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On Context and the Open World Assumption

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***Abstract*—Context-aware systems have historically employed a limited range of available data and while research across a diverse range of domains is addressing an increasingly broad range of data the level of intelligence generated in context-aware systems remains generally very limited. This is arguably due to the highly dynamic nature and inherent complexity of context. Individuals view the world though a unique perceptual filter developed over time; such a filter develops and changes based on an individuals experience of the environment in which they exist and contacts made in the course of social interactions. An individual's reaction to stimuli is driven by their view of the world and an important reactive component is emotion (more accurately emotional response). This paper considers context and the 'next-generation' intelligent context-aware systems incorporating decision-support with emotional response. Traditional approaches to knowledge have adopted the closed world assumption however we argue that adoption of an open world assumption offers exciting potential for improving the levels of intelligence in context-aware systems. The challenges in adopting the open world assumption are discussed with potential solutions and future directions for research. There are exciting opportunities for achieving improved levels of personalisation in context-aware systems if context processing predicated on the Open World Assumption can be realised.**

Keywords*—*Personalisation, Context, Intelligent Context-Aware Systems, Emotional Response, Open World Assumption vs Closed World Assumption

I. Introduction

Mark Weiser, in a seminal paper entitled 'The computer for the 21st century' [1] postulated that: "the most profound technologies are those that disappear, they weave themselves into the fabric of everyday life until they are indistinguishable from it". These observations are the basis upon which pervasive / ubiquitous computer systems are predicated and the concept of context (in computational terms) arguably grew out of concept of pervasive computing. An alternative term for pervasive computing often used in Europe is ambient intelligence and Ramos *et al* [2] have argued that ambient intelligence is the next step for artificial intelligence.

The history of context-aware systems can be traced back to research by in the early 1990's which resulted in the introduction of the Active Badge system [3] which is considered to be one of the first true context-aware applications. The Active Badge system is essentially a location-based system and the focus on location is mirrored in subsequent research by Abowd *et al* [4], Sumi *et al* [5], Cheverst *et al* [6], and Ryan *et al* [7], where context-aware systems are essentially location-based.

In the literature the term 'context-aware' first appeared in research by Schilit *et al* in [8] where context is defined as: "location, identities of nearby people, objects and changes to those objects" [9]. While location has historically been the predominant attribute in context-aware systems [arguably due to the inherent diversity and complexity of context and the difficulty in defining it] research is addressing an increasingly diverse range of attributes.

Possibly the most frequently cited and comprehensive definition of context is by Abowd *et al* [10] who define context as: any information that can be used to characterize the situation of entities (i.e., whether a person, place or object that is considered relevant to the interaction between a user and an application, including the user and the application themselves). This definition of an entity may be extended to include additional concepts including a: person, place, or things (physical or computational objects) [11]. Each entity can be described using attributes (context properties and their Literal Values). The context properties can be classified into four categories: identity, location, status (or activity), and temporal attributes. For a discussion on contextual information see Section III.

Arguably the first reference to emotion can be found in a paper by Abowd entitled: "*Towards a better understanding of context and context-awareness*" *et al* [10] where the context definition includes: "the user's emotional state, focus of attention, location and orientation, date and time, as well as objects and people in the user's environment". Alternative definitions of context have been proposed by Hull *et al* [12] and Brown [13]. Hull *et al* introduce the concept of synonyms to describe a context as the: "aspects of the current situation" while Brown considers context to be the: "elements of the user's environment which the computer knows about". The use of synonyms as discussed by Hull *et al* in [12] has a synergy with the concept of linguistics as espoused in *Kansei* words; for a discussion on the topic see see [14].

Personalisation with targeted service provision [11] is a primary motivator for context-aware systems and emotion (more accurately stated as emotional response) is an important component in describing individuals. Incorporating the concept of emotion is not new however the results obtained to date are limited. This paper considers the challenge of incorporating emotional response in the 'next-generation' intelligent context-aware systems. The restrictions inherent in the *Closed World Assumption* (CWA) arguably limits the ability to realise the overall aim of incorporating emotional response and we argue

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that context processing with the *Open World Assumption* (OWA) has the potential to address the challenges identified and realise improved personalisation with targeted service provision.

The remainder of this paper is structured as follows: the CWA *vs* the OWA is discussed in Section II with an consideration of circumscription in Section II-B. Contextual information is discussed in Section III followed by consideration of computational intelligence in Section IV. Section V considers data processing. An illustrative scenario is presented in Section V-A followed by a discussion in Section VI. The paper closes with conclusions and observations and directions for future work presented in Section VII.

II. CWA *vs* OWA

The CWA, or *Closed World Reasoning* (CWR), is a non-monotonic approach which is predicated on the principle of negation by failure [15][16], i.e., what is not known to be true is false. The OWA however adopts an alternative view which is predicated on the Boolean truth value of a statement or hypothesis which is independent of whether or not it is known to be definitively true (i.e., the result may be for example: unknown as opposed to incorrect or false. A logical formalization of this assumption by Reiter [17] also makes reference to the term CWA. A successful formalization of natural language semantics cannot generally avoid identifying if the logical background(s) are predicated on the CWA or OWA.

A. The Closed World Assumption

In formal logic formalization of the CWA consists of adding to the knowledge base the negation of the literals that are not currently entailed in it. The result of this addition is always consistent if the knowledge base is in Horn form but is not guaranteed to be consistent otherwise [18]. Alternative formalizations which avoid this problem have been proposed; e.g., consider a propositional logic knowledge database: in such a case the formalization of the CWA is based on adding to database the negation of the formulae that are *free-for-negation* (i.e., the formulae that can be assumed to be false [19].

The literature addressing the CWA contains a number of approaches to CWR ranging from the CWA (introduced in the context of databases) to the Extended Closed World Assumption (ECWA) [20] [19] which is equivalent to circumscription [16]. It has been observed in [16] that: the CWR is a common *nonmonotonic* approach for dealing with negative information in knowledge and databases.

The CWA is frequently cited in relation to database systems such as Relational Database Management Systems (RDMS) which generally incorporate the Atomicity, Consistency, Isolation, and Durability (ACID) transaction model [21][22]. RDMS represent structured data however there are important developments in which unstructured data (generally classified under the term 'NoSQL') [22] which is characterised by horizontal and vertical scaling. A discussion on the topic is beyond the scope of this paper however an exposition on the topic can be found in [22]; data processing is addressed in Section V.

The CWA is predicated on the principle of '*negation-as-failure*'. Minker [23] Lifschitz [24] and Wagner [25] have considered the representation of explicit negative information. A detailed discussion is beyond the scope of this paper however in summary a database does not (generally) provide a basis for representing explicit negative information. It has however been known for many years that from '*partial*' and '*constructive*' logic a computationally feasible means to represent and process explicit negative information can be realised. It has been argued [25] that it is desirable to retain the usual form of negation in databases (*negation-as-failure* - also termed *weak negation*). Wagner shows how the interaction between strong and weak negation can be modelled within the framework of partial logic. Lifschitz compares two forms of *non-monotonic* reasoning: (1) *Closed-World Evaluation* (CWE) [for database queries] and (2) *circumscription* [for a discussion on Circumscription see Section II-B] and argues that if consistent the CWA is equivalent to "circumscribing all predicates in the database".

Shepherdson in [15] considers'*negation by failure*' in the CWA and draws a comparison between Clark's 'completed database' [26] and the logical formalization of the CWA by Reiter [17]. Clarke shows that: "*a query evaluation procedure for data base deductions using a negation-as-failure inference rule can be regarded as making deductions from the Completed Database (CDB) obtained by replacing the hIFi clauses* [in a data base] by $\langle IFF \rangle$ clauses".

Shepherdson in argues that such clauses can be "regarded as deductions from the CWA of Reiter". Generally the CDB and the CWA are "incomplete" and deductions may differ in that one may be consistent and the other inconsistent [15]; in cases where both are "separately consistent" they may be incompatible. When a database is Horn consistent and definitive the CDB and CWA are compatible; additionally, when Clark's query evaluation procedure is complete for ground literals they are essentially equivalent [15]. However, When the query evaluation procedure is not complete it may lack some basic closure properties. The conditions given by Clark for the completeness of his query evaluation procedure are generally "not quite sufficient and may be viewed as restrictive"; this observation has relevance with respect to the OWA.

B. Circumscription

Humans and intelligent computer programs reach conclusions based on sparse data [27] and infer that objects have specific properties or relationships [28]. Circumscription [28] formalizes human informal reasoning; e.g., "common sense reasoning" merely reaches conclusions and conveys no information, it merely asserts the suitability of an object for its intended purpose unless there is a tautologous disjunction.

Heuristically, conclusions are confirmation of the suitability of objects for a specific purpose, not merely a suggestion for it's use [28]. The ECWA and the formalism of circumscription coincide on propositional theories [29] with circumscription addressing some limitations in the CWA and pointing to the use of the OWA in intelligent context-aware decision-support system [29].

C. The Open World Assumption

In formal logic, the OWA is predicated on the assumption that the 'truth value' of a statement or hypothesis is independent of whether or not it is known to be true by any single observer or agent. The OWA is the opposite of the CWA and may be viewed in terms of monotonic techniques in many logic systems with entailment applied where statements and hypotheses for any derived fact may be freely extended with additional assumptions (often fact or rule based). In sequent calculi [30][31] [or Sequent calculus which is essentially an approach where where every line of a proof is a conditional tautology and not an unconditional tautology] this property can be captured by an inference rule called "weakening or thinning"; in such systems entailment is monotone $\langle IFF \rangle$ a rule is admissible. Logical systems with this property are occasionally called 'monotonic logics' in order to differentiate them from '*non-monotonic logics*'.

The OWA applies when available knowledge is represented in a system as it is discovered. An important facet of the OWA is that it cannot be guaranteed that all the relevant information has, or indeed ever will, be discovered. In the OWA, statements about knowledge that are not included in, or inferred from, the knowledge explicitly recorded in the system may be considered 'unknown' as opposed to '*incorrect* or '*false*'.

Semantic Web languages such as OWL are based on the OWA. However, the absence of a specific statement means, in principle, that the statement has not (yet) been explicitly made, irrespective of whether it would be true / false or the the *believed truth value*. In essence, from the absence of a statement alone, a deductive reasoner cannot (and indeed must not) infer the statement to be false. Under the OWA failure to derive a fact does not imply '*truth*'; e.g., consider the following example where the limit of the knowledge defined within a system is limited to an assertion that John is a UK citizen: (1) *statement*: John is a UK citizen, (2) *question*: is Peter a UK citizen?, (3) answer based on the CWA: = *No*, (4) *answer* based on the OWA: = *Unknown*. From the available information we can neither conclude that Peter is, or alternatively is not, a UK citizen. Therefore, it is clear that our knowledge of the world is incomplete.

The OWA is closely related to the monotonic nature of first order logic: adding new information never falsifies a previous conclusion; i.e., if we subsequently identify Peter as a UK citizen earlier positive or negative conclusions are retained.

D. Conclusion

The CWA and OWA has been considered with the limitations in the CWA. Many applications and systems are based on the CWA and typical applications [of the CWA] have complete control over information. Such applications include database systems in which the database transaction system acts as a central broker and arbiter of concurrent requests by multiple independent clients (e.g., on-line airline booking system). There are, however, many databases with incomplete information which may include 'NoSQL' systems which function on with a weaker concurrency model model predicated on a Basically Available, Soft State, Eventually consistent (BASE) model as opposed to the ACID transaction model [22]. The BASE approach is predicated on the assumption that updates are eventually propagated, but there are limited guarantees on the consistency of reads. In this model data returned in a search is not guaranteed to be up-to-date; however, updates are guaranteed to be propagated to all nodes eventually.

The predominant approach in knowledge-based systems has traditionally been the CWA however, as we have observed, humans view the world though a unique perceptual filter developed over time. Such a filter develops and changes over time based on an individuals experience of the environment in which they exist and contacts made in the course of social interactions. Additionally humans respond to stimuli, reach conclusions, and make judgements based on sparse data. While the CWA operates on *negation by failure* the OWA utilises all available knowledge as we discover it, a position analogous to human experience. Heuristically, as we have observed, an important facet of the OWA is that it cannot be guaranteed that all the relevant information has, or will, be discovered; analogies can be drawn with the BASE approach in 'NoSQL' systems.

Based on this discussion it is proposed that if emotional response is to be incorporated in intelligent context-aware systems the CWA represents a major restriction and to achieve the stated goal the OWA is required. In subsequent sections the nature of contextual information is discussed as it relates to the 'next generation' intelligent context-aware systems with consideration of potential solutions to the challenge of incorporating emotional response in intelligent context-aware systems discussed.

III. Context and Contextual Information

Context-aware systems have been developed in recent years to improve user interaction and personalised service provision in highly dynamic environments; such environments are characterized by uncertainty and adaptable contextual situations [32]. A context is fundamental in personalising services as it describes and defines an individual's current prevailing state and as such it is inherently complex and domain specific [32].

Contextual information [captured context data processed into information useful in Context Processing (CP)] is central in context-aware applications and systems. In the modelling of context (for a discussion on context modelling see [33]) the requirements for dynamic environments include: scalability, technologies, mobility, tolerance, robust systems, security, constraint satisfaction and preference compliance (CS), and decision-support (DS). A context definition is created using contextual information to describe an individual or entity; therefore a broad range of contextual information is used in the creation of a context definition. In actuality, almost any information available at the time of an individual's interaction with a context-aware system can be viewed as contextual.

When dealing with context entities include: (1) *places*, (2) *people*, and (3) *things* (physical or computational objects). As identified in [34] typical concrete examples of entities may include: places (rooms, buildings etc.), people (individuals, groups) and things (physical objects, computer components etc). Each entity can be described using attributes (context properties and their *Literal Values*). The context properties may be classified into four general categories: *identity*, *location*, *status* or *activity*, and *temporal* attributes.

For a detailed discussion on contextual information see [11][27][32]. Typical examples of contextual information when viewed from the perspective of emotional response are: (1) the *physical* and *social* situation, (2) *spatio-temporal* data, (3) *physiological* information, and (4) *cognitive* and *abstract* information. Cognitive and abstract information may include: e.g., emotional responses, intuition, feelings, and sensibilities expressed in terms of linguistic and semantic terminologies.

The range of potential contextual information identified demonstrates the inherent complexity of context and its domain specific nature. While the list includes cognitive properties, research is generally restricted to EEG and Cognitive Behavioural Therapies (CBT) however research [35][36] is extending the range of information used and the domain(s) addressed.

IV. Computational Intelligence

Computational intelligence may be viewed from a number of perspectives however in this paper we consider it as it applies in intelligent context-aware systems. The focus in this paper lies in the ability of computer systems to model the human intelligence and h/her ability to infer conclusions based on the available (and generally sparse) data.

A goal of computer science dating from the dawn of computing to the present day is to imbue intelligence into computers. Friedberg [37] and Friedberg *et al* [38] were early pioneers in the search for machine intelligence with research dating from the late 1950's. In further early research in the early 1960's Bremermann [39] considered problem solving, theorem proving, and pattern recognition. Bremermann observed that: "these problems are tough" and concluded: "we must look for quality, for refinements, for tricks, for every ingenuity that we can think of". While the results reported by Friedberg and Bremermann were limited their analysis and vision is not as their research represents pioneering work in machine learning [40].

The characteristic of "intelligence" is generally attributed to humans [41] however, recently there have been many claims relating to intelligent artefacts. Intelligence is directly linked to the reasoning and decision making which is fundamental for context and context-aware systems. Wang [42] has investigated intelligence and observes: "human enquiry of both natural and artificial intelligence at the reductive embodying levels of neural, cognitive, functional, and logical from the bottom up". Wang presents an analysis of the 'roles' of information in the evolution of human intelligence along with the need for logical abstraction in modelling the brain and natural intelligence.

There is a synergy between the analysis and vision as set out by Friedberg et al and Bremermann taken with the observations of Wang in that they all consider intelligence from a computational perspective. However, the vision espoused by Friedberg and Bremermann as yet remains unfulfilled [40] and the investigations reported by Wang support this conclusion. In this paper we postulate that imbuing computer systems with 'intelligence' requires the adoption of the OWA.

V. Data Processing

The processing of contextual information is central to achieving effective CP as discussed in [11][32][14] where the Context Processing Algorithm (CPA) is presented. A detailed description of the CPA is beyond the scope of this paper however in summary: the CPA is a rule-based method incorporating the principles of fuzzy set theory with defuzzification.

The CPA can achieve both quantitative and semantic representations of results derived from Context Matching (CM) to identify qualitative outcomes. In operation defuzzification employs decision boundaries (thresholds) and has the capability to implement multiple decision thresholds as discussed in [11][32][14]. The CPA rules use a logic structure predicated on 3 elements: (1) *event* (2) *condition* (3) *action*.

$$\{ON\ \langle event \rangle\ IF\ \langle condition \rangle\ THEN\ \langle action \rangle\}$$

An $\langle event \rangle$: relates to an input which can be either: (1) the $\langle event \rangle$ or the $\langle contextdata \rangle$, or (2) the output resulting from the firing of a rule [which triggers a subsequent rule]. A $\langle condition \rangle$: (a rule antecedent/body) relates to the evaluation of the context properties in which comparisons are drawn between the input property(s) and the output context properties [a potential solution properties and related property values derived from the data structure]. An $\langle action \rangle$: is the result derived from the processing of the rule condition(s). A Boolean decision based on context matching arrived at using context processing. Human inference arguably uses the same basic logical approach to reach decisions; i.e., in response to a stimuli such as an $\langle event \rangle$ or $\langle action \rangle$ humans evaluate the $\langle condition \rangle$ and reach a conclusion in response to the stimuli such as an $\langle action \rangle$ to be executed.

A. OWA vs CWA Scenario

Consider the following relatively trivial but 'real-world' illustrative scenario in which a human emotional response is identified in an intelligent context-aware DS system. Such a system may use an individuals expressed preferences and constraints along with physiological, spatio-temporal, social, and cognitive contextual data collected using with a range of non-invasive sensors and data processing achieved as discussed in this paper and in[32][14].

In this scenario consider a female named 'Jane' who is age 20 and whose context contains personal preferences which include facts that identify her as a vegetarian and a strong supporter of animal rights organisations. Now further consider a situation in which 'Jane' is in a city at midday on a Saturday with friends and the stimuli is an approach as part of a marketing campaign by a major burger chain with a special offer for a burger meal. Given her context definition and preferences, when approached, her emotional response in response to the stimuli (the marketing campaign) is very negative and possibly aggressive given her dietary preferences and attitude to animal rights.

An analysis of the emotional response when viewed from the perspective of the CWA results in a Boolean decision related to the potential response to the marketing campaign, i.e., *true* (yes) or *false* (no). However when viewed from the perspective of the OWA results would be either *true* (yes), *false* (no), or importantly *unknown*. The degrees of *truth*, *falsity*, or *unknown* may be measured in terms of confidence levels. The CPA, in achieving quantitative and semantic (linguistic) representations of results derived from context matching to identify qualitative outcomes as discussed in [11][27][32][14] and in this paper, has the capability to achieve both the nature (truth, falsity, and unknown) of the result with the granularity (confidence levels) for the result.

In practical usage the contextual information and the resulting decision(s) may provide the basis upon which targeted marketing strategies can be developed and deployed with benefits for both the marketing company (who can avoid wasted effort and costs) and potential recipients of the targeted marketing who, in response may: appreciate and accept, be opposed to and reject, or be completely antipathetic to the offer.

VI. Discusion

As discussed in Section IV the 'intelligent computer' can be traced back to the 1950's and notwithstanding the contributions made by countless research studies the stated aims as articulated by Friedberg [37], Friedberg *et al* [38], and Bremermann [39] remain largely unrealised to the present day. In proposing the incorporation of the OWA in context-aware systems it must be realised that in attempting to model human instinctive and emotional reactions it is unrealistic to claim that levels of human inference and reasoning will ever be realised in the foreseeable future, however, in using the OWA we may begin to address the current limitations in respect of intelligence in computer systems.

This paper has considered improvements in computational intelligence with a focus on context-aware systems where emotional response forms an important, and largely unrealised, component. The CPA has been introduced and the rule-based approach employing fuzzy set theory is proposed a basis upon which intelligent context processing can be achieved in a broad range of domains, systems, and technologies. A number of approaches to enable improvements in the processing of data (contextual information) have been considered by Moore and Pham in [11][27][32][14]. The modelling of emotive responses and affective states has been addressed in [27][43] where the methods employed to model emotive responses and affective states in context-aware systems include Ontology Based Context Modelling (OBCM) [33] with Semantic Valence Modelling as discussed in [44][27]. The processing of data in has been discussed in [11][32][14][44]; semantic processing of contextual information using *Kansei* engineering and Hedge algebras has been discussed in [14].

Human responses may not be described in quantitative terms and effective identification of human emotions requires semantic (linguistic) descriptors with a qualitative element. Linguistic information involved in multi-criteria decision problems with a logic-based approximate reasoning method has been developed in [45] to provide decision-support based on information provided. For human beings, language serves as a fundamental basis for cognition in the decision making process; this process can be viewed as a consecutive series of sub-decisions resulting in a Boolean decision. The nature of a decision-making is to identify and select the optimal decision (predicated on an individuals perceptual filter) from a range of appropriate alternative options. As a consequence, in natural languages, human reasoning should incorporate linguistic (semantic) elements [words, phrases, adjective,.etc] to describe alternatives based on a comparison between their properties [46].

Experimental testing [39] has shown how hedge algebras with *Kansei* evaluation can potentially model semantic representations for decision-support in uncertain environments. In summary, the principal advantages to be gained from the use of the approach presented in [14] include: (1) input: context properties model multiple attributes, (2) output: context properties represent alternatives by human feelings and sensibilities with his/her preferences, (3) qualitative factors: support relating to a decisions, sensibilities and preferences are quantified using hedge algebras and *Kansei* evaluation, and (4) In arriving at decisions: decisions can relate to appropriate alternatives based on reasoning in decision-support.

The scenario presented in Section V-A has given an illustration of the results (conclusions) from an intelligent context-aware decision-support system predicated on both the CWA and OWA in respect to emotional response to a specific stimuli humans' may exhibit. It must be emphasised that the prospect of realising computational intelligence that mirrors human inference is remote in the foreseeable future however we consider that the approach presented in this paper and in [14] hold the potential to achieve intelligent context-awareness at a primitive level as compared to human inference capabilities.

VII. Conclusion

This paper has considered the challenge of incorporating emotive response into context-aware systems with the potential to improve the levels of computational intelligence in context-aware systems. An approach has been presented [39] which has been designed to enable CP with CM and the processing of linguistic variables in DS systems incorporating the capability to effectively target service provision while retaining the ability to achieve CS (or at least mitigate violations of CS). The CPA with hedge algebras integrated with *Kansei* evaluation as discussed in [39] is proposed as an approach having the potential to enable the OWA to be implemented in intelligent context-aware systems. However, there are a number of open research questions relating to the optimal approach to: (1) data description, (2) data structures including OBCM, and (3) identifying the optimal approach to implement semantics and linguistics in context-aware systems.

We argue that the realisation of intelligent context-aware systems incorporating emotional response, albeit with limitations as discussed in Section IV, may be achieved in 'real-world' decision-support systems. To achieving this goal the open research questions, which we view as difficult challenges and non-trivial problems, must be addressed and this forms an on-going research direction and a basis for future work.

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