consciousness) in [6] and "organism consciousness" in [7]. In what follows we shall adopt the first term. All subsequent stages of perception rely on the trustworthiness and timeliness of this layer. We shall call this first sub-system the "sensor layer."

[1] In fact what we cannot perceive, we cannot react from—hence we cannot adapt to.

2. Secondly, the system includes a mechanism to reliably associate the registered raw facts to attributes internal to the system. "Qualia" is the term often used in literature for such system attributes. Qualia may be thought of as system-specific, internal representations of the raw facts we have P-consciousness of. An example of such mechanism is given by reflective variables [9, 10, 11]. We shall call this second mechanism the "qualia reflection layer."
3. Finally, the system must be able to reliably retain and access qualia referring to the current sensory experience as well as (to some extent) to past sensory experiences[2]. Here integrity, storage space, and bandwidth are among the key properties affecting the overall system performance. We shall refer to the sub-system providing this service as to the "qualia persistence layer."

It is sensible to assume that any perception system should include the above qualities or "perception layers". Furthermore, any system's ability to perceive (and ultimately *react* from perceived facts) is determined (as well as limited) by the way the above layers are architected and constructed. Not dissimilar to the way computer architects design their systems, nature also produces different solutions for the above layers, each of which introduces specific design trade-offs. The latter ultimately lead to different environmental fits and different strategic fits.

The above reasoning may be applied to natural systems too—an example of this may be found in the design of the human body. Such system is characterized by many highly sophisticated features; still, our sensory system is incomplete: for instance we cannot perceive sounds and light beyond certain thresholds. This is only natural, as assets and resources are usually streamlined towards the achievements of certain intended goals and not others through the processes of natural evolution—what is not essential in view of reaching the intended goals is little by little genetically discarded in favour of other, more relevant features. The ultimate result of this—at least in terms of the ability to perceive—is that throughout their evolutions systems will be characterized by different features or "capabilities" as a result of the design trade-offs mandated by natural evolution and physical limitations. An insightful treatise on this aspect may be found in [13]. Interestingly enough, Leibniz cleverly recognized these differences in perception qualities, which he identified in a system's "power of representation" (PoR). As mentioned above, any system—be it computer-based, biological, or societal—is characterized (and limited) by its perception layers and PoR. Those layers in a sense determine how much "open-world" a given system is.

It is worth remarking how the sensor and qualia layers do not imply awareness—let alone adaptability and resilience. They may be considered merely as a system's *communication and translation service* able to relay "raw facts" of the physical world to that system.

2.2. Perception Model

We now introduce our perception model. In what follows we shall call "context" the set of all the user-, system-, and environment-related figures that may change throughout an (adaptive) system's execution. We shall use symbol "C" to refer to the context. We shall call "perception spectrum" the subset of C our sensor and qualia layers allow us to become timely aware of.

In order to more formally define the perception spectrum we shall first define $\mathfrak{M}$ as a hypothetical perfect open-world system, that is a system characterized by a perfect sensory system and a perfect power of representation allowing that system to be timely aware of *any* physical change within or without its system boundaries. The term used by Leibniz for systems such as $\mathfrak{M}$ is *monad*[3], while Boulding in his classification makes use of the term *transcendental system* [5].

We shall model $\mathfrak{M}$ as function

$$\mathfrak{M} : C \rightarrow S,$$

in which S is some service specification, that is a set of "manifestations of external events perceived by the user as the behavior of the system" [15]. This said, then any real-life system f meant to fulfil the same specification set S may

[2] This concept was expressed in a remarkably clear way already by Dante in his *Divine Comedy*: "Apri la mente a quel ch'io ti paleso // e fermalvi entro; ché non fa scïenza, // sanza lo ritenere, avere inteso" ("Open your mind to what I shall reveal // To you, and keep it there, for to have heard // Without retention does not make for knowledge") [12].

[3] "A mirror of the entire universe, because it is in relation with all other monads, and to that extent reflects them all, so that an all-seeing eye looking at one monad could see reflected in it all the rest of creation" [14].

be modeled as a *domain restriction* of $\mathfrak{M}$ to some subset $\mathcal{PS} \subset C$, that is a partial function

$$\mathfrak{M}|_{\mathcal{PS}} : \mathcal{PS} \to S$$

such that the following relation holds for its graph:

$$G(\mathfrak{M}|_{\mathcal{PS}}) = \{(x, y) \in G(\mathfrak{M}) | x \in \mathcal{PS}\}.$$

A common way to refer to $\mathfrak{M}|_{\mathcal{PS}}$ is $\mathcal{PS} \triangleleft \mathfrak{M}$. The choice of $\mathcal{PS}$ represents a model of a system's available sensors for which persistent qualia can be timely and reliably reflected—namely a system's perception spectrum. Depending on how $\mathcal{PS}$ is defined, the corresponding system $f = \mathcal{PS} \triangleleft \mathfrak{M}$ will or will not be able to perceive, represent, and retain a certain context change. Lacking such ability that system will not be able to react—using a popular English vernacular, it will be a *sitting duck*—to that particular context change.

Please note how such definition of a perception spectrum is a simplified one, as it does not provide a clear and sound definition for attributes "persistent", "timely", and "reliably."

Set $\mathcal{PS}$ puts on the foreground what are the necessary prerequisites to triggering adaptation. Such prerequisites could be regarded as an "adaptation contract" to be confronted with an "environment policy"—in the sense discussed e.g. in [16]. Matching contract with policy in this case would mean to set up a handshaking mechanism between a system declaring its $\mathcal{PS}$ and an environment stating the expected $\mathcal{PS}$. One may visualize this by thinking of a man who arrives to a place where a sign says "minefield". The man knows his $\mathcal{PS}$ does not include mine detection capabilities, hence he walks away.

This relation provides us with a way to compare adaptive systems with one another: given any two adaptive systems a and b, respectively characterized by perception spectra $\mathcal{PS}_a$ and $\mathcal{PS}_b$, then we shall say that $a \prec_{\mathcal{P}} b$ if and only if $\mathcal{PS}_a \subset \mathcal{PS}_b$. In this case we shall say that b has *wider perception* with respect to a.

Clearly the just defined relation is of partial order. The wider the perception, the lesser will be the chances of perception and adaptation failure—the impossibility that is to perceive and react from a change. In what follows we briefly characterize these failures.

2.3. Perception and Adaptation Failures

As mentioned above, a perception system requires (at least) the three sub-services or layers we reviewed earlier. Accordingly, the triggering factors for perception failures (and hence for related adaptation failures) may be located in any of those three layers. In what follows we briefly illustrate this by means of several simple examples.

2.3.1. Sensor shortage and sensor faults

Sensor shortage and sensor faults are the first and simplest originators of perception and adaptation failures. In the first case raw facts go undetected while in the second one they result in "ghost events" or other erroneous perceptions. As an example of the first case we recall how the presence of dangerous amounts of damps in coal mines cannot be perceived by miners, which resulted in dreadful accidents that cost the lives of many a person [17]. In order to augment their perception spectrum miners used to bring along canaries or other animals whose perception spectrum allowed them to detect such a dangerous condition. Canaries were especially used due to their ability to detect small concentrations of gas and react instinctively [18]—which brought to the English expression "to be like a canary in a coal mine". As the miners were regularly monitoring the conditions of their captives the perception spectrum of the system $\vec{s} = \{\text{miner}, \text{canary}\}$ was indeed the union of the two involved spectra. The resulting augmented perception spectrum of $\vec{s}$ led to an enhancement of resilience. Similar mechanisms are still being adopted today—an example of which is the use of landmine detection rats [19].

Note how sensors may be "active" and thus require energy. In turn this may lead to sensor unavailability because of e.g. energy shortage.

A second reason of perception failures is sensor faults. This may be due e.g. to electro-magnetic interference or other disturbances introduced by harsh operational conditions, or for instance to design faults in the sampling algorithms [20]. Sensor fusion is one of the methods used to prevent perception failures due to sensor faults [21].

2.3.2. Qualia mapping faults

Qualia mapping faults (QMFs) are those that result from lack or shortcomings in the creation of a qualia corresponding to a sensed "raw fact". A well-known case in literature manifested itself during the maiden flight of the Ariane 5 rocket [10]. Such rocket was an evolution of a series 4. Both Ariane 4's and Ariane 5's sensor layers were able to report trustworthy values for several flight trajectory parameters. Such "raw facts" were then represented as qualia and used to react to trajectory changes. Unfortunately in both series the qualia for horizontal velocity were based on the same mechanism, which ultimately represented the sensed physical parameters as a 16-bit signed integer. The faster speed of the Ariane 5 with respect to its predecessor resulted in overflows. Even worse, those overflows went undetected because the Ariane 5 designers had considered the corresponding overflow checks as an unnecessary overhead. In fact, these faulty qualia produced false perceptions, which in turn triggered self-destruction as a means to guarantee environmental safety. Despite the availability of reliable sensor layers in both Ariane series, the qualia layer of model 5 (coupled with the characteristics of the mission) produced a QMF—which we called in [10] as a "Horning fault"—that ultimately translated into a perception failure.

2.3.3. Qualia persistence faults

Qualia persistence faults (QPFs) occur when a system fails to retrieve (and consequently make use of) qualia referring to current or past sensory data. Resource leakage and data corruption accrual [20] are two possible reasons for data integrity deterioration leading to QPFs. Electro-magnetic interference is a known cause for data integrity losses [10, 9]. Another case of QPFs occurs when the system first perceives a raw fact, then produces a corresponding qualia, and finally forgets about the originating fact. This may be due e.g. to a missing or erroneous qualia persistence layer. An example of this case may be found when analysing the causes behind the so-called Therac accidents.

The Therac-20 was a safety instrumented system in which unacceptable process conditions such as potentially dangerous service requests were caught and resulted in system shutdown. This safe behaviour was obtained by endowing the system with hardware interlocks. Thanks to its interlocks, the machine was able to perceive safety threats and react accordingly. The Therac-20 was actually the coupling of two sub-systems—the hardware interlock dealing with the fail-safe behaviour and the actual Therac-20 "functional sub-system". To represent this we shall say that

$$\vec{s_{20}} = \{s^i_{20}, s^f_{20}\}.$$

Note how the corresponding perception spectra satisfy in this case the relation

$$\mathcal{PS}_{20} = \mathcal{PS}^i_{20} \cup \mathcal{PS}^f_{20}.$$

Several instances of $\vec{s_{20}}$ were operated for some time in various locations. In a number of cases, the machines did make use of their interlock mechanism, s^i_{20}, which prevented several potentially lethal accidents. Regrettably enough, no mechanism to persist events such as this had been foreseen: its operation left no trace behind. This probably brought the makers of the $\vec{s_{20}}$ to questioning the need for an interlock in the first place. As a matter of fact their new model—the Therac-25—included no hardware interlock and reused (in software) most of the logic of their predecessor [22]; in other words, $\mathcal{PS}_{25} = \mathcal{PS}^f_{25} \simeq \mathcal{PS}^f_{20}$, hence $s_{25} \prec_{\mathcal{P}} \vec{s_{20}}$. Note how a qualia persistence fault in the $\vec{s_{20}}$ ultimately induced a sensor shortage fault for the s_{25}. The latter fault led to severe accidents causing injuries and life losses [22].

3. Apperception

Qualia provide the basic service on top of which a higher-level form of consciousness may emerge. This is called "access consciousness" (or A-consciousness) in [6]. A-consciousness may be defined as the ability to make use of qualia to operate control. A common way to refer to systems endorsed with such an ability is that they are *context* and/or *situation aware*.

Once a raw fact is reflected into a qualia, the awareness of qualia[4] may take different forms. Also in this case we may talk of some *power of representation*. Perfect apperception PoR may be considered as the A-consciousness

[4] We are in fact not "aware of the facts", but of their internal representations, the qualia!

Context agnostic	P-conscious, $\lvert\mathcal{PS}\rvert = 1$	P-conscious, $\lvert\mathcal{PS}\rvert > 1$	$\lvert\mathcal{PS}\rvert \gg 1$, A-conscious, Self-unaware	$\lvert\mathcal{PS}\rvert \gg 1$, Self-aware, Self-unconscious	$\lvert\mathcal{PS}\rvert \gg 1$ Self-aware Self-conscious	All-aware, All-conscious
$[s_0]$=[Framework] =[Clockwork]	$[s_1]$= [Thermostat]	$[s_2]$=[Cell]	$[s_3]$=[Plant]	$[s_4]$=[Animal]	$[s_5]$= [Human being]	$[s_6]$= [Super human]

Table 1. Seven disjoint subsets derived from Boulding's classification (classes 1–7 and 9) [5]. These subsets may be considered as degrees of increasing apperception. Class $[s_6]$ refers to hypothetical systems of even greater apperception than human beings'—whose existence Boulding did not exclude.

equivalent of function $\mathfrak{M}$ defined in Sect. 2.2—an all-aware open-system able to "mirror all things clearly and adequately" [14]. Real-life systems are in general endowed with much less sophisticated apperception PoR; for instance Leibniz refers to human beings as entities able to represent "consciously *but not with perfect clearness*"—as we are constantly reminded [23, 24]. Leibniz also suggests that the qualia corresponding to a system's perception and apperception should be considered as partitioned into a region of *clear representation* and a region of *obscure representation*. Apperception corresponds to the former region and is interpreted as the ability to associate incoming qualia to past perceptions as well as to hypotheses and models produced in past associations [8]. Lycan suggests in [7] that there might be at least 8 (perception and apperception) PoR classes.

According to Herbart [25], qualia accrue into a so-called "apperception mass"—one may think of this as a knowledge base. Depending on the amount of registered qualia and the apperception ability of the system that experienced them, this may trigger the production of new qualia—qualia representing not raw facts but rather "ideas": concepts, hypotheses, theories, and models regarding the current physical condition[5].

Classes corresponding to different apperception may be used as a second criterion, albeit in this case merely qualitative, to compare adaptive systems with one another. This approach was used already by Boulding in his well-known work on General Systems Theory [5], in which essentially he categorizes systems according to their P- and A-consciousness. Table 1 proposes a variant to Boulding's classification based on 8 of his categories.

3.1. Formal Model

We now introduce our apperception model. Lacking objective, quantitative means to refer to a system's apperception, in what follows we shall rank systems by qualitatively assessing their features and accordingly assigning them to either of the subsets $[s_0], \ldots, [s_6]$ defined in Table 1. Symbol $[s_\star]$ will be used to represent set $\{[s_0], [s_1], [s_2], [s_3], [s_4], [s_5], [s_6]\}$.

To express this partitioning and ranking we shall say that

$$\mathcal{S} = \bigcup_{[s_i]\in[s_\star]} [s_i].$$

Moreover we shall assume all subsets to be non-empty: $\forall B \in [s_\star] : B \neq \emptyset$ and all our assignations to be mutually exclusive: $\forall s \in \mathcal{S} : \exists! B \in [s_\star] : s \in B$.

Given the above hypotheses, $[s_\star]$ represents a partition of $\mathcal{S}$ and each block in $[s_\star]$ represents an equivalence class. The symbol we shall use for the corresponding equivalence relation is "$\equiv_{\mathcal{B}}$". We shall call this relation "Boulding equivalence". All systems belonging to the same subset $B \in [s_\star]$ will be considered as sharing the same property—that is, of being mutually Boulding-equivalent:

$$\forall [s_i] \in [s_\star], \forall (p, q) \in [s_i] \times [s_i] : p \equiv_{\mathcal{B}} q.$$

Note also how, by the above definitions, $[s_\star]$ may be also regarded as quotient set $\mathcal{S}/{\equiv_{\mathcal{B}}}$.

Ranking is obtained as follows: by construction we define a total order among the equivalence classes in $[s_\star]$, $\prec_{\mathcal{A}}$, such that

$$\forall 0 \leq i < j \leq 6 : [s_i] \prec_{\mathcal{A}} [s_j].$$

[5]As Plato's Cave reminds us, whatever a system's level of the apperception the absence of trustworthy facts inhibits the production of "clear representations"—that is, of meaningful ideas.

Such total order among classes induces a partial order among the elements of $\mathcal{S}$:

$$\forall (p,q) \in \mathcal{S} \times \mathcal{S} : p \prec_{\mathcal{A}} q \quad \text{iff} \quad \pi(p) \prec_{\mathcal{A}} \pi(q),$$

in which π is the projection map of relation $\equiv_{\mathcal{B}}$, namely function

$$\pi : \mathcal{S} \rightarrow \mathcal{S}/\equiv_{\mathcal{B}} \quad \text{such that} \quad \forall s \in \mathcal{S} : \pi(s) = [s].$$

Rankings such as the just defined one provide us with a second "coordinate" to compare adaptive systems with one another: given any two adaptive systems a and b, if $a \prec_{\mathcal{A}} b$ then we shall say that b is endowed with greater apperception than a. Note how relation $\equiv_{\mathcal{B}}$ provides us with but one possible classification of systems according to their (subjectively perceived) apperception.

3.2. Apperception Failures

As we did in Sect. 2.3 for perception here we focus our attention on an adaptive system's apperception failures. We distinguish two cases of apperception failures:

Design-time apperception failures, namely those due to mistakenly designing a system with insufficient or over-abundant context-awareness with respect to the one called for by the current environmental conditions. Boulding failure is the term introduced in [10] to refer to such case. An example of this type of failures can be found again in the Therac machines, in that they were lacking introspection mechanisms (for instance, self-tests) able to verify whether the target platform did include the expected mechanisms and behaviors.

Run-time apperception failures, which are the result of erroneous analyses of the current environmental conditions leading the system to adapt in the wrong direction. Speculation failures regarding e.g. the expected future workload in a distributed environment [26] may lead to such failures. This class of failures also includes the lack of the ability to perceive past failures and to learn from them, as it is the case for adaptive systems in perpetual oscillation due to e.g. unforeseen stigmergy.

4. Future Work and Conclusions

An adaptive system may be under- or over-dimensioned with respect to the current design goals and the current environmental conditions. This quality is changing with adaptations, which dynamically move a system in the adaptation spectrum. Such adaptations may occur at design time or at run-time, and may be carried out by entities within or without the system. In the first case the system is said to be capable of autonomous adaptation. Whatever the case, adaptations will apply certain modifications to a system's structure and functions. Such modifications may range from simple parametric adjustments to structural changes, and they may evolve a system up or down the perception and apperception categories—for instance, they may deprive a system of a sensory capability or they may augment it with advanced apperception capabilities. In practice, system adaptation may be considered as the application of a (potentially infinite) sequence of system structures $(s_1, s_2, \ldots)$ such that for any index $v > 0$, s_{v+1} is obtained from s_v at a given time t_{v+1}, with t_v occurring before t_{v+1}, that is $t_v < t_{v+1}$. Such structures may be interpreted as software versions if the modifications are carried out at design time.

The partial orders among ESS that were presented in Sect. 2 and Sect. 3 possibly coupled with other considerations pertaining e.g. costs and energy expenditure provide us with preliminary selection criteria for a "best" system structure matching the current situations and scenarios in ubiquitous and pervasive environments. Such selection may take place through an explicit handshaking mechanism between an ESS declaring its current capabilities and an environment stating certain expected features. This may take the form of an "adaptation contract" to be matched with some "environment policy"—as discussed e.g. in [16]. Another possibility would be that the ESS makes use of its current apperception capabilities and its current perception spectrum in order to choose a new structure on its own. Obviously in this case effectiveness would be limited by the available PoR.

As mentioned above, perception and apperception put on the foreground the necessary prerequisites to triggering adaptation in environments characterized by rapid and sudden changes. Clearly these are far from being the *only* such prerequisites. Our current work is aimed at extending our models so as to include the higher-level functions of ESS.

In particular we are defining a semi-formal model for the evolution engine of ESS. Such model will include aspects as diverse as the structure, the complexity, and the *multiplicity* of the evolution engine, the latter being defined as the number of independent "agents" concurrently defining the evolution strategies. Preliminary results on this front are available in [27]. Other work will be devoted to the study of ubiquitous and pervasive social organizations [28]—namely software eco-systems evolving in those environments and corresponding to the eighth level in Boulding's classification [5].

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