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Smart environment interaction: A user assessment of embedded agents

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Abstract. Agent-based systems have long been recognized as a candidate technology for delivering autonomous and autonomic behaviors; however it is only recently that their usage has been explored in a new, emerging generation of systems that involve embedding agents on computationally challenged devices. The prudent harnessing of such agents can offer software engineers additional tools in their efforts to construct and deploy innovative mobile services or to realize practical smart environments. However, documented results of comprehensive evaluations of mobile services conducted in real world environments are rare; evaluations of systems that harness the agent paradigm are almost non-existent. This paper seeks to remedy this deficiency. It is hoped that the results of this study will encourage researchers to reflect further on the potential and implications of harnessing the intelligent agent paradigm in the broad Ambient Intelligence domain, from a software engineering perspective, and as an enabler of intelligent interaction.

Keywords: Usability, embedded agents, ambient intelligence, mobile computing

1. Introduction

From an end-user perspective, mobile computing represents perhaps the dominant computer usage paradigm; this is manifested in the popular take-up of mobile communication devices over the last few decades. Successive generations of these devices bring increasing power and sophistication, resulting in powerful and robust platforms for third-part applications and services. This paradigm shift has had many ramifications. One of these is that the mobile phone has become a viable platform for Multi-Agent Systems, both as independent agent ecosystems resident on the individual devices, or as constituents of a broader agent community.

In recent years, the viability of embedding agents on a range of mobile and resource-bounded devices has been demonstrated [6,10,14,44]. The availability of a ubiquitous data communications infrastructure enables agents to communicate with other agents on networked servers, or on other mobile devices. The result of this development is that software engineers can model their applications as Multi-agent System frameworks, encompassing static and mobile computational components, and can harness the various attributes of agents in the delivery of services to mobile users. Though the viability of the embedded agent paradigm has been demonstrated in the literature, there is a noticeable deficit in the number of systems that have reported evaluations on applications that incorporate an embedded agent approach. This paper seeks to remedy this deficiency and is novel in its presentation of a pioneering, systematic user evaluation of two similar classes of embedded agent system.

Many systems focusing on the mobile tourist domain have been described in the literature – see for example [19,31,32,36,43,49,50,53]. For the purposes of this discussion, two agent-based applications –

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CRUMPET and Gulliver's Genie have been systematically evaluated from a usability perspective using an identical instrument. This facilitates a broad comparison of both systems from a usability perspective, and a subsequent reflection on the applicability of the agent paradigm in embedded and mobile scenarios. A common application domain and shared embedded agent paradigm suggested the validity and desirability of this study. Moreover, the transparent yet systematic nature of the usability analysis undertaken by CRUMPET enabled this process to be duplicated in the case of the Genie.

An outline of this paper is as follows: Section 2 presents a brief overview of developments in embedded agents' technologies. An overview of the respective architectures of CRUMPET and Genie is given in Section 3. Section 4 describes in detail the methodologies used for the user evaluations after which an analysis of the results is presented in Section 5. Section 6 details a comparative analysis, after which some guidelines for harnessing embedded agents in mobile applications are presented in Section 7.

2. Background

Significant research effort has been expended in the broad mobile computing domain, including technologies pertinent to the discussion presented here. Location-based Services (LBS) [26], mobile guides [20] and mobile indoor navigation systems [16] have been the subject of intense research effort. In the case of embedded agents for resource constrained devices, a number of agent platforms have been developed. The motivations behind the developments of each differ, as does their support for agent attributes. CougaarME [52], SAGE-Lite [21], KSACi [3], Agilla [11], Mobile-C [7] and MAPS [2] are just some examples. However, other platforms are extensions of established agent platforms. These include LEAP [1], an extension of JADE [5], 3APL-M [25], an extension of 3APL [15], MicroFIPA-OS [51], an extension of FIPA-OS [40] and Agent Factory Micro Edition (AFME) [29], an extension of Agent Factory [8]. In the case of Android, a number of agent frameworks have been implemented for this platform, for example, JaCa-Android [45] and Micro-agents on Android (MOA) [12]. An increasing number of platforms thus exist for those wishing to consider an embedded agents solution.

While significant effort has been expended in developing agent platforms for resource-constrained devices, documented prototypes that harness these platforms are infrequently described in the literature, and, to the best of the authors' knowledge, there has been no systematic usability analysis carried out on applications and services that specifically incorporate an embedded agent paradigm, outside of those that will be described shortly. In 2003, it was reported that of 102 papers in the area of mobile Human Computer Interaction, 61% reported on the building of actual systems [24]. Of these, 41% involved evaluation of which 71% was done through laboratory experiments, 19% through field experiment and 10% through surveys. This is testimony to the difficult and time-consuming nature of evaluating mobile applications in realistic environments. Nevertheless, there has been a growing awareness of the importance of mobile HCI [27]. A critical difficulty encountered is that while traditional Human Computer Interaction (HCI) is associated with static usage contexts and has reached a high degree of maturity, mobile HCI is younger discipline, and the inherent dynamic contexts raise particular challenges [18]. For example, a study undertaken in 2007 [4] concludes that dramatic changes in behavior can result from varying common contextual cues. More research is needed in this area. In the meantime, the approach adopted in this paper has been to evaluate CRUMPET and Gulliver's Genie in realistic physical environments that enables an authentic replication of the tourist experience.

A number of observations may be made. Firstly, many of these prototypes have been demonstrated under laboratory conditions, and not in the actual physical environment for which they are designed. Secondly, there is a notable paucity of documented user evaluations. A significant factor contributing to this situation concerns the lack of computational resources that characterize the average mobile device. Matching user expectations within these constraints is a formidable challenge, and one which the current generation of devices and wireless networks is only starting to address. However, given the importance of usability issues, the lack of documented user trials nonetheless remains surprising.

3. Architecture

CRUMPET [41] and Gulliver's Genie [34] subscribe to the intelligent agent paradigm. Detailed descriptions of each may be found elsewhere in the literature [33,37,38,47,48]. Each was conceived, designed,

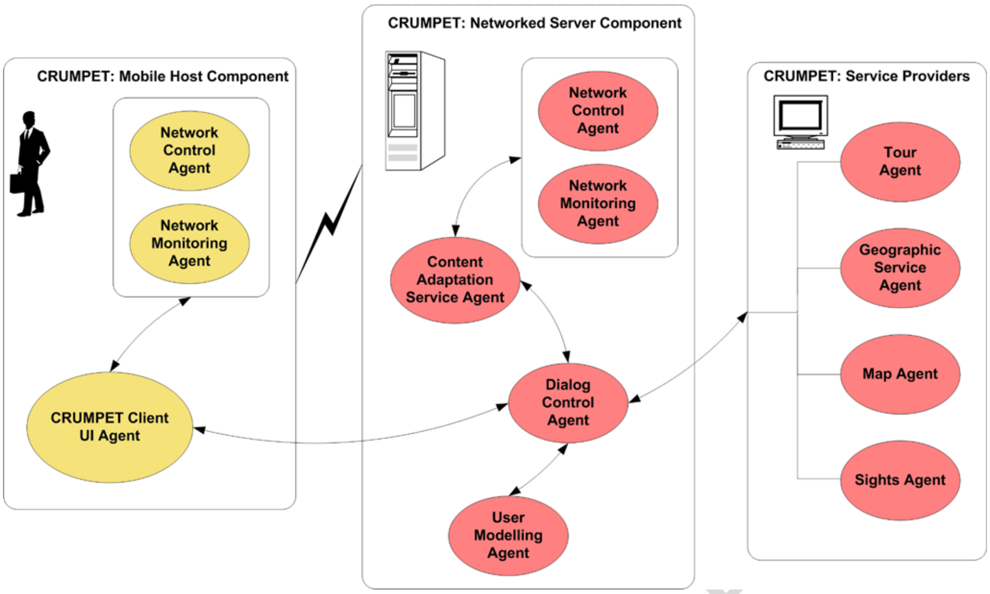

Fig. 1. Architecture of CRUMPET.

implemented and evaluated independently; thus it was impossible for the Genie to subsume the CRUMPET and augment the services offered, as might have been the expected approach. Nevertheless, the broad objective is identical in each case, namely the delivery of context-sensitive information to roaming tourists. However, each differs in a number of important respects. The motivating research question in each case was distinct – innovative service delivery for tourists in the case of CRUMPET, intelligent content precaching in the case of the Genie. As well as differing architecturally, the agent infrastructure employed in each case differs both in terms of agent model and enabling framework. Furthermore the approach to content delivery differs with the Genie specifically a *just-in-time* precaching mechanism. For the purposes of this discussion, a brief overview of each system is now presented which is both necessary and sufficient to contextualize the evaluations presented herein.

3.1. Architecture of CRUMPET

CRUMPET seeks to present information to tourists according to their context, namely, their location, personal profile as well as device and network characteristics. Each service supported by CRUMPET is encapsulated as an agent. An advantage of this approach is that CRUMPET is extensible, allowing the incorporation of legacy third-party services. A standard configuration of CRUMPET is illustrated in Fig. 1. Identifying prevailing network operating parameters and adapting supplied services are distinctive features of CRUMPET. Two agents collaborate to achieve this:

1. Network Control Agents can manipulate and control the link between the remote mobile CRUMPET host and the fixed networked server;
2. Network Monitoring Agents enable the prevailing QoS be identified at any moment in time.

To ensure maximum responsiveness to changes in prevailing network operating conditions, these agents must be hosted on both the mobile host and centralized server.

A number of standard services, provided by CRUMPET, are encapsulated as a suite of intelligent agents:

1. Tour Agent – recommends tours for the tourist to follow;
2. Map Agent – provides maps that correspond to the tourist's spatial context;
3. Sights Agents – identifies tourist attractions that the tourist might like to visit;
4. Geographic Service Agent – provides some standard location-aware services to tourists, for example, location of nearby restaurants.

The Dialog Control Agent acts as the interface to these agents and all requests must be routed by this agent. Finally, there are a number of agents concerned with the pragmatic task of information delivery:

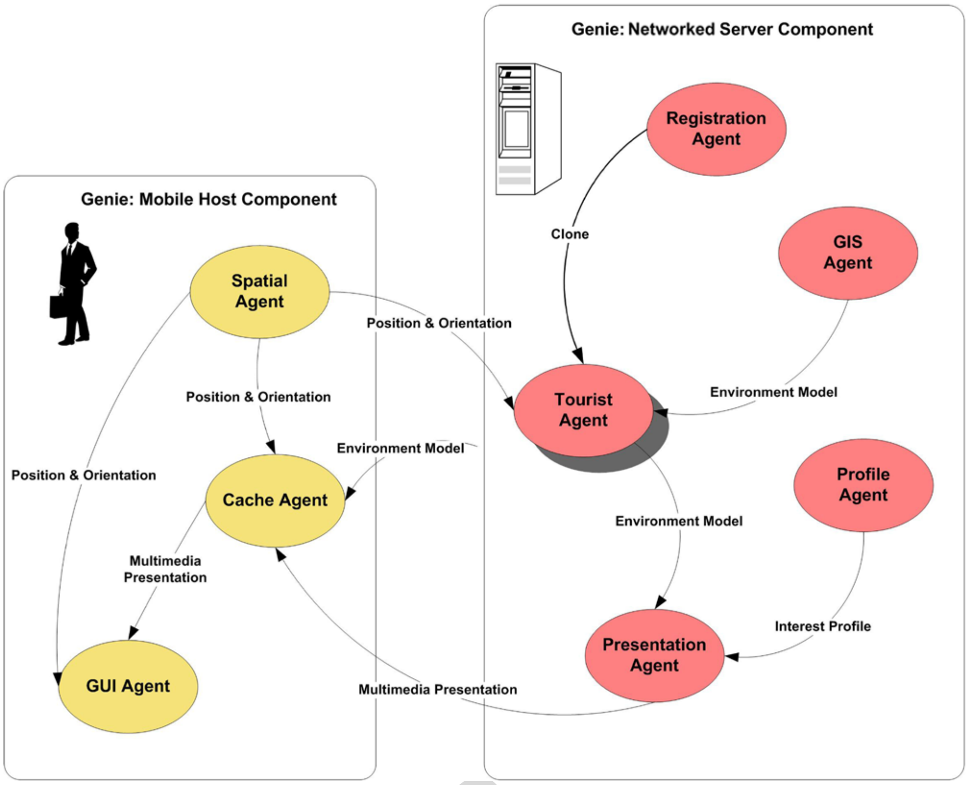

Fig. 2. Architecture of Gulliver's Genie.

1. CRUMPET Client UI Agent – resides on the mobile device, captures user interactions, and proceeds to communicate with the Dialog Control Agent; all responses are displayed on the user interface;
2. Content Adaptation Service Agent – adapts information based on the network parameters and the tourist's device characteristics;
3. User Modeling Agent – adapts content according the tourist's personal profile.

There are two configurations of CRUMPET. The standard configuration envisages a suite of agents hosted on the tourist's device. Should the computational resources of the device be insufficient, a lightweight configuration of CRUMPET may be adopted. In this configuration, there is no network adaptivity on the device. It was this later configuration that was used for this particular evaluation.

3.1.1. Implementation

CRUMPET is implemented in Java and typically hosted on a standard IPAQ device. Communications occurred via WiFi while GPS is used for position determination. The open-source FIPA based agent toolkit – microFIPA-OS was used for agent fabrication and deployment. From an agent architecture perspective, microFIPA-OS broadly subscribes to a belief-based mentalistic model. Recall that FIPA (Foundation for Intelligent Physical Agents) focuses on standards that seek to promote agent-based technology and interoperability with other technologies [39].

3.2. Architecture of Gulliver's Genie

Gulliver's Genie seeks to address the cultural information needs of tourists as they explore their surroundings. Two distinct functionalities support this. Firstly a map of their location with their current position and bearing highlighted is always available. Secondly, as tourists encounter items of cultural interest, multimedia enriched presentations are presented on their device for further consultation. From an architectural perspective, the Genie encompasses a suite of agents which reside on a fixed network server. These agents support a number of embedded agents residing on tourists' devices (Fig. 2).

Embedded device agents Three agents are embedded on the tourists' device, and although remote, they represent a distinct community of agents in the Genie MAS. These collaborate with each other and with the fixed server agents to deliver the tourist information service. Their roles are as follows:

1. Spatial Agent – Interfacing with the GPS device and determining position and bearing are the key tasks of the Spatial Agent. On the availability of a new position, the other agents on the device are informed, as is the tourist's representative agent on the Genie server.
2. Cache Agent – The task of the Cache Agent is to ensure that multimedia content pertinent to the tourist's location is available for display.
3. GUI Agent – Ensuring that the interface is up-to-date and managing tourists explicit interactions with the Genie are the tasks assigned to the GUI Agent.

Server agents A suite of agents are deployed on a fixed networked server to provide services to the roaming agents on the tourist's host devices. Their roles are as follows:

1. Registration Agent – Enables the tourist to register for any services supported by the Genie. During registration, a tourist must indicate some seed attributes for subsequent personal and cultural profiling.
2. Tourist Agent – An agent conforming to the tourist agent role is instantiated for each tourist that is actively using the Genie. This agent may be regarded as the tourist's proxy in the Genie MAS, and acts as the point of contact for those agents deployed on the tourist's device.
3. GIS Agent – The task of the GIS agent is to relate the geographical position of the tourist (available courtesy of the Spatial Agent) with a cultural attraction.
4. Profile Agent – Advising on user profile and cultural interest attributes represents the core service supported by the Profile Agent.
5. Presentation Agent – the construction and provision of multimedia presentations is the key task of the presentation agent. To do this, it must collaborate with the Profile and GIS Agents for presentation construction, and with the Cache Agent to enable access to the tourist's device.

Supporting the suite of agents on the server is a multimedia database appropriately populated with geo-tagged multimedia elements. Unlike CRUMPET, a wireless connection is a prerequisite for service access.

3.2.1. Implementation

Gulliver's Genie is hosted on an IPAQ device. A GPRS connection links it to a fixed networked server. Position was obtained using GPS. From a software perspective, the Genie is implemented in Java. All agents were designed and implemented using Agent Factory, which fabricates agents that conform to the BDI paradigm.

4. Methodology

Both CRUMPET and the Genie were subject to systematic evaluations. Though these sought to validate each system under a number of dimensions, the usability dimension is the focus of this discussion. An identical methodology was adopted in each case. Initially, evaluations of CRUMPET [46] and the Genie [35] took place at different times and using different methodologies. However, to facilitate cross comparison, it was necessary to again evaluate the Genie whilst adopting the methodology originally used in the CRUMPET study. This methodology comprised two distinct components – the first using a specifically constructed tourist-specific questionnaire, and a second based on the industry standard Software Usability Measurement Inventory (SUMI) [22,23] instrument. The questionnaire was designed to ascertain the information needs of tourists and measure the degree towards which these needs were met. Thus it is beyond the scope of this paper and the ensuing discussion focuses only on SUMI as this articulates the usability dimension of the user experience.

4.1. SUMI methodology

SUMI is a tested and proven method of measuring software quality from an end-user's perspective. It enables the comparison of software products and the comparison of interim releases and versions of the same product. In addition, it can serve as a diagnostic tool for identifying areas in which a product is weak and requires further development. SUMI is a commercial product. It is acknowledged by the ISO 9241-11 standard [17] as a recognized method for testing user satisfaction, which is one of the three conceptual dimensions of usability as defined by the ISO – the others being efficiency and effectiveness. These latter two categories can be measured objectively, but satisfaction is subjective. However, high scores in efficiency and effectiveness metrics will not compensate for a poor score in satisfaction. If the end-user is a paying customer, the results of an unsatisfactory experience are obvious. At present, there is some debate about the merits of measuring usability solely in terms of these three conventional dimensions, and concepts such as engagement, presence and fun amongst others have emerged [28]. However, until such time as these dimensions have been clearly defined in terms of what it is they are actually measuring, then conventional instruments must continue to be employed.

In measuring satisfaction, two methods are supported by SUMI – those of Profile Analysis and Item Consensual Analysis.

4.1.1. Profile analysis

Six dimensions of the user's experience are quantified as SUMI scales:

1. Efficiency – which reflects the user's perception of how successful the software is in enabling them to complete their task(s) in a quick, effective and economical manner.
2. Affect – which refers to the user's emotional response to the software, in terms of stimulation.
3. Helpfulness – which refers to the perception that the software communicates effectively and assists in the completion of tasks.
4. Control – which refers to the perception that the software is responding in a normal and consistent way.
5. Learnability – which refers to the perception that the user can quickly familiarize themselves with the software and its capabilities.
6. Global Usability – which represents a general satisfaction measure representing the perceived quality of use of the software under investigation.

4.1.2. Item Consensual Analysis (ICA)

In conjunction with the Profile Analysis, Item Consensual Analysis (ICA) enables the evaluator to analyze individual responses and compare items with the expected response for individual items from the SUMI questionnaire. The difference between what is observed in an arbitrary system evaluation and the SUMI projected value is expressed as a Chi Square (χ^2). ICA is a powerful diagnostics tool that permits the evaluator to analyze responses at a finer level of detail than is permissible with Profile Analysis.

4.2. SUMI principles

Normative tables that define a generic software standard have been constructed by the SUMI creators. Data collected from users via the questionnaire is collated and compared to the normative data. Using the *z-transform*, the output is standardised such that population mean score is 50 and the standard deviation is 10. Thus the standard score for the state-of-the-art is 50. A score of above 50 suggests that the software is better than the state-of-the-art; a score of less than 50 suggests it is worse. A score is always reported together with its 95% confidence intervals, that is, the region where the true mean or median would be expect to be found 95% of the time. A user group of more than 10 subjects is a minimum requirement if generalizations are to be made.

Up to 10 questions from the questionnaire contribute to each of the first 5 scales of the Profile Analysis listed above – the SUMI questionnaire has 50 questions (items) in total. The Global Usability scale may be regarded, somewhat simplistically, as a summary scale or a weighted sum of each of these 5 scales. Nonetheless, the Global data is transformed in exactly the same way as the other 5 scales, that is, with a mean of 50, and a population standard deviation of 10. Interpreting scores for scales is relatively straightforward; however, the ICA requires more consideration if further useful insights are to be gained. ICA is based on the standard Chi Square (χ^2) distribution which enables SUMI to express the difference between patterns observed or profile (using user supplied data), and the patterns expected (from the normative SUMI tables). The Chi Square is expressed for each of the three responses allowed by SUMI (Agree, Disagree and Undecided), enabling a total Chi Square value be computed for each of the 50 items in the questionnaire. SUMI will indicate when this value is statistically significant, in which case the responses received in answer to the item differ significantly from what would normally be expected, immediately suggesting it warrants further investigation. However, interpreting what this statistic actually means in practice is ultimately dependent on what the evaluators' expectations for the software artifact under investigation are, as articulated by the question being asked of the subject. High values for *Agree* and *Disagree* are relative easy to interpret. High values for *Undecided* indicate indecision on the part of the user. When values are more uniform for all three categories, more reflection and study is needed. However, a statistically significant Chi Square does not necessarily mean there is a problem; it could also be interpreted as meaning that the software is regarded as state-of-the-art, within the context of the question under investigation.

4.3. Sample size

Sample size is important; however there is no ideal size. The larger the group, the greater the confidence one can ascribe to the results. Nevertheless, a large heterogeneous group may be limited in its effectiveness; hence smaller but more homogenous groups may yield more useful results. SUMI will give stable statistical results from groups of at least 10 subjects, and has produced useful information from groups of less than 5 subjects. For the CRUMPET and Genie trials, a group of 19 and 20 was used in each respective case. It was considered that such a group size would establish any prevailing trends within the data, and that additional subjects would only be confirming these trends. In this way, any particular issues that were perceived as causing a problem would be highlighted earlier on in the process. These could then be addressed and the process repeated; otherwise, a more extensive user evaluation would be pursued.

4.4. Evaluation procedure

Both systems were evaluated at different geographic locations. CRUMPET was evaluated in both Heidelberg and Helsinki, both historic cities and popular tourist destinations. The Genie was evaluated on the scenic campus of University College Dublin at a time when the campus was host to many international students attending summer schools and language classes, as the regular student body was on summer vacation. Both systems were evaluated outdoors; the scale, heterogeneity and complexity of outdoor environments pose particular challenges to tourists – the alleviation of which was the primary motivator for the design in each case. Subjects were asked to explore their vicinity, and undertake a number of tasks. For example, subjects were asked to use the interactive map as a means of locating and orienting themselves, as well for determining objects of potential interest in their vicinity. Likewise, subjects accessed multimedia information on tourist attractions in their vicinity. The basis of the evaluation was a short tour undertaken by each subject in the area for approximately 20 minutes but no longer that 30 minutes. Time constraints meant that not every subject could complete the SUMI questionnaire; however, it was ensured that a sufficient number completed it so as to enable a valid usability analysis. One advantage of restricting subjects to a set of archetypical tasks over this relatively short time period was that it reduced the scope for external factors influencing the evaluation. Likewise, the risk of information overload was reduced.

Briefly, a typical evaluation session proceeded as follows:

1. The subject was briefed on the purposes of the evaluation.
2. Part 1 of the general tourist questionnaire, including personal information and so on, was completed.
3. The subject was then introduced to the mobile device, and either CRUMPET or the Genie. The evaluator ensured that they were capable of interacting with the device before proceeding with the evaluation.
4. A handout of instructions was presented to the subject. This included the tasks the subject was to perform on their tour – for example, to get a map, identify nearby attractions, obtain directions, or react as they saw appropriate to system prompts, amongst others.
5. The subject undertook a short tour and tried to accomplish the requested tasks.
6. Part 2 of the general tourist questionnaire is then completed.
7. On request, the subject completed the SUMI questionnaire.
8. Finally, the subject was debriefed.

5. Analysis

In this section, the results from the evaluations of CRUMPET and Gulliver's Genie are presented.

5.1. Analysis of CRUMPET

Four user trials were conducted in order to systematically evaluate CRUMPET, each taking place in a different location – Heidelberg, Helsinki, London and Aveiro. However, 19 subjects from Heidelberg and Helsinki elected to complete the SUMI questionnaire. Figure 3 summarizes the score for CRUMPET on the various SUMI scales. CRUMPET scores above 50 on all scales with a *Global* score of 55. This suggests that subjects viewed CRUMPET as a usable software implementation. As can be seen from Table 1, CRUMPET scores highest in the *Learnability* scale, indicating that the subjects found it easy to use, understood its use of context, and were confident that they could master it. *Helpfulness* represents the next highest scale at 54, suggesting that the subjects found CRUMPET

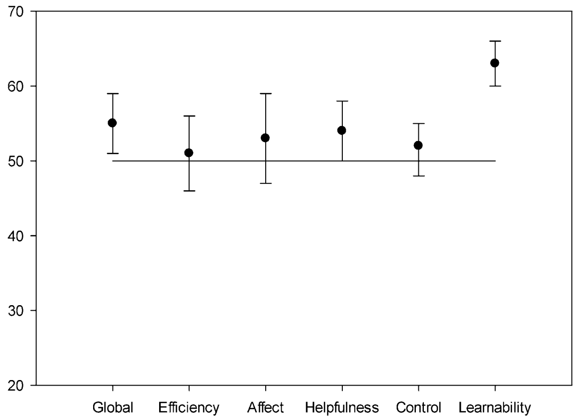

Fig. 3. SUMI Profile Analysis for CRUMPET.

Table 1
SUMI scales for CRUMPET ($n = 19$)

Scale	Median	Delta
Global	55	$+5$
Efficiency	51	$+1$
Affect	53	$+3$
Helpfulness	54	$+4$
Control	52	$+2$
Learnability	63	$+13$

consistent and the prompts and instructions easy to follow. Both of these scores are reassuring as they confirm that subjects had learnt CRUMPET sufficiently well for the evaluation, and that the impact of external factors was minimal. A score of 53 for *Affect* suggests that subjects were not stressed when using CRUMPET, and found the experience interesting. Yet a higher score might reasonably be expected here. However, *Control* and *Efficiency* at scores of 52 and 51 respectively reinforce this perception. In summary: though the scores are broadly positive, there are indications subjects were not quite achieving what they expected, and further investigation is needed through the ICA.

From an ICA perspective, nine items out of a total of 50 indicated statistical significance. Recalling that the ICA is the enabler of the Profile Analysis just discussed, four exemplar items, illustrated in Table 2, are now considered both to illuminate how the Profile Analysis is delivered, and how further consideration of individual ICA items may lead to further insights. A discussion on the items common to both CRUMPET and the Genie will be presented in Section 6.2.

Item 17, in particular, reinforces the conclusion drawn from the Profile Analysis above – the high number of respondents in the undecided category indicates some reservation about CRUMPET, but without identifying why this might be the case. A brief analysis quickly identifies two problematical areas, namely those of responsiveness or speed, and the interface. Items 1 and 29 clearly pinpoint speed and responsiveness as being problematic issues. There can be little doubt that these would negatively influence the perceived performance of CRUMPET. The issue of the interface is more complex. Item 42 suggests ambivalence; again, why this is the case would require further investigation.

Observations from an agent design perspective From an Agent-Oriented Software Engineering (AOSE) prospective, a number of observations can be made. Agents tend to be computationally expensive, when considered from an embedded computing perspective. Each will normally require at least one thread, which would quickly give rise to memory overhead if a number of agents are deployed. Furthermore, agents may have a deliberation component that could significantly consume memory and CPU cycles, depending on the attention given to the design and implementation. In an embedded context, memory and CPU access comes at a premium; thus agents must be harnessed cautiously and judiciously, otherwise the speed and performance of the application will be compromised resulting in an unsatisfactory user experience. Furthermore, implications for power must be considered as increased or sustained power draw will reduce the time interval for charging, as well as possibly reducing the operational lifespan of the battery.

Wireless communications introduce issues of latency. In and of itself, this is a potential problem. However, agents depend on their social ability to collaborate with their peers. Should this ability be compromised, the resultant performance will be adversely affected. Embedded agents on mobile devices are particularity susceptible to the vagrancies of the communications link. Inherent in any wireless communications link is the issue of roaming charges and these should be quantifiable; however the increased availability of WiFi hotspots in urban areas reduces their impact.

Finally, when designing Multi-agent Systems, there is a natural tendency to model the entire solution in terms of agents. This results in a conceptually elegant design, and when computational resources are not an issue, inefficiencies may be disguised or tolerated. This approach needs to be re-evaluated when working with embedded agents. Rather than modeling all the functionality on the embedded platform in terms of individ-

Table 2
CRUMPET Item Consensual Analysis (ICA)

Item 1	This software responds too slowly to inputs.		$X^2 = 37.41$	$p < 0.001$
	Agree	Undecided	Disagree	
Profile	14	2	3	
Expected	3.6	2.9	12.5	
ChiSq. (X^2)	29.92	0.28	7.21	
Item 17	Working with this software is mentally stimulating.		$X^2 = 9.63$	$p < 0.01$
	Agree	Undecided	Disagree	
Profile	4	13	2	
Expected	7.7	6.6	4.7	
Chi Sq. (X^2)	1.78	6.28	1.57	
Item 29.	The speed of this software is fast enough.		$X^2 = 6.53$	$p < 0.05$
	Agree	Undecided	Disagree	
Profile	6	3	10	
Expected	10.7	3.2	5.2	
Chi Sq. (X^2)	2.03	0.01	4.49	
Item 42	The software has a very attractive presentation.		$X^2 = 7.81$	$p < 0.05$
	Agree	Undecided	Disagree	
Profile	5	10	4	
Expected	10.7	5.2	3.1	
Chi Sq. (X^2)	3.04	4.53	0.24	

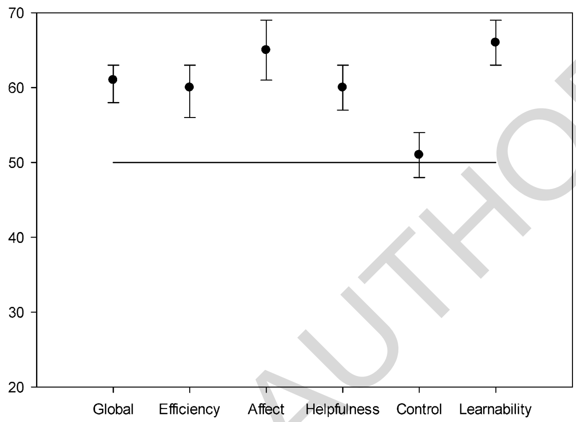

Fig. 4. SUMI Profile Analysis for Gulliver's Genie.

Table 3
SUMI Scales for Gulliver's Genie ($n = 20$)

Scale	Median	Delta
Global	61	+11
Efficiency	60	+10
Affect	65	+15
Helpfulness	60	+10
Control	51	+1
Learnability	66	+16

ual agents, it may be more effective to adopt a hybrid approach, even at the cost of a more complex design.

5.2. *Analysis of Gulliver's Genie*

User trials of the Genie were conducted on the campus of University College Dublin (UCD). A total of 20 subjects completed the evaluation.

The SUMI profile scales for Gulliver's Genie are illustrated in Fig. 4 and Table 3 respectively. A *Global* score of 61 indicated that the Genie was well received by the evaluation group. Like CRUMPET, the Genie scored highest in terms of *Learnability*. The next highest scale was *Affect*, suggesting that the subject group found the Genie stimulating and pleasant to use. Scores of 60 for the *Efficiency* and *Helpfulness* scales respectively indicate that subjects perceived the Genie as acting in a quick and effective manner, and that they perceived the Genie interface positively. A score of 51 for the *Control* scale suggests that this dimension merits further consideration.

From the ICA perspective, 10 items out of a total of 50 indicated statistical significance; however, for the reasons outlined in the previous section, four items are now considered (Table 4). Items 46 and 13 confirm that subjects understood the purpose of the Genie and found it clear and understandable. However, items 1 and 29 confirm that speed and responsiveness were perceived as problematic. As with CRUMPET, there can be little doubt that these would have af-

Table 4
Item Consensual Analysis (ICA) for Gulliver's Genie

Item 1	This software responds too slowly to inputs.		$X^2 = 21.25$	$p < 0.001$
	Agree	Undecided	Disagree	
Profile	11	5	4	
Expected	3.8	3.1	13.1	
Chi Sq. (X^2)	13.65	1.24	6.36	
Item 46	This software occasionally behaves in a way which can't be understood.		$X^2 = 18.81$	$p < 0.001$
	Agree	Undecided	Disagree	
Profile	0	2	18	
Expected	6.4	5.0	8.5	
Chi Sq. (X^2)	6.44	1.83	10.54	
Item 29	The speed of this software is fast enough.		$X^2 = 16.61$	$p < 0.001$
	Agree	Undecided	Disagree	
Profile	3	4	13	
Expected	11.2	3.3	5.5	
Chi Sq. (X^2)	6.02	0.13	10.46	
Item 13	The way that system information is presented is clear and understandable.		$X^2 = 8.88$	$p < 0.05$
	Agree	Undecided	Disagree	
Profile	19	1	0	
Expected	12.6	4.4	3.0	
Chi Sq. (X^2)	3.25	2.62	3.01	

fected performance and perceived control. Due to the design of the Genie, the situation regarding control is more complex. Recall that the Genie adopts the implicit interaction modality in addition to the more conventional explicit stimulus/response modality. This, in addition to its use of adaptivity, reduces the need for the user to interact with the Genie. Thus reducing the amount of control users had over the Genie was an explicit design decision, and the poor score for *Control* reflects this. In contrast, the high scores attributed to the Genie in the other scales, for example *Learnability*, may be the result of ceding control to the Genie. This raises the question as to whether the subjects were happy to do this, although they may have understood the benefits that accrued from such an approach. It may have been the case that they desired an option for fully controlling the behavior of the Genie, whilst progressively ceding control to it as their trust in it increased.

Observations from an agent design perspective All the observations raised from the use of agents in CRUMPET also apply to the Genie; however some additional comments may be made. Deliberation is a key characteristic of the agents employed by the Genie. Naturally, this comes at a performance cost, yet not at the expense of a good score in the *Global* or *Affect* scales. Outside of the *Control* scale, the scores for the other four scales are very good, and it is instructive to reflect on the contribution of agents to these scores.

Recall that adaptivity is fundamental to the operation of the Genie. The Genie continuously monitors spatial context, anticipates likely future behavior and delivers personalized services in a just-in-time basis. The autonomous, reactive and proactive attributes of its constituent agents are fundamental to its operation. In the first instance, the tourist's context is continuously (autonomously) monitored. The Genie responds (reacts) to changes in context, deliberates on its meaning, and proactively identifies or reaffirms a number of possible future scenarios. This results in a significant computational load, and one which the embedded agents are instrumental in activating and contributing to, though of course the load is distributed between the agents on the mobile device and the networked server. External factors including poor communications bandwidth exacerbate the performance overhead. The net result is that the Genie is perceived as being quite successful in the pursuit of its defined objectives, as understood by the subjects, resulting in high scores for *Affect*, *Learnability*, *Helpfulness* and *Efficiency*. All of this is achieved at the expense of a performance penalty, one that is tacitly acknowledged by the subjects in their feedback. The autonomous nature of the Genie undoubtedly contributes to ease-of-use, as indicated in the scores for learnability and helpfulness.

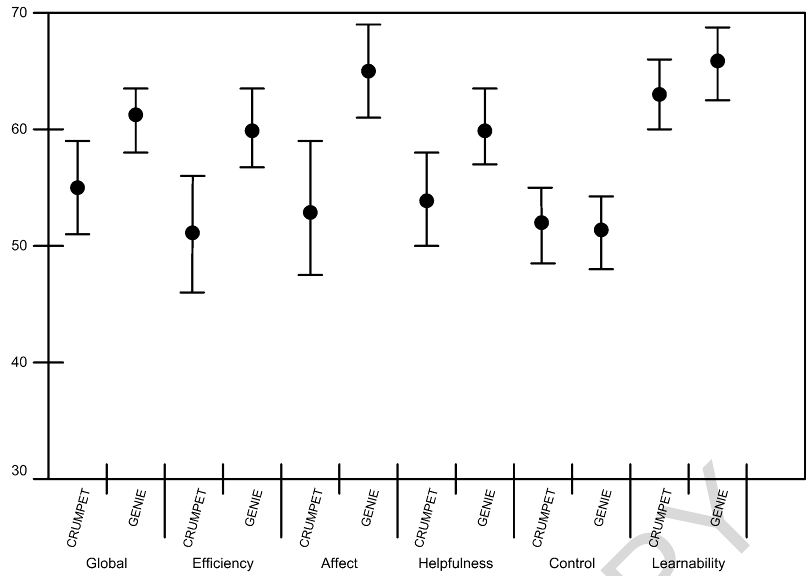

Fig. 5. Profile Analysis comparison of CRUMPET and Gulliver's Genie.

Likewise, the proactive and reactive nature of the Genie results in personalized and adaptive services being successfully realized within a variety of constraints. This results in a high score for the *Affect* scale.

6. Comparative analysis

In this section, both the CRUMPET and the Genie are considered in terms their SUMI profile scores and subsequently in common ICA items which were significantly different.

6.1. Profile comparison

Scores for the *Affect* and *Efficiency* scales differ for both systems with the Genie scoring higher (Fig. 5). Indeed, in the case of *Affect*, a score of 65 SUMI points for the Genie indicates a z-score of 2 meaning it was very well regarded by the users. The relatively low scores for CRUMPET for both these scales indicate some reservation on the subjects' behalf about how it functioned and how effective they were in accomplishing the required tasks. It was concluded that both poor speed and responsiveness were key factors contributing to these scores. In the case of the Genie, the scores are noticeably higher for both scales yet greater dissatisfaction was expressed in terms of speed and responsiveness. How is this contradiction reconciled? One explanation may be found in the anticipatory behavior and intelligent precaching exhibited by the Genie. This ensured that subjects had access to multimedia content appropriate to their contexts for the most part, thus mitigating the effects of network latency and bandwidth. In terms of responsiveness, it should be noted that both systems used a stylus for interaction, and a lack of experience with this may have contributed to the poor score for responsiveness.

Though the demographics of each user group were similar, intuitively, one would imagine the user cohort on the university campus as being younger. However the campus acts as a major recreational resource and as such the profile of each user cohort was almost identical in terms of age profile (90% of each in the 20 to 39 age group) and experience of mobile devices (everybody had experience of a mobile phone). Thus, demographics is not perceived as a major influence and it is most unlikely that these contributed to the differing scores, particularly for *affect*, where the z-score is 2. However, a potential influencing factor may be found in the timing of the evaluations. Recall that these took place at different time intervals with that of the Genie taking place some years later. Thus while each subject may have had some experience of mobile computing devices, those evaluating the Genie could reasonably be expected to have had some more. Though this experience cannot be quantified, it may be transferable, resulting in them being more comfortable with the software than might otherwise be the case.

For the *Control* scale, both systems score relatively poorly on the SUMI scale with CRUMPET having a slightly better score (52 for CRUMPET as against 51 for the Genie). Nevertheless both are still above the median, though with a z-score of 1; however, a better score would have been hoped for. The reasons for this are attributed to the interaction modality employed by each. CRUMPET placed more emphasis on explicit interaction, thus requiring the subject to explicitly interact with the system while undertaking the evaluation. In the case of the Genie, an implicit interaction approach was emphasized, enabled by the autonomous and proactive nature of the supporting agents. This resulted in subjects usually interacting with the Genie in response to its prompts or as their own cultural interests motivated them.

6.2. ICA comparison

An analysis of the ICAs for both CRUMPET and the Genie indicate that there were five items common to both that proved statistically significant. Essentially, these are confirming the issues discussed above but are briefly considered here for completeness.

Item 1: This software responds too slowly to inputs. (CRUMPET – $p < 0.001$; Gulliver's Genie – $p < 0.001$.) The responsiveness of both systems was perceived as being slow. For the most part, this is attributed to the computational load required by the agents. However, the issue of poor communication bandwidth and unfamiliarity with the stylus may also contribute to this situation.

Item 29: The speed of this software is fast enough. (CRUMPET – $p < 0.05$; Gulliver's Genie – $p < 0.001$.) The issues raise under the previous point are equally applicable here, though the issue of speed is more pronounced in the case of the Genie. In addition the rendering of multimedia data, used in both but particularly by the Genie, may have been a contributory factor. Likewise the BDI deductive apparatus harnessed by the Genie would have significantly consumed computational resources.

Item 40: I will never learn to use all that is offered in this software. (CRUMPET – $p < 0.01$; Gulliver's Genie – $p < 0.01$.) Both user groups disagreed with this statement indicating that both were confident that they would master the use of each.

Item 32: There have been times in using this software when I have felt quite tense. (CRUMPET – $p < 0.001$; Gulliver's Genie – $p < 0.01$.) CRUMPET users were ambiguous here with many in the undecided category, but there was a tendency to disagree. In the case of the Genie, most of the subjects disagreed indicating that they felt reasonably at ease during the evaluation.

Item 45: It is easy to forget how to do things with this software. (CRUMPET – $p < 0.05$; Gulliver's Genie – $p < 0.05$.) Both sets of subjects disagreed with this statement, reinforcing in part the conclusions to Item 40 discussed above. One contributory factor to this score may well be the adaptivity employed by both systems.

7. Discussion

CRUMPET and Gulliver's Genie have demonstrated the viability of embedded agents, and indeed the intelligent agent paradigm, as an enabling technology for realizing mobile intelligent information systems. Recent developments in agent frameworks together with the availability of a new generation of smartphones, as typified by the now commonplace iPhone and Android platforms, represent a watershed for those software engineers who wish to deploy agent-based solutions for mobile users. The issue of raw computational performance is becoming less of an issue with this generation of smart phones. Likewise, with 4G telecommunications systems on the horizon, integrating embedded agents with conventional fixed networked multi-agent systems, such that they may be regarded as a seamless community, is valid. Indeed, the next frontier for embedded agents is likely to be the Wireless Sensor Network (WSN) domain where exploratory research is already taking place, for example, the Agilla and MAPS platforms alluded to earlier. It is envisaged that this development will have significant implications for the practical realization of Ambient Intelligence (AmI) [30,42].

7.1. Guidelines for harnessing embedded agents in smart environments

To the best of the authors' knowledge, this opportunity to compare the performance of two agent-based applications which facilitate smart environment interaction is unique. The implications for the user experience of an agent-based design are now considered. Furthermore, this is augmented with the authors' own insights, given their role in the design, implementation and evaluation of both systems. Seven issues, segmented across both the end-user and software designer's perspective, have been identified that should inform the design of interactive mobile services that harness embedded agents.

Users must be the final arbiters of control policy Harnessing the autonomous and proactive properties of agents may be a valid strategy in many instances. However, this may result in an experience that the user is uncomfortable with, as indicated in both CRUMPET and the Genie. Thus, a strategy must exist for user's to share or cede control to an application as they decide. This is essentially an issue of trust – a recurring issue in ubiquitous computing [9]. As understanding and trust in the system increases with use, control may be ceded more easily. However, external factors, for example poor experience with other software services, or even personality traits, may result in an arbitrary user never ceding control to the extent envisaged by the designer.

Agents enable judicious management of user attention in smart environments User attention is a valuable resource; in mobile computing, the circumstances in which it is sought should be clear and unambiguous, given the variety of situations that users may find themselves in. Embedded agents offer an apt solution for managing an application through a user proxy, identifying circumstances where user attention is required, and when it is most appropriate to seek it. Feedback from both CRUMPET and the Genie indicated that users valued this capability.

Embedded Agents enable adaptive interaction within smart environments User interfaces and the presentation of content can be adapted in response to a variety of criteria. Embedded agents offer an effective mechanism for realizing adaptivity in mobile computing scenarios. In particular their ability to collaborate via their social skills is fundamental in fusing those diverse data sources necessary to achieving adaptivity, or in certain circumstances, intelligent user interfaces. While adaptivity is a key characteristic of both CRUMPET and the Genie, and represents a viable approach for improving the user experience, it must be acknowledged that not all scenarios will require this facility.

Agents are an effective vehicle for capturing & interpreting context Agents offer an intuitive mechanism for capturing and interpreting contextual states, either individually or in collaboration. Handling highly dynamic contexts which typifies mobile computing scenarios can prove inherently difficult. Agents are particularly suited to such circumstances as their reactive and autonomous nature enables them to respond quickly to such. Agents can also deliberate on the meaning of changes in context, and identify their associated ramifications. Likewise future contextual scenarios can be identified and appropriate plans constructed, as demonstrated in the pre-caching mechanism employed by the Genie.

Factor pragmatic system constraints into the design process Engineering agents for mobile devices is partially an exercise in embedded systems design and programming; thus some of the heuristics and practices common to embedded systems development are applicable. For example, should an agent possess its own control thread as might normally be expected, there is an immediate penalty in terms of memory overhead, amongst others. For a single agent, this may not be a problem; for multiple agents, a situation could quickly arise in which significant resources are being consumed. Thus the implications for system resources for any given task assigned to an agent, and implicitly, the strategy adopted to handle this task, must be quantified and understood, in a variety of dimensions, including the user perspective.

Compromise effectively between design and performance There is an obvious attraction to modeling an arbitrary solution as a suite of collaborating agents, assuming the problem at hand justifies the choice of the agent paradigm. If this affects performance, then how the agents are harnessed must be systematically reviewed and justified, as discussed above. However, software engineers must be prepared to compromise, and adopt hybrid approaches, even if this compromises the perceived elegance of the design, though not its integrity. For example, CRUMPET adopts the pragmatic approach of encapsulating legacy services as agents, rather than indulging the temptation of reengineering those services as pure agents.

Design for an unpredictable communication medium Multi-agent Systems (MAS) assume a reliable communications medium, given the reliance upon the inherent social ability of its constituent agents. Wireless communications pose a number of challenges, not least a limited and unpredictable bandwidth together with latency issues. When a MAS encompasses a mobile host and a fixed network node, the wireless element may come to represent a constraint, reducing the efficiency and responsiveness of the MAS. Again, these effects should be modeled and reflected within the MAS design. It must also be remembered that each communications episode comes at a cost – additional power is consumed by the device, and the end-user pays a financial toll.

7.2. A domain perspective

Supporting mobile tourists is the motivation for both CRUMPET and the Genie. E-tourism in a variety of manifestations has received significant attention by the research community in a range of disciplines. For example, in [13], a framework is proposed for categorizing and classifying mobile tourist guides via a number of orthogonal dimensions. Two issues arose. Firstly the issue of customization was not fully exploited, meaning that while individual contextual elements were harnessed, such elements were not harnessed in combination. Secondly, the push-approach was not sufficiently utilized. From the previous discussion, it can be seen that both CRUMPET and the Genie addressed each of these issues independently, and successfully. In each case, intelligent agents were key enablers of these features. Though the focus here has been on the tourist domain, it can be conjectured that these problems typify many mobile service domains; therefore we can generalize our results to conclude that the agent paradigm offers a potential solution for the broader range of mobile applications.

7.3. The need for usability instruments

There is a noticeable lack of instruments for measuring the usability of generic mobile computing applications and smart environments. Furthermore, validating intelligent techniques and adaptivity within such applications introduces a further level of complexity. Thus a major challenge facing the HCI community in particular surrounds the development of appropriate metrics that will enable developers to specifically evaluate and compare usability designs within the broad mobile computing and AmI domains, and additionally, where the agent paradigm enables key aspects of the service or user interface. Pre-existing usability instruments such as SUMI, though not explicitly developed for either the mobile or embedded computing domains, may nonetheless, provide an interim solution yielding useful feedback and insights into system behavior and end-user perceptions of performance. To date, the agent research community has been somewhat reticent in embracing such usability tools and undertaking usability studies. Though this reticence is understandable, there is an urgency that a consensus emerges in the research community as to how best to evaluate AmI platforms and services in all their dimensions. The ubiquity of the smartphone at present, and its potential as mobile AmI enabling platform, makes this endeavor a priority.

8. Conclusion

This paper has subjected two similar but distinct agent based systems to the scrutiny of user evaluations. Reaction by users to each system was broadly equivalent; however, in the case of the Genie, the scores for the dimensions of affect and efficiency were more favorable. Agents and the multi-agent paradigm offer a compelling and effective approach to the modelling, design and engineering of AmI systems. As AmI evolves, the demand for innovative services will increase, posing significant challenges for both service providers and software engineers. Embedded agents offer a tractable and scalable approach to managing the complexity and heterogeneity that characterize smart environments.

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