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A Contribution to the Incorporation of Sociability and Creativity Skills to Computers and Robots

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Abstract

Intelligent Data Science and Artificial Intelligence Research Center
Knowledge Engineering Research Group

Doctor

A Contribution to the incorporation of Sociability and Creativity skills to computers and robots

by Cristóbal Raya Giner

This dissertation contains the research and work completed by the PhD candidate on the incorporation of sociability and creativity skills to computers and robots. Both skills can be directly related with empathy, that is the ability to understand and share the feelings of another. In this form, this research can be contextualized in the framework of recent developments towards the achievement of empathy machines.

The first challenge at hands refers to designing pioneering techniques based on the use of social robots to improve user experience interacting with them. In particular, research focus is on eliminating or minimizing pain and anxiety as well as loneliness and stress of long-term hospitalized child patients. This challenge is approached by developing a cloud-based robotics architecture to effectively develop complex tasks related to hospitalized children assistance. More specifically, a multiagent learning architecture is introduced to be based on a combination of machine learning and cloud computing using low-cost robots (Innvo labs's Pleo rb). Moreover, a wireless communication system is also developed for the Pleo robot in order to help the health professional who will conduct therapy with the child, monitoring, understanding, and controlling Pleo behavior at any moment.

As a second challenge, a new formulation of the concept of creativity is proposed in order to empower computers with. Based on previous well established theories from Boden and Wiggins, this thesis redefines the formal mechanism of exploratory and transformational creativity in a way which facilitates the computational implementation of these mechanisms in Creativity Support Systems. The proposed formalization is applied and validated on two real cases: the first, about chocolate designing, in which a novel and flavorful combination of chocolate and fruit is generated. The second case is about the composition of a single voice tune of reel using ABC notation.

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This research has also been supported by the INVITE Research Project (TIN2016-80049-C2-1-R and TIN2016-80049-C2-2-R (AEI/FEDER, UE)), funded by the Spanish Ministry of Science and Information Technology.

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Chapter 1

Introduction

1.1 Motivation

News in scientific journals and general audience newspapers are showing every day how Artificial intelligence is becoming more and more sophisticated, as well as its ability to perform human tasks is growing exponentially. We no longer look for computers or robots (processing devices, in general) to just perform repetitive tasks. Now we seek to replicate purely human skills such as intuition, insight, imagery, creativity, empathy or common sense. Terms such as data mining, big data, cloud computing or machine learning are invading more and more professional areas that have traditionally required human skills. Higher-skilled job categories in factories, medicine, legal services, accounting, finances, law or art are all in scope to be occupied, to a large degree, by cognitive technologies [Vin+15].

As one more step, we also look for computers and robots interacting with us, so generating hybrid work teams made up of computers, robots and humans, understanding, collaborating and helping each other. Artificial Intelligence is never more aiming to be a replacing new technology, but one empowering humans to complete cognitive tasks. From 'winning' machines beating humans in well-structured domains as chess or Go games, we are moving to collaborative devices helping humans to deal with skilled tasks in general human non-structured domains, leading to the so-called Intelligence Augmentation. Empower cooperation and collaboration means a lot of research to be performed about machine interaction, from the human perspective.

Unlike the advances in the mechanical features of robots are impressive, progress on social interaction has been slower. Fortunately, these improvements in both, computing architectures and robotics technology, have opened new possibilities for its effective use in social, therapeutic, cultural and even artistic fields. These improvements are being possible thanks to the multidisciplinar collaboration between scientists in the fields of engineering, computer science, robotics as well as clinical, nursery, humanities, and psychology. As a result of this tight collaboration, a new science-research cross-disciplinary area, *Social Robotics*, has emerged.

A social robot can be defined as an autonomous robotic device that interacts and communicates with humans and other autonomous physical and virtual agents. It can interpret people's actions and respond appropriately. Normally, social robots are mainly humanoid or animaloid in form. Their shape is of fundamental importance, since their function is to interact with humans on *an emotional level*, and this type of interaction is grounded in visual and tactile perception no less than in verbal communication. A recent literature review on Social Robotics can be found in [Cam16]. Typical types of social robots are mobile servant robots, physical assistant robots, person carrier robots[1], robots for monitoring, therapeutic robots and robots for companionship [SYD06].

This thesis is primarily focused on the use of social robots to improve children's experience when long-term hospitalized by reducing pain, anxiety as well as loneliness and stress. Anxiety disorders are among the most predominant psychiatric disorders during childhood and adolescence. These remain frequently undiagnosed and largely undertreated. As regards the aspects surrounding child hospitalization, it is known that the anxiety triggered by this situation is characterized by a series of stress and threatening factors that make the child psychologically imbalanced; these in turn tend to result in negative consequences for the treatment of the main disease and for his/her development. In particular, children in the oncology area suffer unpredictable and uncontrollable pain that drives the child and his/her family to a desperation, despondency and distress. In addition, most painful treatments provoke a level of anxiety that can generate a vicious cycle for subsequent painful experiences. In order to minimize stress and anxiety in children and parents, many hospitals make efforts to provide socio-emotional support for these patients and their families to create a less intimidating and more comfortable health-care experience. Unfortunately, many hospitals are not able to provide children and parents with adequate support due to a lack of available human resources. Social robots can help to fill the gap and can mitigate these psychiatric disorders in hospital pediatric care.

On the other hand, the thesis is also dealt with another different aspect related to the human skills that have always wanted to be replicated: creativity. While computers are

[1] ISO13482:2014 from International Organization for Standardization specifies requirements and guidelines for the inherently safe design, protective measures, and information for use of personal care robots, in particular in mobile servant robots, physical assistant robots and person carrier robot

known for mathematical precision and logic, creativity was long thought to be in the exclusive domain of humans beings. Creativity research has been mostly in the domain of philosophers, educators and psychologist. The interest in research on computational and neuroscience approaches to creativity is thus quite recent. Nowadays it is already admitted that creativity is no longer an exclusively human quality and there are many examples of artificial systems able to build creativity artifacts or to assist to creative tasks.

Creativity, defined by Sternberg [Tay88] as "*the capacity to create a solution that is both novel and appropriate*", is basically a combination of two skills: the capacity of applying old knowledge to new situations and the capacity of empathize with other people, understanding emotions and the impression that a solution to a problem causes in these other people. Computational creativity is the study of "*building software that exhibits behavior that would be deemed creative in humans*" [Lóp13]. Such creative software can be used for creative tasks, such as proving and proposing mathematical theories, writing poems and stories, painting pictures and composing music. Computational creativity is an emerging, multidisciplinary branch of Artificial Intelligence whose goal is to model, simulate or serve as a support tool for creative task.

One of the few attempts in the literature to address the problem of creative behavior and its relation with Artificial Intelligence was performed by Margaret Boden [Bod91; Bod94]. She aimed to study creativity processes from a philosophical viewpoint focusing on understanding human creativity rather than trying to create a creative machine. In order to clarify and to formalize some of the Boden's theory, G. Wiggings [Wig06] presented several papers in which he emphasized the notion of search as the central mechanism for creativity. Besides Boden and Wiggings work, there have been other formalizations of specific aspects of the computational creative process. Although these formalizations are very helpful in clarifying the nature of creative computation and have given rise to some applications in diverse domains including graphic design, creative language, video game design and visual arts, the details of most of them are unspecified and the concepts they include are tricky to be implemented. A study that redefines the formal mechanism of some aspect of creativity that facilitates its implementation is not only important because it allows us to better understand this human skill but also allows it to be incorporated into current computer and robotic systems.

1.2 Contextualization

Of all those human qualities that are added to the objectives of Artificial Intelligence, this thesis deals with two of them: *socialization* and *creativity*. In fact, according to the definitions from the previous section, both of them can be directly related with *empathy*, that is the ability to understand and share the feelings of another [ANI12].

First part of the thesis dissertation contains the research and implementation completed by the PhD candidate into a research project that aims to develop a social assistant robot architecture for improving the children experience when they are hospitalized. For this aim, it is pursued to endow the robots with the social capacity of empathize by understanding and interpreting human emotions and feelings.

On the other hand, this dissertation is also introducing more recent research and work related to the formalization of creativity in such a way that it facilitates the computational implementation of the creativity mechanism. Again, empathize with other people, understanding emotions and the impression that a solution to a problem causes in these other people is one skill to be searched.

Overall, our main research question can be expressed, in a general form, as: *How can we endow machines with the empathy skill?* [Kal17].

This dissertation contains the work performed by the PhD candidate in two different research coordinated projects during the last years. These projects are:

1. PATRICIA 2013-2016 [TIN2012-38416-C03-01, 02, 03] (***P****ain and* ***A****nxiety* ***T****reatment based on social* ***R****obot* ***I****nteraction with* ***C****hildren to* ***I****mprove p****A****tient experience*). Funded by the Spanish Ministry of Science and Information Technology, Universitat Politècnica de Catalunya and La Salle Universitat Ramon Llull participated as technological partners with the Hospital Sant Joan de Déu de Barcelona being the clinical site [Ang+12].

2. INVITE 2017-2019 [TIN2016-80049-C2-1-R, TIN2016-80049-2-R] (*Mathematical structures for linguistic assessments in decision processes*). It is also funded by the Spanish Ministry of Science and Information Technology and composed by researchers of Universitat Politècnica de Catalunya and ESADE Universitat Ramon Llull [Rui+15].

The challenge of the former project was to design pioneering techniques based on the use of social robots to improve the patient experience by eliminating or minimizing pain and anxiety as well as loneliness and stress of long-term child patients. For this end, a cloud-based robotics architecture to effectively develop complex tasks related to hospitalized children assistance was proposed. More specifically, a multiagent learning system is introduced that combines machine learning and cloud computing using low-cost robots (Pleo rb).

The PhD candidate responsibility in this project focused on designing and developing a wireless communication system with the Pleo robot in order to help the clinical professional who conducts therapy with the child to monitoring, understanding, and controlling Pleo behavior at any moment.

PATRICIA can be considered as a continuation of the Program Child Life that was started in 2004 at Hospital Sant Joan de Déu in Barcelona with the purpose of designing pioneering techniques to improve child's experience by reducing pain and anxiety during hospitalization [SC10]. In 2010, more than 200 children and teenagers along with their families have participated in this program.

On the other hand, the still ongoing coordinated project INVITE focuses its attention on the development and implementation of decision-making and innovation processes for the management of leisure and culture in the ecosystem of the Smart City. The PhD candidate responsibility in this project focuses on the formalization of the concept of creativity. Based on previous well-established theories from Boden and Wiggins, the project proves to define the formal mechanism of exploratory and transformational creativity in a way which facilitates the computational implementation of these mechanisms in Creativity Support Systems. The fields to which this formalization has been applied are the creation of pastry products and musical composition.

The two projects mentioned above have been carried out by researchers who currently belong to IDEAI-UPC, a research center in Intelligent Data Science and Artificial Intelligence at the Universitat Politècnica de Catalunya · BarcelonaTech, in which the PhD candidate currently performs its research task. IDEAI-UPC devotes its efforts to research in these both areas, Intelligent Data Science and Artificial Intelligence, for the resolution of real problems related to the economic and industrial contexts. Specifically, it is promoting research and technology transfer in the fields of machine learning, science and data engineering, natural language processing, support decision systems and computational reasoning.

1.3 Objectives

The general objective of this thesis is to prove that it is possible to incorporate some of the skills that have always been considered purely human to computers and robots. We hypothesize that it is a first step to achieve that computers and robots interact with us generating hybrid work teams made up of computers, robots and humans, understanding, collaborating and helping each other. Of all those human skills, this thesis deals with two of them, socialization and creativity, having in mind to research towards the ultimate empathy machine.

The precise objectives of this dissertation are divided into two groups, both of them aligned to the objectives of the before mentioned projects.

1.3.1 Assistant Social Robot

The main objective in this part is to design a new cloud architecture that allows users and artificial agents to induce behavioral states to a cloud composed of Pleo robots. For achieving this main objective, the sub-objectives more closely related in this thesis are:

- To explore commercial pet robots developed by several companies (Fujitsu, Innvo Labs, AIST,...) and determine by experimental work which ones fits better for companionship and assistance tasks. Moreover, its features and projects in which they have been used will be also analyzed.
- To increase our knowledge about Pleo robot's hardware and software: motors, sensors, IR transceivers, microphones, camera, battery, SD card... as well as the structure of Life OS (its operating system).
- To expand Pleo connectivity minimizing the intervention over the hardware of the system. That means that we will neither modify its pre-programmed bio-inspired behavior nor its embodiment. Furthermore, we will keep a reliable trade-off between power consumption, data transfer, and connectivity to the cloud.
- To develop an interface that allows customizing Pleo behavior in a easy way for non-expert professionals by changing its parameters and descriptors. This interface will be developed as an Android app along with physical modification for wireless communication.

1.3.2 Computational Creativity

The main objective of this part is the reformulation of the concept of creativity in such a way that facilitates its implementation in computing systems. The subobjectives of this part are:

- To understand the previous theories of creativity of Boden and Wiggins which are based on the concept of conceptual space and search in this conceptual space.
- To formulate conceptually the concepts of framework, conceptual space, appropriateness and relevance in such a way that facilitates its implementation.
- To apply the proposed formulation to the problem of combining a fruit with dark chocolate. The system should foresee if this is an appropriate combination from the relevance of this fruit in other different culinary frameworks that haven't nothing to do with chocolate.
- To apply the proposed formulation to the problem of musical composition. In this case, the system should foresee if a piece of melody is appropriate in the song from the relevance of this piece of melody in other different musical frameworks.

1.4 Thesis Organization

The thesis is divided into two parts, each part related to one of the research projects mentioned above. Chapters 2 and 3 described the work developed under the PATRICIA project. Chapters 4 and 5 are associated to the work developed under the umbrella of the INVITE project. Finally, Chapter 6 corresponds to the conclusions and future work.

Unlike this dissertation is dealing with a general question about designing and implementing an ultimate empathy machine, it has been approached from two very different research areas, social robotics and creative support systems. Hence, the general organization followed in most of the thesis dissertations by introducing the studied research topic with a chapter devoted to the review of the state of the art is not the approach to be followed. In our case, the literature referring to the general framework has been introduced along the Chapter 1, in order to motivate the research. Besides, the more precise literature reviewed for both research areas under study will be introduced along the chapters related with.

- The purpose of Chapter 2 is about describing the problem and objectives of PATRICIA project. This chapter details the anxiety and stress phenomena observed in children under leukemia treatment. It also describes the overall benefits of introducing pet robots in social scenarios, summarizes the features, facilities and limitations of the Pleo robot (the robotic platform used in the project) to reduce the aforementioned effects, and describes the cloud robotics architecture to boost the Pleo capabilities and the distributed intelligent system deployed on top of it. More specifically, a multiagent learning system is introduced that combines machine learning and cloud computing to (1) collect and perceive children status, (2) build a human-readable set of rules related to the child-robot relationship, and (3) improve the children experience during their stay in the hospital. Conducted preliminary experiments proof the feasibility of this proposal.

- Chapter 3 deals with the technological issues of the project. This is the area where the PhD candidate has made his most relevant contributions. In this chapter, a few of the many robots developed as therapeutic robots are introduced. The platform used in the project, the robot Pleo, is described with more detail, both the hardware as well as its operating system (Life OS). The chapter also introduces some reflections about technical limitations and hardware modification to overcome these difficulties. In particular, the development of a system to wirelessly communicate with Pleo is described. This development is performed in order to help the coordinator who leads the therapy with the kid to understand and control Pleo's behavior at any moment. This chapter explains how this technological part was being developed and the obtained technical results.

- Chapter 4 proposes a new formulation of creativity based on the ideas of Boden's well-established theory on combinational, exploratory and transformational creativity. This new formulation, based on the idea of conceptual space, redefines some terms and includes several types of concept properties (appropriateness and relevance), whose relationship facilitates the computational implementation of the transformational creativity mechanism.

  Computational creativity is an emerging, multidisciplinary branch of Artificial Intelligence, closely related to Cognitive Science, whose goal is to model, simulate or serve as a support tool for creative tasks. In this chapter, we focus on systems for achieving the latter goal. Such systems are normally referred to as Creativity Support Systems, that is, systems capable to enhance human creativity without necessarily being creative themselves.

- Chapter 5 analyses the application of the formulation presented in the previous chapter to two different fields: a real case of chocolate design, study conducted jointly with the chocolate chef Oriol Balaguer and his team, and a second case in the field of music. This last application analyses the relationship between appropriateness and relevance of a music concept in order to obtain a computer tool to support the musical composition task. Concretely, it describes the task of composing a single voice tune of a specific style, *reel* (a folk rhythm originated in Scotland) using ABC notation.

- Finally, Chapter 6 summarizes the thesis, discusses its findings and contributions, points out limitations of the current work, and also outlines directions for future research.

1.5 Methodology

The research group in the PATRICIA project was proposing the architecture of health care robots combining cloud robotics and artificial intelligence with the aim to provide children with an effective and individualized assistance to their therapy. After a six-month study of experiences with children evaluating several commercial robotic platforms, the robotic platform finally selected for the study was Pleo, a robot that imitates a baby Camarasaurus dinosaur [Hee+12]. This robot exhibits an appealing expressiveness and contains an array of different behavior and moods. Pleo has already been tested in several research studies that have been focused on the effect of pet robots in long-term interactions with children.

The aim is to supply each patient with a personal Pleo that uses this cloud multiagent system to perceive, collect and share the status on a child. Using Artificial Intelligence techniques, the behavior of every patient's robot can be modified. Finally, since this information is in the cloud, the system can explore the most effective actions to carry out to improve its own patient's experience.

Until now, it is not possible to modify the software system of Pleo since the software is not open sourced. However, it does allow users to modify some values or commit to some precise actions. For example, it is able to notify people about how hungry is it, how happy, and perform a number of tasks such as ask a person to go out on a walk, or perform a trick such as giving a user its paw for a handshake.

Hardware communication with the current version of the robot is not as easy as in previous Pleo commercial versions. In order to obtain data in real time, Pleo was connected to an external power source while performing communications between its USB connector and a remote computer. It is possible to get values from Pleo's sensors in real time using this system setup. It is also possible to connect via bluetooth to a

UART port [Nav+13a] to bridge Pleo and a Raspberry Pi. Other processing platforms like Intel Galileo or Edison, and wireless communications like ZigBee or WiFi can also be implemented depending on power, processing, and privacy needs. The Raspberry Pi module can access the Internet via a WiFi dongle to upload data to the cloud.

Two problems arose when developing this communication setup: firstly, there was a lack of physical space to work with since the original battery of Pleo was employed with compacting wires and left the bluetooth module visible. Secondly, new Pleo robots are not equipped with this UART connector, so they could be exclusively tested in old versions.

Talking about creativity formalization and construction of Creativity Support Systems, the methodology combines a theoretical model of several aspect of creativity and two experiments to assess this theoretical model.

First application was developed and tested with the support of the chocolate chef Oriol Balaguer and his team[2]. This Catalan pastry chef is actively involved in the research and development of new products. Oriol Balaguer assessed, according to his expertise the combination of different fruits and their suitability in combination with dark chocolate.

A multiclass and a two-class Support Vector machines were used with data obtained from large online recipe databases. The main objective is to relate the relevance of a product in these databases with the appropriateness given by the expert. Some images of the experiments held at ESADECREAPOLIS with Oriol Balaguer and his team as a part of SENSORIAL project can be seen at Vimeo platform[3].

The second application of computational creativity was considered to prove the suitability of the formulation proposed in music composition task. In this case, single voice folk songs written using ABC notation were considered. ABC notation is a text-based music notation system popular for transcribing, publishing and sharing music, particularly on the Internet. ABC has gone from strength and is widely used by folk musicians, specially from Western European origin, e.g. English, Irish, Scottish, and which typically produce single-voice melodies. The database for the experiment is conformed by 2386 tunes classifying in 16 different rhythms extracted from different online public databases. The result of this experiment was new single voice folk songs composed from the relationship between relevance and appropriateness of different pieces of music.

[2]watch on http://www.oriolbalaguer.com.
[3]watch on https://vimeo.com/35454467.

1.6 Thesis Contributions

This thesis have contributed to prove that some of the purely human skills that have always been considered characteristic only of human beings can also be incorporated, in some extent, to computers and robots. Concretely, the thesis deals with two of these skills: socialization and creativity.

The work developed has allowed the construction of a cloud architecture that allows users and artificial agents to induce several behaviors in Pleo robots. These robots can capture by means of its sensors the state of the child and, through the artificial agents, to act accordingly to mitigate the negative effects of that state. This development has been possible thanks to the hardware modifications of the robot platform.

On the other hand, the thesis have also contributed to better understand the mechanism of creativity, formalizing the concepts of appropriateness and relevance. This can be considered the more theoretical contribution of the thesis. Besides this theoretical contribution, two interesting applications show the mechanism to incorporate this skill in two different tasks: the design of a cake recipe and the composition of a musical piece. These two examples show how to apply this methodology to other different tasks.

1.7 Publications

As part of the outcomes of this research, the following journal and conference papers have been produced:

1.7.1 Journal

- F. Larriba, **C. Raya**, C. Angulo, J. Albo-Canals, M. Díaz, R. Boldú (2016) "Externalising moods and psychological states in a cloud based system to enhance a pet-robot and child's interaction". Biomedical engineering online. Vol. 16, num. Supl. 1:S72, pp. 187-196 DOI: 10.1186/s12938-016-0180-3. **Impact Factor 2016: 1.683** (Q3 of ENGINEERING, BIOMEDICAL).

- F. Ruiz, **C. Raya**, A. Samà, N. Agell (2015). "A transformational creativity tool to support chocolate designers". Pattern Recognition Letters. Vol. 67, Part 1, pp. 75-80 DOI: 10.1016/j.patrec.2015.05.012. **Impact Factor 2015: 1.995** (Q2 of COMPUTER SCIENCE, ARTIFICIAL INTELLIGENCE).

1.7.2 Conference

- **C. Raya, C**, F. Ruiz, C. Angulo, A. Samà, N. Agell (2017). "A transformational creativity tool to support musical composition". *International Conference of the Catalan Association for Artificial Intelligence*, "Recent Advances in Artificial Intelligence Research and Development: proceedings of the 20th International Conference of the Catalan Association for Artificial Intelligence: Deltebre, Terres de l'Ebre, Spain, October 25–27, 2017". Deltebre: IOS Press BV, 2017, p. 287-292.
DOI 10.3233/978-1-61499-806-8-287.

- M. Diaz-Boladeras, C. Angulo, M. Domènech, J. Albo-Canals, N. Serrallonga, **C. Raya**, A. Barco (2016) "Assessing pediatrics patients' psychological states from biomedical signals in a cloud of social robots". *XIV Mediterranean Conference on Medical and Biological Engineering and Computing*, MEDICON 2016, Paphos, Cyprus. IFMBE Proceedings vol 57, pp. 1179-1184
DOI: 10.1007/978-3-319-32703-7-229

- F. Ruiz, **C. Raya**, A. Samà, N. Agell (2015) Creativity support System for cake design. Jornadas de ARCA. "Actas de las XVI Jornadas de ARCA. Sistemas Cualitativos y sus Aplicaciones en Diagnosis, Robótica e Inteligencia Ambiental". Cádiz: 2015, pp. 99-104.

- F. Larriba, **C. Raya**, C. Angulo, J. Albo-Canals, M. Diaz, R. Boldú (2015) Externalising Moods and Psychological States to Smooth Pet-robot/Child Interaction through Bluetooth Communication. International Work Conference on Bioinformatics and Biomedical Engineering, IWBBIO 2015, Part II, Lecture Notes in Computer Science, vol. 9044, pp. 683-693. Springer International Publishing Switzerland
DOI 10.1007/978-3-319-16480-9-66

- J. Albo-Canals, A. Fernández-Baena, R. Boldu, J. Navarro, D. Miralles, **C. Raya**, C. Angulo (2015) "Enhancing Long-term Children to Robot Interaction Engagement through Cloud Connectivity". Tenth Annual ACM / IEEE International Conference on Human-Robot Interaction (HRI'15), pp. 105-106, Portland, USA. ACM.
DOI 10.1145/2701973.2702045.

- F. Ruiz, **C. Raya**, A. Samà, N. Agell (2014). "A Computational creativity system to support chocolate designers decisions". *International Conference of the Catalan*

Association for Artificial Intelligence, "Recent Advances in Artificial Intelligence Research and Development: proceedings of the 17th International Conference of the Catalan Association for Artificial Intelligence:Barcelona, Spain. IOS Press. DOI 10.3233/978-1-61499-452-7-285.

- J. Navarro, A. Sánchez-Asensio, C. Garriga, J. Ortiz-Villajos, J. Albó-Canals, **C. Raya**, C. Angulo, D. Miralles (2013). "A Cloud Robotics Architecture to Foster Individual Child Partnership in Medical Facilities". Workshop on Cloud Robotics, RSJ IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2013), Tokyo Big Sight, Japan.

Part I

PATRICIA Research Project

Chapter 2

The PATRICIA Proposal

A major focus for children's quality of life programs in hospitals is improving their experiences during procedures. In anticipation of treatment, children may become anxious and during procedures pain appears. The challenge of the coordinated project PATRICIA is to design pioneering techniques based on the use of social robots to improve the patient experience by eliminating or minimizing pain and anxiety. According to this proposed challenge, this research aims to design and develop specific human - social robot interaction with pet robots. Robot interactive behavior will be designed based on modular skills using soft-computing paradigms.

2.1 Introduction

Long-term hospitalization is a serious event that affects children and their families' lives. Hospitalized children are confronted with stressful conditions including physical pain and fear [Día+11b; Jeo+15]. In this scenario, social support becomes almost limited to hospital staff and relatives, who often are affected themselves by feelings of sorrow and concern.

The PATRICIA project [Ang+12] (TIN2012-38416-C03-01,02,03) (***P**ain and **A**nxiety **T**reatment based on social **R**obot **I**nteraction with **C**hildren to **I**mprove p**A**tient experience*) was a project funded by the Spanish Ministry of Science and Information Technology where Universitat Politècnica de Catalunya (UPC) and La Salle Universitat Ramon Llull (La Salle URL) participate as technological partners with the Hospital Sant Joan de Déu de Barcelona (HSJD), the clinical colleague. PATRICIA project is based on the use of social robots with the aim to design pioneering techniques to improve children's experience when hospitalized by reducing pain and anxiety as well as loneliness and stress of long-term child patients. This project was a continuation of Child Life Program that was started in 2004 in HSJD and where more than 200 children and teenagers and their families have participated.

This kind of projects encourages easily to anyone to get interested in it: it is an innovative project with many unresolved horizons to explore, with a high diverge team, where so different concepts as robotics and human feelings are mixed, therefore multidisciplinary. Engineers, physicians, nurses, psychologists... working together looking for improve the life quality of those kids that were unlucky for living together with serious diseases.

This chapter describes general aspects related to the project, in which the PhD student carried out tasks that are described more explicitly in the next chapter. First, the problem that is being addressed is described: the psychological affect of children who suffer long hospital stays and how negatively it affects the efficiency of your treatment. It also describes how these conditions are currently addressed through social therapies (music, games, activities, pet care, ...). The project proposal is to introduce the robotic pets that have some of the advantages of animal pets and stop having some of their disadvantages. Further, the ability to collect information from the sensors of the pet robots will allow the processing of this information either to collect data for medical purposes and to process actions executed by the same pet robot that serves of therapy to the child. As the pet robots that can be available today still do not have a large information processing capacity, a cloud robotics based architecture is proposed in which the information collected by each unit is shared and processed in the cloud in different layers. This chapter describes this architecture, which has been proposed for the PATRICIA project. Finally, the technological limitations of hardware and software for the selected pet robot made necessary the modification of both aspects (hardware and software). These modifications have been designed and developed mainly by the PhD candidate taking into account the proposed architecture described in this chapter.

The reminder of this chapter is organized as follows. Section 2.2 presents the taxonomy of social robotics. Section 2.3 a concise classification of Social Robots applications in children's hospitals. Section 2.4 details the anxiety and stress phenomena observed in children under leukemia treatment. Section 2.5 describes the overall benefits of using pet robots and some cases already developed. Section 2.6 summarizes the features, facilities, and limitations of the Pleo robot to reduce the aforementioned effects. Then, Section 2.7 articulates the designed cloud robotics architecture to boost the Pleo capabilities and the distributed intelligent system deployed on top of it. Finally, Section 2.8 describes the learning phase of this architecture and Section 2.9 concludes the chapter.

2.2 Taxonomy of Social Robotics

A taxonomy of design methods and systems components used to build socially interactive robots that is still valid was presented in [FND03]. Following this taxonomy, the current state of the art is studied and categorized by use and application area.

Design Approaches: Talking about the design approaches, the objective of the *Functionally designed approach* is to design a robot that outwardly appears to be socially intelligent, even if the internal design does not have a basis in science or nature. Hence, design must show the mechanisms, sensations, and traits according to the psychology of the people by which they understand that a creature is socially intelligent. Unlike the Functionally designed approach, in the *Biologically inspired approach*, designers try to create robots that internally simulate, or mimic, the social behavior or intelligence found in living creatures.

Design Issues: *The Real-time performance* of the socially interactive robots operating at human interaction rates. Thus, a robot should simultaneously exhibit competent behavior, convey attention and intentionality, and handle social interaction. This approach fits the behavioral needs of our robotics platform. Conversely, a *Human-oriented perception* robot should proficiently perceive and interpret human activity and behavior, including detecting and recognizing gestures, monitoring and classifying activities, discerning intent and social cues, and measuring the human's feedback. This kind of ability requires a high cost of computational resources, sensors and additional hardware. For *Natural human–robot interaction* the robot should manifest believable behavior: it should establish appropriate social expectations, regulate social interaction (using dialogue and action), and follow social convention and norms. A bidirectional communication should be established, which may not be feasible due to hardware limitations. Finally, for the *Readable social cues approach*, a socially interactive robot should send signals to the human in order to: (1) provide feedback of its internal state; (2) allow human to interact in an easy and transparent manner. This approach requires a high level of bidirectional communication.

Embodiment: It will be considered from two perspectives: (1) *Morphology*, because the shape and structure of the robot is very important considering that it helps to establish social expectations; (2) *Design Considerations*, since a robot is designed to perform tasks for the human, then its shape must convey an amount of "productness" so that the user will feel comfortable. Moreover, a robot's design should reflect an amount of "robot-ness". This is needed so that the user does not develop detrimentally false expectations of the robot's capabilities. On the basis of the embodiment, a robot can be classified as *Functional*. The robot's embodiment should first, and foremost, reflect the tasks it should perform. The choice and design of physical features is thus guided purely by operational objectives especially service robots. *Anthropomorphic* embodiment tends to attribute human characteristics to a robot with a view to helping rationalize their actions, and robots with *Zoomorphic* embodiment have been designed to imitate living creatures, which is important to establishing human-creature relationships and empathy.

Emotion: Emotions are complex phenomena and often tightly coupled to social context. Moreover, much of emotion is physiological and depends on embodiment. The primary purpose would be that emotion helps facilitate believable human–robot interaction. Artificial emotions could also provide feedback to the user, such as indicating the robot's internal state, goals and intentions. Similarly, Emotions as control mechanism, Speech, Facial expression and Body language are highly effective methods for communication. Due to the complexity of interacting with emotions with human beings, is often opted for non-verbal unidirectional communication to express and communicate the needs and objectives of the robotics platform.

Dialogue: This is an important subject in social robots. Natural Language dialogue is determined by factors ranging from the physical and perceptual capabilities of the participants, to the social and cultural features of the situation. The most viable option is usually Non Verbal (Social conventions) dialogue. There exist many non-verbal forms of language, including body positioning, gesturing, and physical action. Since most robots have fairly rudimentary capability to recognize and produce speech, nonverbal dialogue is a useful alternative. Work developed in [BV18] helps to understand the central idea of expression as a form of dialogue, which we think of as externalizing hidden information of an agent, in our case a mobile robot. This proposal analyzes the implementation of LED lights as a means of communication between the mobile robot and humans. Some advantages of this system are its simplicity, cost, ease of communicating at a distance. Social conventions [FND03], or norms, can also be expressed through non-verbal dialogue.

Personality: Personality may provide a useful affordance, giving users a way to model and understand robot behavior. The behavior of social robots can be implanted or could be learned. It is organized in social robots into five groups: Toollike, Pet or creature, Cartoon, Artificial being, Human-like. A robot's embodiment (size, shape, color), its motion, the tasks a robot performs may also influence the way its personality is perceived.

Human-oriented perception: To interact meaningfully with humans, social robots must be able to perceive the world as humans do. People tracking, Speech recognition, Gesture recognition, Facial perception are currently techniques of perception not completely reliable and impose restrictions of use in controlled environments.

User models: In order to interact with people in a human-like manner, socially interactive robots must perceive and understand the richness and complexity of natural human social behavior. Detecting and recognizing human action and communication provides a good starting point. More important, however, is being able to interpret and reacting to human behavior. A key mechanism for performing this is user modeling. There are many types of user models: cognitive, emotional, attentional, etc. A user model generally contains a set of attributes that describe a user, or group, of users. Models may be static (defined a priori) or dynamic (adapted or learned). Information about users may be acquired explicitly (through questioning) or implicitly (inferring through observation). They are employed for a variety of purposes. User models will be useful for adapting the robot's behavior to accommodate users with varying skills, experience, and knowledge.

Socially situated learning: In socially situated learning, an individual interacts with her/his social environment to acquire new competencies. Robot social learning should be used for transferring skills, tasks, and information. Imitation is another important mechanism for learning behaviors socially in primates and other animal species

Intentionality: It is the last topic to be considered. Attention means that a robot should be able to identify relevant objects in the scene, address its sensors towards an object, and maintain its focus on the selected object. Expression in detail is understood as the intentionality that a robot should exhibit in goal-directed behavior.

2.3 Classification of Social Robots Applications in Children's Hospitals

As explained in [San+14] there are three ways of using the robots in the classrooms that cover from perceiving the robot as an object to a subject: 1) Design Robots, 2) Use the robots as a facilitator, or 3) Use the robots as social partners (classmate, teacher, etc.).

The first way is already considered in the taxonomy of social robots. In a similar way to classrooms, in social robotics focused on the use in children's hospitals, we are focusing in the second and third usages of the robot (facilitator and social partner). In order to clarify the difference between these two usages we define each type of robot as:

- *Robot as a facilitator* that creates a context where patients are engaged and focused on achieving the educational goals of the tasks requested by the hospital staff.

- *Robot companions* (social partner) as a technology to serve humans as assistants. Such robots can learn new skills and tasks in an active open-ended way and to grow in constant interaction and co-operation with humans.

In both cases we can take advantage of the benefits of the social behavior of the robot to engage children attention, and thus, a higher immersion that concludes in a better healing process. This enhancement of the knowledge acquisition process can be done in two different ways: THROUGH the interaction with the robot or WITH the interaction with the robot. For example:

- A robot can help the hospital staff collecting relevant data while the child is interacting with it.

- Playing with the robot has positive effects such as affection and fun in children similar to real contact with pets, as the child may come to empathize with the state of the robot pet.

- The child can improve different skills and physical conditions just playing with the robot.

In the following list, we detail a set of five roles that a Social Robot might play. These roles are linked to one or more tasks that the robot can perform and that justify the use of social robots in hospitals:

1. Observing Station: due to the sensing capabilities of a robot, it is easy to use the robot to collect data directly or indirectly from the child. Sometimes this acquisition of information takes place passively, i.e. the robot records the state of its sensors during the interaction with the child, or it is obtained from the user in an active way through the social interaction (for example asking how are they feeling). We can use all these features to keep the patient's activity and mood up to date.

2. Hospital staff assistant: A robot with a set of previously programmed activities can adapt customized tasks according to the progress, reinforcements needed, etc. At the same time, the robot can score these activities and complete reports about the state of these activities. In other situations, a robot can be a social mediator that assists the patient in an activity creating a proper context and a good atmosphere.

3. Caregiver: The robot can detect when there are behaviors out of the regular pattern and habits and trigger an alarm process directed to hospital staff. One of

the most common tasks could be to follow up a medication process. As well as a robot can physical monitor the child and detect any potential illness.

4. Friend: Maybe the most aligned role with the adjective "social" is the role of being a friend. Social Robots seek the goal of creating an emotional link and empathize with the patient. Through this connection, the robot can improve the engagement with a task or improve the emotional state of the child.

5. Educational Tool: A social robot enhances the child's possibilities of understanding aspects of his or her general hospital stay, either because he or she has to follow a treatment, or because he or she is not well, etc..... Always focused on positive aspects and thus improve his mood. A social robot with the ability to be customized or programmed increases success for this purpose. Due to the possible absence from school for a long time, it can also be used to reinforce or acquire new knowledge according to their school level.

A perfect Social Robot should be able to play the previously mentioned roles according to the application and character that has to play. However, a trade-off between cost, general purpose, quality of interaction, and quality of the product are constraints that prevent the robot to have all the possibilities.

2.4 Anxiety, Stress and Pain Associated to Children under Leukaemia Treatment

In the middle of past century, most children with cancer died within a few months after the onset of the disease. Rapid advances in medical research have luckily decreased this mortality rate. Nowadays, over 90% of children with acute lymphoblastic leukemia with standard risk features survive [Mye+14]. However, the improved survival rate is, in part, due to more intensive therapies of two or more years duration. Current medical treatment regimens for these children include recurrent painful procedures such as bone marrow aspirations and lumbar punctures. These interventions cause high frequency of psychological problems such as needle phobias, anticipatory vomiting, generalized fear responses to hospital, stress, anxiety and depression.

Children in oncology units often suffer unpredictable and uncontrollable pain that drives the child and his/her family to desperation, despondency and distress. In addition, most painful treatments such as injections and especially bone marrow transplantation provoke anxiety that can create a vicious cycle for subsequent painful experiences.

Parents are also affected with both the diagnosis and the child reaction during the treatment. It is noteworthy that parents may exhibit physical and emotional symptoms such as loss of control, self-esteem, depression, anxiety, and present a higher risk of developing mental illness [Lin+12]. These reactions may be present in the relationship with the health care team and negatively influence the child treatment.

The medical methods that have been and could be used, such as general anesthetic or sedation have drawbacks. These medical methods are often not effective and results in undesirable reactions that hinder the correct treatment.

What all recommendations have in common is that try to engage in activities beyond the illness experience helps to improve patient quality of life. In [KH99], distraction is introduced as an action with a positive effect on children's distress that reduces the level of pain.

2.5 Therapy with Robots

Recently, pet-like robots have been introduced in health related interventions. These life-like creatures seem be able to reproduce the social-emotional benefits associated with the interaction between children and companion animals such as entertainment, relief, support and enjoyment. Therapy with pets has been proved to be successful in several paediatric interventions [Chu+14] provided children tend to develop engagement, empathy, and enjoyment feelings with their animal pets [Hal08], reducing accordingly their stress and anxiety. Therefore, robotic pets able to elicit similar social bonds with children are being considered in hospitals to provide therapy relevant effects in the way real pets do [Far+14].

One of the main challenges of this role is not only to attire children attention –what literature supports they do easily–, but to remain compelling in the long-term to achieve the therapeutic related intended effects over time. While this field is well studied between humans, it is not between humans and robots.

There is a lot of controversial in the literature about how much is the minimum duration of an intervention to consider an interaction as a long-term relationship. Time periods vary from 2 months [SCG09] to 5 weeks [Kar+09]. In a different way, a long-term relationship can be also defined by the quality of the relationship rather than by its length [LMP13]. Hence,for this study, long-term interaction is considerd the one that extends beyond the novelty effect.

The PATRICIA project proposes the use of a robotic pet as a complementary therapy to the offered generic support. In the literature we can find some examples of therapeutic alternatives aligned in the same direction: in [Lee+12], toys and animated cartoons were used for distraction purpose; in [Ngu+10] music was played as entertainment; finally, in [Fav+01], art therapy is proposed against the fact that during the treatment the child's balanced growth is under danger because of everything related to the illness cure.

The main reason to propose a pet robot for the approximation to reduce pain and stress is because being the owner of a pet is a rewarding experience, which may let children feel better. There are studies like in [Gag+04; Mus84; Hal08] as relevant references, where the therapy with pets demonstrated to be a success increasing the benefit from factors like warmth, mood, creativity, capacity for enjoyment, and empathy obtained from evaluation through vital signs, pain ratings, salivary cortisol levels, emotions, activity/rapport, perceived benefits, child/parental satisfaction, and impact on environment via self-report, interview, or observation and videotaping. Even more, there are a list of few aspects that makes an artificial pet robot a better solution than a real pet:

1. The risk of getting an infection, which is higher if you are under disease treatment, and

2. the maintenance of a pet in a medical environment.

In [Hee+13] is shown how a pet robot demonstrates a high social presence, thus it might be considered a good approximation to have a real animal.

Therapy with animal pets has been proved to be successful in several situations [Gag+04]. Children tend to develop engagement, empathy, and enjoyment feelings with their animal pets [Hal08]. These feelings reduce their stress and anxiety. Pet-like robots are an alternative to real pets when improving patient experience at hospitals by being a distractor that reduces anxiety in situations such as before surgery or painful treatments [Nav+13a]. In [Hee+13] a study is presented as well as a comparison of different commercial pet-robot animals to describe the relevant characteristics to foster a useful interaction between pet robots and humans. One of the key parameters identified in [Hee+13] to be measured is the *engagement*. The challenge to increase the engagement between the robot and the child is based on the fundamental that similarly to the master-pet bond, also a bond may emerge between a child and a pet robot with social skills. This bond implies a hierarchy between master and pet that could be improved if the robot has a positive response to a master demand during the long-term interaction [LMP13].

There exist a few antecedents of robots being deployed in paediatric hospitals supporting children and relatives well-being during hospitalisation in a long-term basis. According to a recent survey [LMP13], studies on long-term effects of social robots as companions in health organisations are mainly focused on elderly people in nursing homes, featuring both, robotic-pets like *Paro* and anthropomorphic ones like *Robovie*. Moreover, in the few studies on social human-robot interaction in the scenario of paediatric hospitals, the robot took the role of a coach or assistant in rehabilitation routines [Wu+10], education or a short-time distractor in stressful or painful procedures like vaccination [Ber+13].

Social engaging robots able to establish satisfactory interaction and eventually long-term relationship with children have been proposed as supplementary tool in paediatric hospitals for rehabilitation [Pla+00], autism therapy [Alb+15a] [Beg+15], treatment adherence and compliance, and even provide entertainment, enjoyment and comfort [OMC10; NP14; Fer+15].

Latest advances in hardware architectures and software developments have raised robotics platforms to the foreground of human healthcare: from elderly mental therapy [SW11], to assisted surgery [Gom11], including rehabilitation medicine [Kre+03] and medication monitoring [Dat+11]. Typically, these healthcare robots are devoted to conduct specific and repetitive tasks that have been previously scheduled and detailed by an expert according to every patient sickness. So far, this approach has been shown to work properly for a considerably large number of situations where the disease parameters and possible patient outcomes are strictly delimited [BA06]. However, there are some illnesses that still require a clinical professional in order to provide patients with the most appropriate treatment and guidance. An appealing use case that portraits this framework concern is seen on how physicians and nurses deal with the pain and anxiety that children generally feel when they must be hospitalized. This process requires a deep and personalized interaction with every child in order to select the most convenient actions to reduce these symptoms

In fact, the reduced processing power, storage capabilities, and number of sensors included in these robots prevent themselves to go beyond their historically static and predefined behavior [HTW12; VX06]. Unlike what has been achieved in other domains

[Nav+13b], it is still not feasible to codify the knowledge of the expert (i.e., medical staff) inside a single robot on a reliable and cost-efficient way. Nonetheless, looking at the computer science field, an overwhelming amount of research has been conducted on distributed systems that take benefit from the Internet as a key resource to enable massive parallel computation and share vast amounts of data using commodity hardware –lately referred to as *cloud computing* [VZ09; ADE11]. Such observation drove practitioners to officially coin the term *cloud robotics* in 2010 [Kuf10], which basically consists on applying the fundamentals of cloud computing (i.e., elastic resources, on-demand services, virtually infinite scalability) to robots.

The purpose of the rest of the chapter is to present a prospective view of a new generation of healthcare robots –combining cloud robotics and artificial intelligence– that provide children patients with an effective and individualized assistance. More specifically, we aim to use a low cost robot named Pleo –a human-social robot that successfully connects with children [PK10]– to:

1. supply young patients with a kind partner to enhance their stay in medical facilities,

2. build a cloud multi-agent system able to perceive, collect, and share hospitalized children status,

3. design an intelligent layer to guide the behavior of every patient's robot, and

4. explore the most effective actions that the Pleo robot can carry to improve the patient experience by eliminating or minimizing pain and anxiety.

The underlying idea behind this PhD thesis is to monitor the interactions between the robot and its associated patient in order to share their local conclusions (e.g., when the robot flashes its lights the child relaxes) with other robots and obtain a dynamic pool of possible actions to be applied at every situation (e.g., flash robot lights when child is excited). Note that the intelligent system is in charge of selecting the best action at any time, since every patient may react differently to the same stimulus.

2.6 Pleo rb, the Robot Mate

The robot used in this study is the *Pleo rb* robot, a low-cost commercial entertainment pet-like robot imitation of a baby Camarasaurus dinosaur developed by *Inno Labs*. It is endowed with a set of characteristics like expressiveness, baby-likeness, behaviors, and others that make the platform suitable for long-term interaction, mainly with children, as is shown in [Hee+12; Día+10; Fer+10; Jac09]. All these studies found the development of a social relationship and bond with the robot. More specifically, in [Hee+12] the authors proved that the score of *social presence* of the Pleo robot is correlated with the score on *attitude*, *emotional attachment* and the attribution of social adjectives. In addition, children who interacted with the robot spent more time on affective relationship and request for reciprocity activities against using the robot as an object.

The Pleo robot is powered with a *Life OS* operative system that allows the robot to evolve through time and to interact in a bio-inspired way. It is an event-based behavior that plays its implemented micro behaviors like a role game character according to the experience, the acquired skills, and a set of parameters that change over time.

To identify the key Pleo behavioral parameters we initially ran sessions using the robot in a regular school with 20 kids playing with the robot in pairs, in different hospitals facilities in one-to-one kid-Pleo interaction and in group sessions with multiple kids and multiple robots at the same time, and in a robotics summer camp with kids who already saw the Pleo robot in the past. Before and after each activity we measured the internal variables of the Pleo robot. Specifically, these parameters are: *Mood*, *Physical*, *Emotion*, *Health*, *Feed*, *Activity*, *Obedience*, and *Skill*. All of them are in a percentage scale. Values for these variables affect the Pleo's response when interacting with kids. For instance, if the *Feed* is at 100%, the robot will refuse to eat, or *Obedience* close to 0% means that the robot is not following orders. As a real pet, if these parameters are not modified, the interaction can drive into frustration and decrease engagement. Through the observation, we identify the *Physical*, *Feed*, *Activity*, and *Obedience* as the key factors that play a significant role in the drop out of kids during the play game with the robot.

So it is clear that Pleo's characteristics provided by the equipped hardware like the different tactile sensors, speakers, microphones, a camera sensor, IR sensors, and a RFID sensor, as long as the software that compose the *Life OS* system inside the robot with the internal drives like hunger, sleep, and several mood modes: angry, happy, scared, etc., are good to have a similar social interaction experience compared to real pet animals. However, the robot has a strong technical limitation in terms of extracting internal data that can be useful to determine the causes of its behavior and how others are interacting with it. Furthermore, from the commercial version is impossible to bias the actions of the robot as we can do with trained pets. What manufacturer provide to remotely interact with the Pleo are:

1. one micro SD card slot next to the battery, and

2. a serial interface that can be wired connected to a monitor device.

In order to develop an on-line system to monitor and control the robot internal variables we propose to add wireless connectivity to the Pleo. We can perform it in a non-invasive way, adding a Bluetooth / WiFi gateway between the USB connector and remote computer. Otherwise it can be implemented in an invasive way that consist on soldering two wires in an universal asynchronous receiver/transmitter (UART) placed in the body board. At the start of the project we were using a wired connection with the USB terminal and an external power supply. Further technical development will be referred in the next chapter most focused in technical aspects of the robot.

2.7 The Cloud Concept

The cloud maximizes the effectiveness of the shared resources from a set of devices connected to a network. What we proposed in the PATRICIA framework is a cloud architecture that allows users and artificial agents to induce behavioral states to a cloud composed of several Pleo robots. Figure 2.1 shows the cloud architecture that allows human users and artificial intelligent agents to stimulate the pet robot by modifying its internal states. It depicts a conceptual overview of the overall project where the three key elements are the cloud, the robot companion, and the therapy performed using the Pleo robot.

The system was designed, developed and deployed in a private network with a local server on a computer. The local server runs over AMPPS and uses a Linksys N750 router. The treatment to the kids in different places is performed with several Pleo rb whose behavior is biased through the cloud and its interactive devices.

The three stimulation elements in this cloud robotics design that can modify Pleo's internal states through the cloud are [Alb+15b]:

The artificial intelligent agent. It is aimed at learning which decision parameters and descriptors are relevant.

The interface. It induces customized behavior to Pleo by changing its parameters. This element has been currently developed as an Android app along with physical modifications for wireless communication.

The VLEO. It is a tangible user interface that combines a virtual avatar with augmented reality to reproduce the Pleo robot (see Figure 2.2). It interacts with other pet robots on the cloud.

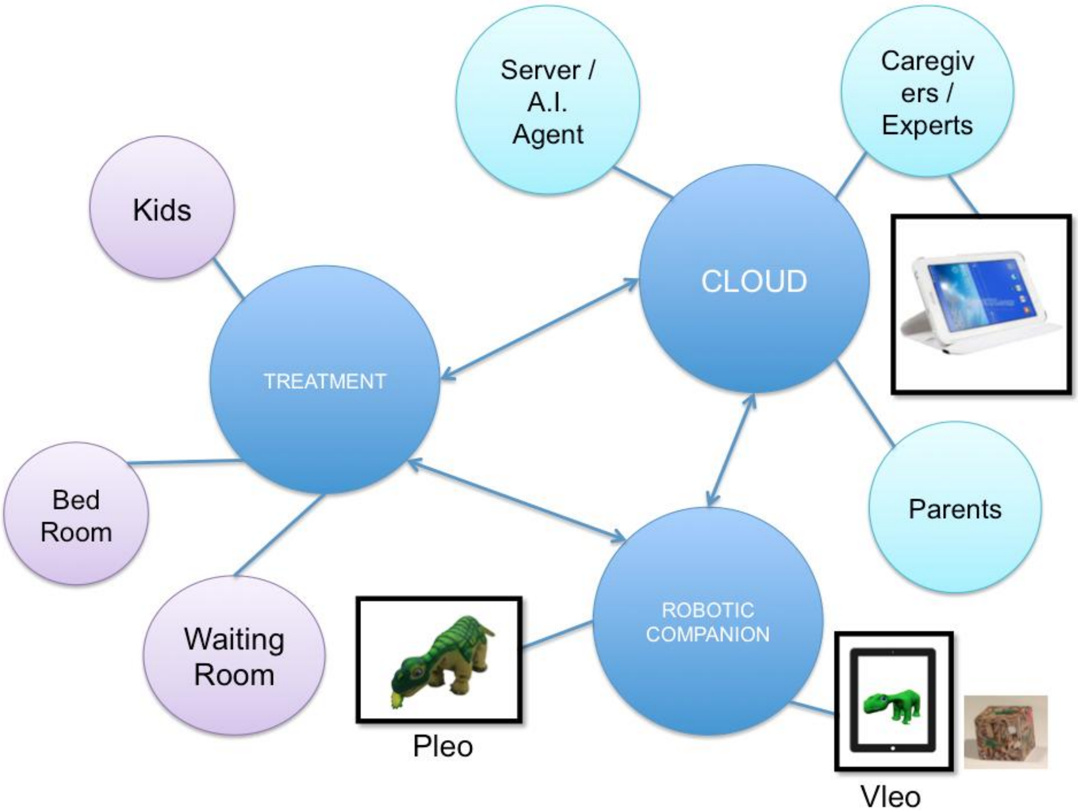

FIGURE 2.1: Cloud system layout for the PATRICIA framework. The three key elements are the cloud, the group of robot companions, and the therapy treatments.

VLEO is a smart avatar. What makes VLEO unique is that it is a virtual character that interacts with both humans and Pleo robots. It is proven that tangible devices increase the quality of interactions compared to those interactions with virtual agents. A down side is that physical agents are constrained by their size and shape as well as their environment. By combining a virtual agent and a physical robot it is possible to increase the complexity of an interaction through narratives and virtual worlds.

VLEO's controller is a cube. Each face of the cube represents a Pleo's state change. By turning the cube children can modify the states of Pleo. The cube's faces have a pattern that is read by the camera of a tablet, and the tablet is connected to the cloud server where the game engine (Unity) enables a graphic rendering of a virtual Pleo. The visual tracking of the cube is performed by using Vuforia Unity Extension, and the magnitude of the state change is controlled by the angle of the cube. Pleo's connectivity to the server is done through a local processor (computer or Raspberry Pi) using the battery system with Bluetooth.

FIGURE 2.2: The VLEO smart avatar and the cubic tangible user interface (TUI).

2.8 The Learning Phase

Although Pleo robot is a powerful and versatile tool to deal with children [PK10], its behavior must be carefully addressed in order to effectively reduce their anxiety and stress when they are hospitalized. Indeed, every child may react differently to the same robot-driven-stimulus, which prevents practitioners from programming Pleo with a closed set of predefined actions. Therefore, we propose to use data mining techniques in order to:

1. automatically analyze the behavior of every child,
2. compare it with past experiences, and
3. build the most appropriate response to the particular child status.

Data mining techniques are traditionally classified into two distinct disciplines, namely supervised and unsupervised learning paradigms. The former aims to make accurate predictions after assuming an underlying structure in data, which requires the presence of a teacher during to train the system and obtain a reliable knowledge model. On the contrary, the latter aims to discover regular-occurring patterns beneath the data without making any a priori assumptions concerning their underlying structure.

Nevertheless, some modern problems in data mining have failed to fully fit into one of these paradigms [CDC13]. In fact, constructing a predictive model from a pure supervised way in real world domains is often unfeasible due to:

1. the dearth of training examples and

2. the costs of labeling the required information to train the system [Nav+13b].

In addition, the unsupervised paradigm does not take into account the particular characteristics of the problem domain, thus it cannot exploit the search guidance that uses the supervised approach. This issue makes pure unsupervised learners prone to fail at recognizing the interesting patterns –i.e., those that are uncommon and valuable– from the uninteresting ones. This situation has driven practitioners to explore a new technique coined as semi-supervised learning, which consists on combining both approaches to overcome their individual limitations.

2.8.1 Semi-supervised Learning in Hospitalized Children

Certainly, neither supervised –too many examples to be labeled– nor unsupervised learning –some rare and specific examples might be relevant– approaches should work when discovering patterns of relations between Pleo robots and children. Differently, semi-supervised learning exploits the unsupervised strategy to obtain accurate predictive models from a reduced set of previously labeled (i.e., supervised) instances, which minimizes the costs associated to obtaining a reliable and fully mapped training set from real-world domains. In this regard, the algorithm first trains the system with a reduced set of labeled examples to obtain a preliminary *protomodel*, which will be used to label the vast amount of remaining data. This strategy is referred to as *self-training* [HH12]. Then, the final model obtained by the learner is used for future predictions.

So far, this strategy has been successfully applied in a variety of challenging domains such as artificial olfaction [De +12], gene classification [HF12], protein prediction [Wan+12], image retrieval and segmentation [Mar+11], handwritten word segmentation [SM07], and non-invasive diagnosis of scoliosis [Seo+10], which supports its effectiveness.

An appealing framework for semi-supervised learning lies in the *Michigan-style Learning Classifier System* (LCS) approach [But06]. This framework consists of an online cognitive-inspired system that combines a credit-apportionment algorithm with Genetic Algorithms (GAs) [Gol02].

In what follows we introduce the intelligent architecture of the proposed algorithm in order to obtain high quality predictive models from the domain of long-term hospitalized children.

2.8.2 Intelligent System Architecture Based on Cloud Robotics

The reduced capabilities and features of Pleo robot prevent itself to behave as a LCS. Besides, selecting a more powerful robot may derive into an expensive approach, which is not suitable for this use case. Therefore, we proposed to build a multi-agent system using the idea of cloud robotics. Specifically, we propose to connect every robot to the Internet as shown in Figure 2.3 and, thus, build a cloud of Pleos that continuously upload and share their collected data.

In order to obtain reliable models from the huge amounts of data provided by the cloud, it is mandatory to build a scalable approach. To settle this hurdle, we have divided the system into two distinct layers as shown in Figure 2.3:

1. the low level layer, composed by a set of Children Assistant Agents (CAAs), each one integrated in a different Pleo, which perceives information from the sensors of the robot, and

2. the Information Management Agents (IMAs), the upper layer that aggregates the information received by the CAAs thus building the knowledge model.

From time to time, defined by the user, distinct IMAs exchange rules in order to fulfill a global solution.

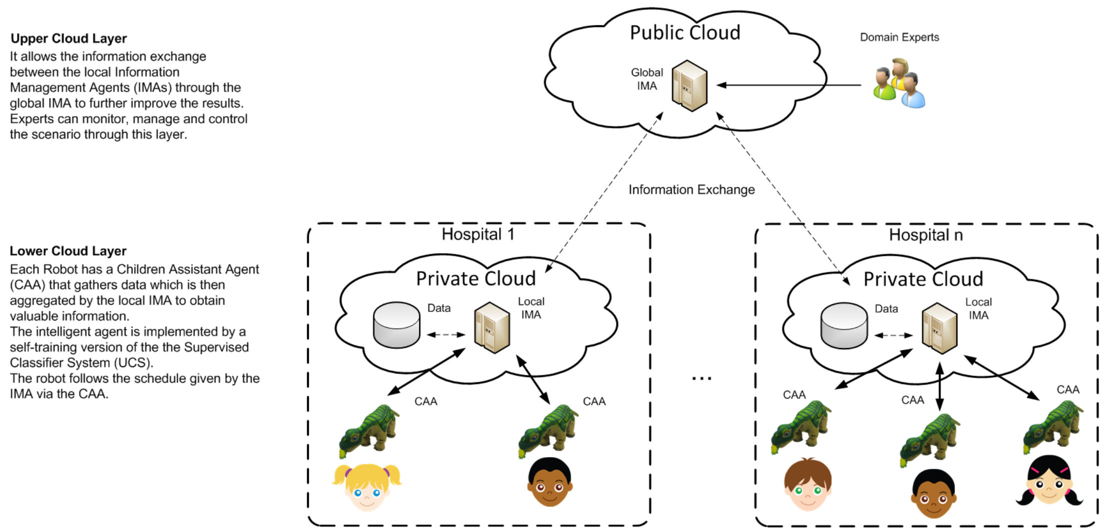

FIGURE 2.3: Scheme of the proposed cloud architecture. The Children Assistant Agents in the lower layer, integrated in Pleo robots, send information to the Information Management Agents in the upper layer, networked to the cloud.

2.8.3 The Intelligent Layer

Each Information Management Agent incorporates an intelligent algorithm which trains in a self-supervised way in order to obtain the predictive models. More specifically, IMAs incorporate a Michigan-style LCS that is specifically suited for these tasks due to its online nature. The most successful architecture for this class of task is found in the *supervised classifier system* (UCS) [OB08]. UCS is an accuracy-based Michigan-style LCS that takes advantage of knowing the class of the training instances, thus minimizing the explore phase by searching for the *best action map*, which consist of the set of maximally general and accurate classifiers that predict the correct class. UCS *evolves* a population $[P]$ of classifiers that, together, cover the input space, learning from streams of examples. The core of each classifier consists of a production rule and a set of parameters that estimate the quality of the rule. A rule takes the form

$$\textbf{if } x_1 \in [\ell_1, u_1] \wedge x_2 \in [\ell_2, u_2] \wedge \cdots \wedge x_k \in [\ell_k, u_k] \textbf{ then } c_j,$$

where the leftmost part contains k input variables that take values of the interval $[\ell_i, u_i]^k$, with ℓ_i and u_i being the lower and upper limits, respectively, of each interval and the rightmost part denotes the predicted class c_j. Each classifier has a set of parameters that evaluate the quality of the rule. These parameters are (1) the rule accuracy acc, (2) the fitness F of the rule, (3) the experience exp, (4) the numerosity num or number of copies of this particular classifier in $[P]$ and (5) cs, an estimate of the average size of the correct sets in which the classifier has participated.

The learning organization is the following: UCS receives input instances from the environment in the form of streams, that is, it receives a training example in the form $e = (e_1, e_2, \ldots, e_k)$. If the system receives a supervised event, the correct label of the example c is also given. Otherwise, c is estimated by the semi-supervised step. Then, the match set $[M]$ is created, containing all the classifiers in the population whose condition matches the example given by the environment. Afterwards, the correct set $[C]$ is generated out of all classifiers in $[M]$ that predict the class c. If $[C]$ is empty, the covering operator is activated generating a single classifier with a generalized condition matching the input instance e and predicting the class c. Following that, the parameters of all the classifiers in $[M]$ are evaluated in the following way:

$$cl.exp \leftarrow cl.exp + 1 \tag{2.1}$$

$$cl.acc \leftarrow \frac{\text{number of correct classifications}}{cl.exp} \tag{2.2}$$

$$cl.cs \leftarrow cl.cs + \frac{\sum_{cl_j \in [C]} cl_j.num - cl.cs}{cl.exp} \tag{2.3}$$

Finally, the fitness of the classifier is updated. In the first place, the relative accuracy $cl.k$ of each classifier is computed. For classifiers belonging to $[M]$ but not to $[C]$, $cl.k$ is set to zero; that is $\forall cl \notin [C] : cl.k \leftarrow 0$. For each classifier belonging to $[C]$, $cl.k$ is computed as $\alpha(cl.acc/acc_0)^{\nu}$ if $cl.acc < acc_0$ where acc_0 is the accuracy threshold and ν is an exponentiating function defined by the user, and 1 otherwise. Afterwards, the classifier fitness is updated:

$$cl.F \leftarrow cl.F + \beta \left(\frac{cl.k \cdot cl.num}{\sum_{cl_i \in [C]} cl_i.k \cdot cl_i.num} - cl.F \right) \tag{2.4}$$

Finally, if the average time since the last application of the GA of classifiers in $[C]$ is greater than the user-defined θ_{GA} threshold, the genetic rule discovery is triggered: a steady-state niche-based GA [Wil95]. In our implementation, we used tournament selection and two-point crossover [But06].

In the case of the deletion scheme, the offspring are introduced into $[P]$ via the subsumption mechanism: if there exists a sufficiently experienced and accurate classifier cl in $[P]$; that is, if $cl.exp > \theta_{sub}$ and $cl.acc > acc_0$ —where θ_{sub} is a user-defined parameter—, whose condition is more general than the new offspring, the numerosity of this classifier is increased and the offspring discarded. Otherwise, the new offspring is introduced into $[P]$. At this step, until the population is full, classifiers in $[P]$ are deleted following:

$$cl.P_{del} \leftarrow \frac{cl.d}{\sum_{\forall cl_i \in [P]} cl_i.d}, \tag{2.5}$$

where $cl.d \leftarrow cl.num \cdot cl.cs \cdot F_{[P]}$ if $cl.exp > \theta_{del}$ and $cl.F < \delta F_{[P]}$, where $F_{[P]}$ is the average fitness of the population, θ_{del} is the classifier deletion threshold, and δ is and user-defined scaling factor, or $cl.d \leftarrow cl.cs \cdot cl.num$ otherwise.

During the test stage, UCS class inference is performed using the knowledge acquired during the previous training stage. A new unlabeled example, previously unknown by the system, is given to UCS and all the matching classifiers vote for the class they predict proportional to the fitness and accuracy, that is,

$$P(c_i) \leftarrow \sum_{cl_j.c = c_i} cl.F \cdot cl.acc \tag{2.6}$$

The most voted class is returned as the output. Notice that during this stage $[P]$ is never modified.

The following section details which sensors of the Pleo robot are used by this intelligent system in order to learn from the children behavior and provide them with the best stimulus to reduce their anxiety and stress.

2.8.4 Experiment Design

The proposed overall system will be tested under the PATRICIA research project challenge. The test scenario ranges from acute patients, even in emergency-room (e.g., orthopedic surgery), middle-term intervention (up to around 8 days) and long-term hospitalization and companionship at home in chronic diseases. Patients will be recruited from Hospital Sant Joan de Déu in Barcelona, as they are part of the coordinated project. First studies will be conducted with leukemia diagnosed children who have to stay in the hospital for at least a month.

Pleo rb software is structured with virtual machines. One of this virtual machines, called SensorVM, registers in real time a huge number of software variables able to perceive the intensity of the interaction between the pets and the children. Part of these variables like `SENSOR_HEAD`, `SENSOR_CHIN`, `SENSOR_BACK`, or `SENSOR_LEFT_LEG` come from real electronic sensors like 12 touch sensors in the head, chin, shoulders, back and feet of the pet. Other variables like `SENSOR_SOUND_DIR` or `SENSOR_SOUND_LOUD` come from 2 microphones that can be used to detect the direction of the sound or changes in sound volume. There are also variables like `SENSOR_LIGHT` or `SENSOR_LIGHT_CHANGE` that come from a camera-based vision system that can be used to detect light levels but also to take pictures in order to identify people, objects, etc. We have also variables like `SENSOR_TILT` that come from a g-force sensor to identify how the pet is oriented once the children hands it. Other variables are processed through in-built functions to give values (derived sensors) about the kind of interaction between the children and the pet like `SENSOR_TOUCH_PETTED` to detect from a series of touch sensors how the child is petting its Pleo (i.e. caress the pet from back to head), or `SENSOR_TOUCH_TAP`, `SENSOR_TOUCH_HOLD` and `SENSOR_PICKED_UP` to detect how touch sensors are pressed or if the pet is lifted up from the surface. There are also many other variables coming from additional sensors that will probably not be monitored as they are not directly related with the interaction we are interested: foot switches, IR sensors, temperature sensors, timers, etc. In the first studies we will probably monitor the values of 25 different sensors from the 53 possible sensors of Pleo. In a second stage we will include information related to the camera.

As each Pleo is different and reacts in a different manner, we will also take into account information about its personality and behavior. This information is registered in different system variables but the robot can be hacked to report data about its age, gender, courage, temper, intelligence, health, feed, skill level, etc. Furthermore information about the actions the robot performs are also possible (i.e. joint movements or sounds). Part of this information is fixed and cannot be modified but some data vary as children interact with the robot. The overall number of variables is very high and data will be considered in different stages, beginning with those data related to its personality (basically 15 parameters) and later with the data related to dynamic behavior.

2.9 Conclusions and Discussion

The architecture proposed in this chapter aims to establish an interesting paradigm to address the problem of human-robot interaction where the volume of information we have to monitor in real time is significantly high. We expect results can foresee cause-effect reactions between the pets and the children in cooperative environments between one child and his or her pet or even between several children and their pets. These results should help the therapists to determine possible relations between the anxiety of the patients and the interaction with their robots in comparison with classical video analyses.

Chapter 3

Hardware Developments for the PATRICIA Architecture

In the previous chapter, the cloud robotics based architecture PATRICIA was introduced. The learning system for the user feedback was developed and the experimental setup was designed from the technical point of view. In this chapter, a technological contribution is provided going one step beyond to what seems a long path. Concretely, the development of a technical system is required for wireless communicating with Pleo in order to help the medical professionals who lead the therapy with the kid, to understand and control Pleo's behavior at any moment. The main aim with this development is externalising moods and psychological states to smooth pet-robot/child interaction through this Bluetooth communication. This chapter explains how this technological part was being developed as well as the obtained technical results. This chapter can be considered the core contribution of the candidate for this first technological approach to ultimate empathy machines in the form of social robots.

3.1 Introduction

In the last years many robot platforms have been introduced to be used as companion and therapeutic devices. However, most of them are closed systems with not enough flexibility in computing or hardware for a project like PATRICIA. After analyzing much of the existing platforms, the researchers of PATRICIA opted for Pleo, a commercial entertainment platform developed by Innvo Labs. In fact, the newest version of this platform, Pleo rb, has been considered. This device will be transformed into a cloud system client, by expanding its connectivity and power capacity. In addition, a graphical user interface capable to interact with Pleo will be built. This chapter is devoted to describing the associated modification of this platform to be adapted to the needs

FIGURE 3.1: The robot PARO, designed by Takanory Shibata and developed by AIST.

of the project. This part of the project is the one that the PhD candidate has had the greatest responsibility.

In Section 3.2 a list of robots developed as therapeutic platforms are presented according to our interests. In Section 3.3, the chosen platform, Pleo rb, is described with more detail. Section 3.4 briefly describes the operating system of Pleo: Life OS. In Section 3.5 some reflections about the technical framework and what hardware modification would be desirable for the project are depicted. In Section 3.6, the proposed solution in both aspects, hardware and software, is explained. The results are described in Section 3.7 and finally, in Section 3.8, some conclusions are drawn.

3.2 Companion and Therapeutic Robots

It is not an easy task to build a machine able to satisfy the human need for companionship in hard times in the form of pet robots. However, companies like Fujitsu, Innvo Labs or AIST are working hard on it. In the last years many studies worldwide have been presented with positive outcomes.

PARO (*comPAnion RObot*) is an interactive robot develop in the form of a seal (see Figure 3.1) by AIST, a leading Japanese industrial automation pioneer, and designed by Takanory Shibata in 1993, but did not begin to be commercialized until 2004 [SCG09]. It allows to provide the benefits of animal therapy to patients in environments such as hospitals and extended care facilities where using live animals present treatment or logistical difficulties. It is equipped with five kinds of sensors: temperature, touch, light, audio and position sensors. Additionally PARO is able to learn behaviors. This pet offers similar benefits as zootherapy, and is used in treatments to people with symptoms of Alzheimer and other disabilities.

FIGURE 3.2: The Huggable Teddy Bear, developed by Fujitsu.

Huggable Teddy Bear displayed in Figure 3.2 is being developed by Fujitsu as a therapeutic companion for hospitals or nursing homes, for health care, education, and social communication applications [Sti+05]. Hides a dozen of sensors to recognize facial expressions and movements of the patient by the camera on its nose. It is intended to record the patient's emotional state and react accordingly using a range of 300 shares scheduled actions to interact with the people around it. The robotic Teddy Bear can be plugged to a PC using a USB port. A voice synthesizer inside the device lets it channel the voice of a young boy. The sound is projected from a built-in speaker and synchronized to the robot's behavior.

ROMIBO is the newest robot in the category of open coded therapeutic robot [Shi13] specially designed to the research and treatment of autism disease in kids as well as traumatic brain injury and dementia (see Figure 3.3). It includes features taken from other therapeutic robots currently used in research, such as Pleo and Paro. ROMIBO can drive around, blink its eyes, speak and move its antennae. It has WiFi, Bluetooth, light sensors, an IR proximity sensor, accelerometers and an Arduino Mega. It has also an SD card to help teach it some new words.

Finally, **Pleo**, our chosen platform, is a robot with a shape imitating a Camarasaurus dinosaur, as it can be appreciated in Figure 3.4, that exhibits an appealing baby-likeness, expressiveness, and an array of different behavior and mood modes. Pleo has been tested in several research works focused on the effect of Pleo in long-term interaction, especially with children[Ang+12; Día+11a; CDA12; Hee+12] . Another kind of interesting research using this platform is robot ethics [Dar12], which plays a very important role in robotherapy.

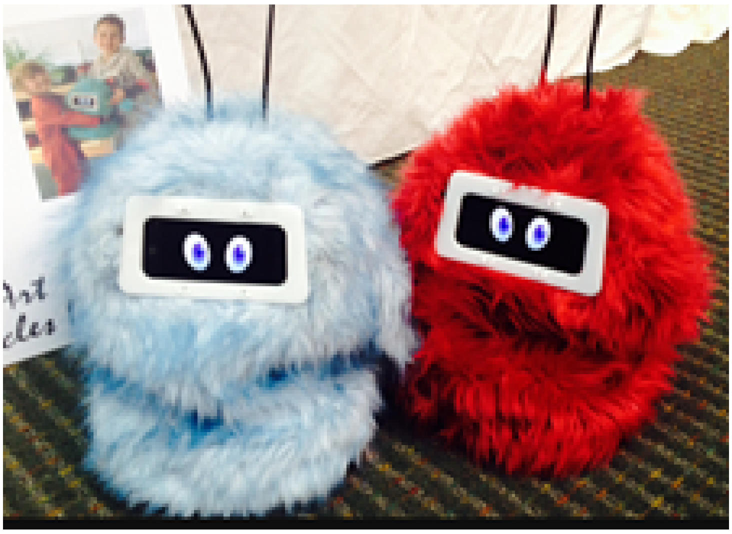

FIGURE 3.3: The ROMIBO robot, an open coded therapeutic robot.

3.3 Pleo and Pleo rb

Pleo is a commercial entertainment platform developed by Innvo Labs, a company located in Hong Kong and Nevada. It was designed by Caleb Chung. Pleo was unveiled on 2006 but Pleo shipments started on 2007. Since 2009, Pleo is owned by Innvo Labs Corporations (a division of Jetta). In 2011, a new version called Pleo rb (standing for ReBorn) was released. Pleo rb is similar to the original Pleo but the new version is endowed with more senses than the original one.

The robot is equipped with 2 ARM7 CPUs, 14 motors, 12 touch sensors, IR transceivers, 2 microphones, and 1 camera. It also has beat detection, 4 ground foot sensors, 14 force-feedback sensors (one per joint) and orientation tilt sensor. Pleo rb has more senses than the original. The enhancements include (see Figure 3.5):

1. Eyes: It can recognize colors and patterns.
2. Ears: It can hear and recognize the sound source direction.
3. Nose and mouth: It can sense what kind of "food" or "medicine" owners are feeding.
4. Skin: It can sense the temperature of its surroundings. It is also able to distinguish whether it is being petted or hit.
5. Time: It can recognize the time to wake up, eat and sleep.

FIGURE 3.4: The Pleo robot, the chosen platform for our study in the PATRICIA project.

There are altogether 9 new kinds of food and medicine items made for Pleo rb in different health and life situations and 7 new "learning stones": these can teach Pleo rb how to bow, dance, sign, walk towards their owner, play games, etc.

Pleo rb is designed to behave like a life-form, with 4 distinct life stages. When unboxed, it behaves like a newborn and needs to be "hatched" and brought up. With proper care, it will "grow up" into a juvenile after about two days. It starts to stand and walk smoothly during its teenage stage, and can then be taught to recognize its name. As owners continue to teach verbal commands, it will get to the mature stage and all features will be fully enabled.

It features also a pet like personality which develops in time, internals drives like hungry or sleep, and several mood modes: happy, extremely scared, curious...

3.4 Life OS

The software built into Pleo is referred to as the LifeOS. The LifeOS architecture is broken into three major layers:

- **Low-level**: This layer is an interface to the real hardware components, including the motor control, sensors, SD Card, battery, USB, camera, sound input and sound output. This includes the drivers that read sensor information, passing it

FIGURE 3.5: Main differences between Pleo and Pleo rb.

up to the mid-level layer, and output systems like the motor controllers which move joints.

- **Mid-level**: This layer provides the application services to the high-level. It performs much of the processing of the sensor input, and provides the native function interfaces to the high-level layer. This layer contains:Sequence system, Sound system, Motion system, Property system and Script system.
- **High-level**: This layer is where the majority of applications will reside, implemented using the Pleo scripting language. This is essentially Pleo's personality, determining how and when he responds to sensor input and internal goals.

3.5 Technical Framework

From the literature and preliminary studies, Pleo ability to engage children over time like a real pet would benefit from some kind of augmentation (augmented naturalness) to the autonomously displayed behavior.

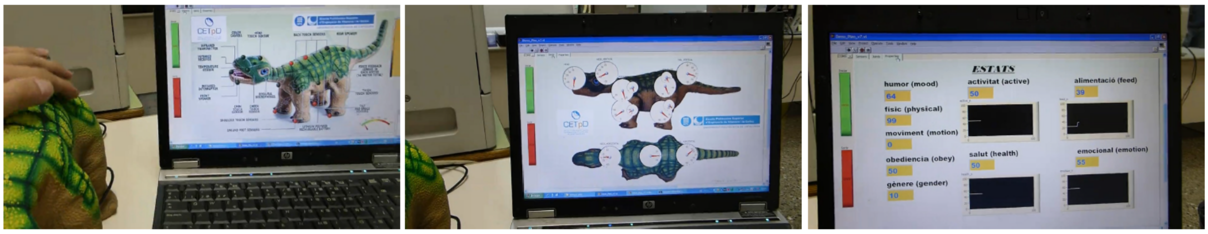

FIGURE 3.6: A graphical user interface developed for the PATRICIA project externalizes Pleo's sensors, actuators and internal state.

Long-term studies on people-robots relationships report however some drawbacks on Pleo's interactive behavior such as lack of responsiveness to social requests, lack of contingency to events, changes in behavior too subtle to be noticed by non-trained users. These drawbacks should discourage exploration and engagement [Jac09].

Technically, they have been determined in this project four degrees of Pleo's autonomy to be deployed when interacting with children in the real scenario of the hospital:

1. *Full autonomous behavior according to implicit –opaque to users– internal states*. Pleo's behavior is not totally predictable by the user at any time but may be inferred, anticipated or understood by the user according to previous experience in interaction, expectations and social comprehension of Pleos drives and situation awareness.

2. *Full autonomous behavior according to observable internal states*. A graphical user interface externalizes Pleo's internal states that facilitates the understanding and management of the interaction (see Figure 3.6).

3. *External control of Pleo's states*. The coordinator is enabled to modify or control the robot changing the internal states and letting the robot perform the correlative activity (see Figure 3.7).

4. *External control of Pleo's behavior*. Fully teleoperated control of the movements and actions of the robot. Children's behavior monitoring.

The three last technical set up implies the modification of the Pleo pet-like robot to expand its connectivity. Hence, it can be considered the implementation of a scalable cloud layout to manage the data transfer between the cloud agents, and different interactive devices to get better engagement.

To transform a toy robot like Pleo into a cloud system client we need to expand its connectivity minimizing the intervention over the hardware of the system, without modifying its pre-programmed bio-inspired behavior, without modifying its embodiment, and keeping a reliable trade-off between power consumption, data transfer, and connectivity to the cloud. Thus, we aimed to implement a new battery system with an embedded Bluetooth antenna that links up to multiple Pleos to a Raspberry Pi based hub/router [Alb+15b].

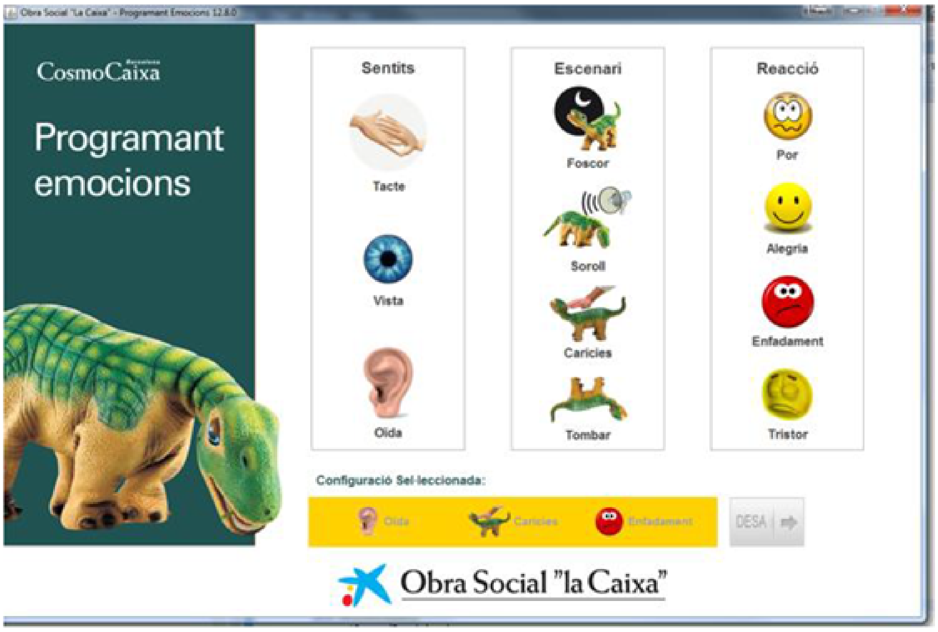

FIGURE 3.7: Emotions screen developed for the PATRICIA project allows to modify or control the robot behaviour.

Moreover, wireless communication with Pleo rb was implemented through a graphic user interface running on smartphones allowing:

1. remote acquisition of on-line information of Pleo internal states without stopping its interaction,
2. on-line control of Pleo's states and behaviors (e.g. a particular movement or sound), and
3. control other devices as the on-board camera [Lar+15].

Based on the previous ethnographic studies and the technical developments the next challenge is to be able to use Pleo in the paediatric hospital to:

1. Observe systematically the interactive behavior with Pleo and the dynamics of bond forming.

2. Assess the effect on children in terms of therapy related outcomes such as well-being, anxiety, perception of support, optimism.

3. Design internal states and Pleo interactive behavior to enhance the beneficial effects of Pleo's company.

Until now, it is not achievable to modify the software system of Pleo due to it is not a full open source. However, it allows to modify some values or to commit some precise actions in a certain moment. For example, it can change or just show how hungry is it, how happy is it, or also to ask it for walking or "to give paw".

Hardware communication with the robot is not so easy as in previous Pleo commercial versions, as long as the new one has the USB port, the serial interface and the Bluetooth connectors behind the battery spot. In order to obtain data in "real time" from Pleo whereas it is powered, it was connected to an external power while stabling a gateway between the USB connector and remote computer.

It is possible to get in real time the distinct values for the different sensors of Pleo adopting the method described. After that, some Bluetooth connections appear connecting a Bluetooth module to the UART port [Nav+13a] as a bridge between Pleo and a Raspberry Pi. Other processing platforms like Intel Galileo or Edison and wireless communications like ZigBee or WiFi could be also considered, depending on the power, processing or privacy needs. Then, the Raspberry Pi should be set into a little bag specially made for Pleo, and can access to the Internet thanks to a WiFi dongle, uploading the data to the cloud. However, there were two problems in that communication: first a lack of space, because original battery of Pleo was employed compacting the wires with the battery and leaving the Bluetooth module in sight[1]. It is a trouble taking in consideration that Pleo will be used by kids, then it will not accomplish the user specifications. Secondly, new Pleo robots are not equipped with this UART connector, so it could be exclusively tested in old versions.

Therefore, unfortunately each workshop that the psychologist/pediatric group has performed with the children of HSJD (the real scenario) to test the interaction between Pleo and the kids have been performed without any communication provided. And as this platform is new not only for the kids but also for the pediatric group, when Pleo has a bad mood or acts in a non-normal way there is no form to know exactly what is happening to it. So in that cases the pediatric group interact with Pleo based in their personal experience in order to correct the situation.

[1] You can check a video at https://www.youtube.com/watch?v=2qNdZFt8by8)

According to both, the desired robot autonomy, and the technical drawbacks when using the platform, this set of objectives will be pursued along this work:

- Bluetooth (Bth) communication for Pleo: to build a removable part that will be able to be mounted in any Pleo providing Bluetooth communication.
- Modification of Pleo's states: the coordinator must have the ability to control Pleo to make a specific action because the situation requires it. Android application has been chosen as interface to do that, due to it is an open source easy to spread in the society.
- Bluetooth-battery package: the removable part would fit inside the battery hole, in order to assemble the module in one package.

3.6 The Proposed Solution

This section includes a description of the solution to be developed and other features that have been considered.

3.6.1 Hardware

The proposed solution for the hardware challenge, shown in Figure 3.8, is to switch Pleo's battery for a battery-Bluetooth package. Distinguishable components are listed below.

1. *PCB*. Its main function is to become the conductive element between the batteries to the springs that feed the robot. Located in the base of the battery, it must fix the 4 pins that establish contact to the Bluetooth output of Pleo.
2. *Connector pogo pins*. They catch the signal that Pleo sends and will be processed in the Bluetooth module.
3. *Bluetooth module*. It receives the data signal from the robot and sends it to the device connected. The JY-MCU industrial serial port is one of the cheapest Bluetooth serial port modules in the market, but provided voltage is not enough. Then, a more sophisticated module is needed, for instance RN-41 microchip (see Figure 3.8(Middle)).

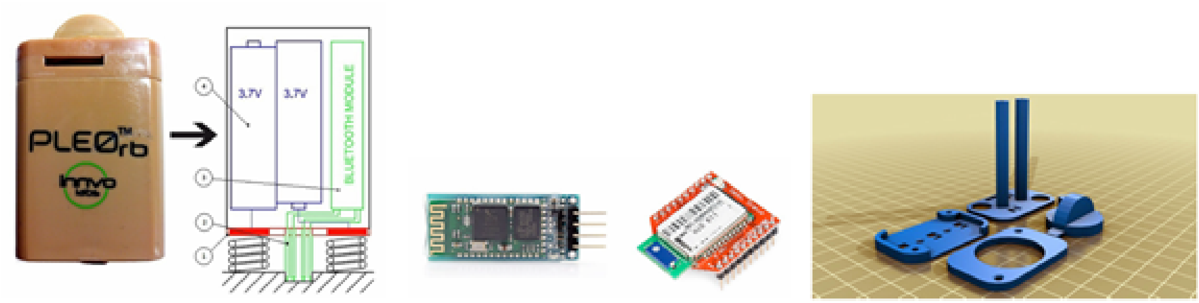

FIGURE 3.8: (Left) Layout of the proposed assembly; (Middle) Modules JY-MCU and RN-41; (Right) 3D print model.

4. *Battery pack*. Specifications of Pleo's battery are for voltage (7.4V), charge (2800mAh), power (20.72Wh) and max temperature (60ºC). So, it should be replaced by a couple batteries of 3,7V of size AA without problems However, we will check in the Subsection 3.6.3 how this sentence is not really true.

Once all the components are assembled and tested, a case to pack it with a 3D printer is made[2] . It can be seen in Figure 3.8(Right).

3.6.2 Interface

The interface must be as simple and comfortable for the user as possible, using buttons and images to understand Pleo's behavior. Moreover connecting to the Pleo robot must be user-friendly: Bluetooth must turn 'on' when the app is launched and a button should be present to search Pleo's signal and establish the communication. A first sketch of the main menu is shown in Figure 3.9. It should have a list of the different Pleo states, be able to modify the emotional status of Pleo, allowing to the user to ask for their value. If needed, it is possible to add more buttons for Pleo actions, in order to make a specific action when the situation requires it.

3.6.3 Connection via Terminal

Pleo USB connection does not support Win 64 bits, so a virtual image for XP 32 bits was implemented. The easiest way to connect to the robot is via PuTTY and USB connection[3]

[2]In fact, there are already some free models of Pleo's battery case in the Internet to download (http//www.thingiverse.com/thing:31721/ files.

[3]In order to do this, it is necessary to download the Pleo Development Kit, http://ipr10.wikidot.com/pleo

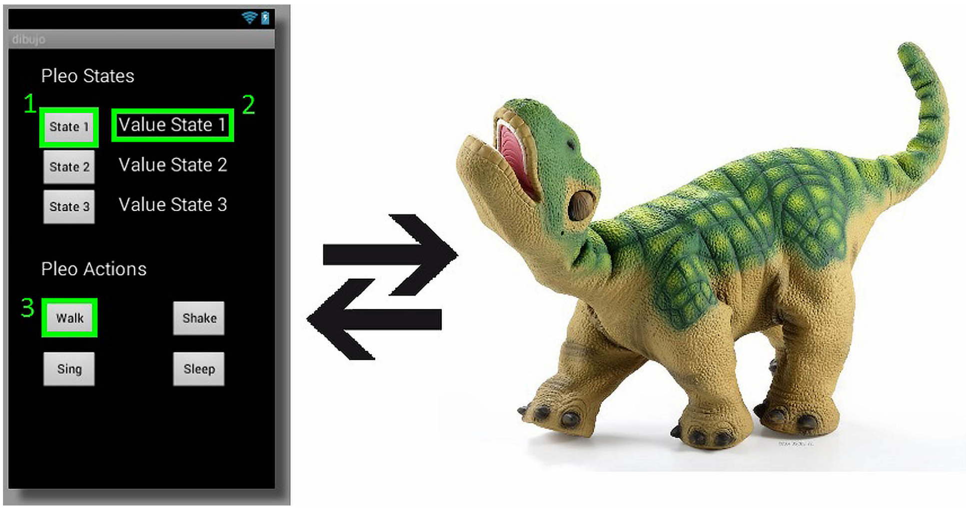

FIGURE 3.9: Sketch of the proposed interface using Bluettoth between the Pleo robot and the smartphone.

3.6.4 Bluetooth Assembly

One of the hardest challenges in this work is the difficulty to take measures to build the Bluetooth assembly. On the rear face of the battery inside the hole it is impossible to insert a vernier caliper to take measurement. Moreover the rear is a little wider than the external perimeter of the hole. This impossibility to get the Bluetooth pins positions to draw the layout coexists with very restrictive tolerances as long as the pins are separated less than 2 mm.

To solve the problem of obtaining the correct pin positions, a thin sheet of transparent plastic have been cut, introduced inside the hole and marked with a fine-tipped pen. Then the plastic is extracted, measured with the vernier caliper and drawn with a CAD tool.

Once drawn the layout, the next step is to build the PCB. Holes are drilled with a diameter of 1mm to set the Bluetooth pins and also at each path to pass the wires through them. The resistor must be welded and each of the corresponding wires.

Pins are pasted with contact glue, but it is not enough, because they are thin and can bend easily. It is also usual that the pins sink after using the PCB in the Pleo, reducing the distance of the pins and losing the contact between the pin and the robot.

Finally, a 10 times female header is welded to connect the RN-41 without welding directly to the module, that could damage it.

FIGURE 3.10: (Left) The battery works perfectly. (Right) Once Pleo has no power to make it run, its battery have exactly 7.39 V.

3.6.5 Power Issues

When the PCB is set inside the Pleo, batteries power the robot, but after pressing its button to turn it on, the robot does not move. It was thought that probably both batteries are not enough to power the robot and the Bluetooth module, so a button cell of 3,3V was used to power the RN-41, without taking up too much space. Then, after pressing the button, Pleo's makes the sound as wakening up, and sends some data to the screen of the terminal with it is communicating with, but afterwards the robot snores and turns off stopping the communication.

It seemed like a power failure, hence the minimum tension and intensity to make the robot work was measured. There it was discovered that the minimum power to supply to Pleo rb is 7.4V (equivalent to 3A), turning the robot to the sleep position in case of reducing its values a little bit. That explains why the same battery that Pleo carries provides more than 8.4V when it is completely full.

Another discovery was that Pleo rb, unlike USB wired communication, does not allow Bluetooth communication if the robot is not running.

3.6.6 Android App

Figure 3.11 shows how the interface looks like. First scene is a presentation to introduce the user. Here the application itself turns 'on' the Bluetooth of the smartphone or device where the app is installed.

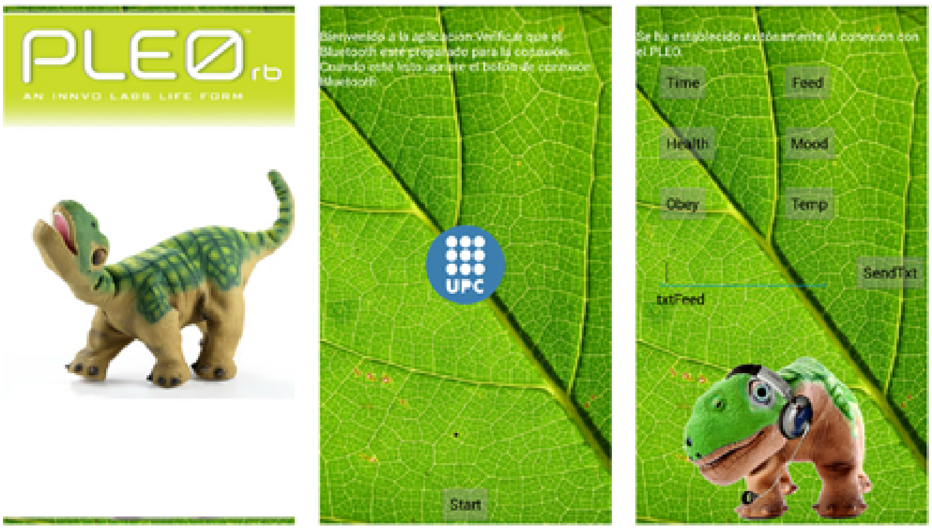

FIGURE 3.11: Different scenes of the application "PleoSays": (Left) Presentation; (Middle) Pairing with Pleo: (Right) Communicating.

At the next scene there is a button that users must push once the module RN-41 is powered in order to pair it with the device. Then the app searches the corresponding MAC direction and in case that it does not find it, displays an error message. On the other hand, if the communication is established the app redirects the user to the third scene or command window, where the user sends and receives data from Pleo.

When Pleo is switched on, unlike USB communication the robot starts sending data, information of the initialization of the source. Hence, the application developed cannot receive Pleo's states values or to send any motion command until all this initial info has been received and processed. If this is the aim, it is possible to hide all this data to the user.

3.7 Results and Discussion

Wireless communication between Pleo rb and an Android device is finally achieved. With the Android app developed, the user is able to obtain any state of the robot without stopping its interaction with the patient. It also contains an editable textbox to allow the user to send orders to the robot, authorizing the user to a long permission list of actions, as modifying Pleo's states, ordering to commit any action or sound, camera's options, etc. It has been a success to achieve the communication with the robot connecting the Bluetooth module to the output set behind the battery spot. As newest Pleo's versions have no UART port connection, the incoming works with Pleo should adapt to a solution similar to what has been explained in this chapter. From now it can be ensured that the bottom connection works properly and can be used in further research.

During the trials, it has been made evident that using a couple of 3.7 V cells is not enough to make Pleo run due to this values are too close to the operating limit. Using a third cell is needed to make the Pleo robot move.

Moreover, the developed Android app can be installed in many devices and its interface is easily understandable for users. After many hours working with Pleo, several observations can be expressed about it, which three have been highlighted and described below:

- Pleo is not a robust platform. It is a common fact for people that work with Pleo that one day without doing anything different of what they have already done before it does not turn on. Then, why to spend so many effort in working with this tool, if sometimes it breaks without knowing why? The answer is economy. If Pleo "survives" for more than one month working with the kids in therapy, investment can be considered as recovered, since it is very affordable.

- Pleo is selfish. It is not like a dog because Pleo does not react if the kid cries, laughs, plays,... This is a very important issue because it leads to an interest lost by the kid, and is known that the progress of the therapy is directly proportional to the motivation of the patient. If Pleo does not care of the kid, the kid will not care of Pleo and the therapy will be a failure.

- Related to the previous observation, and considering that the future of this research is the cloud net as explained, the cloud should collect the "emotional states" of the kids.

3.8 Conclusions

The first objective of this part of the dissertation, the Bluetooth communication with Pleo, has been achieved completely. Using the PCB with the extensible pins, we can supply Bluetooth communication to any Pleo, even those without UART connection.

The second objective, to modify Pleo's states from an Android device, or any of their possible actions, has been successfully achieved too, so helping the coordinator to understand and to control the robot using an easy app.

The third objective, to assemble a Bluetooth + Batteries package has not been fully completed. Pleo will work using 3 (not 2) AA cells and it will fit to the designed package in this work, but it was not completely developed, since 3D cage was built for two AA cells. However, it should be possible to build this assembly.

As far as Pleo is a commercial closed platform, alternative platforms should be considered in the near future. In this sense, two technical research lines are opened. The first one is either to consider commercial platforms as Pleo's alternative or to develop a pilot robotic platform to be certified for commercial use. The second line is working in the possibility to certify the employed modified device as a medical device for therapeutic purposes.

Part II

INVITE Research Project

Chapter 4

A Creativity Support System based on Transformational Creativity

The previous chapters of this thesis dealt with the incorporation of the socialization capacity into robots. The next chapters will deal with the incorporation of another 'purely' human skill capacity: creativity.

A new formulation of the central ideas of Boden's well-established theory on combinational, exploratory and transformational creativity is presented. This new formulation, based on the idea of *conceptual space*, redefines some terms and includes several types of concept properties (*appropriateness* and *relevance*), whose relationship facilitates the computational implementation of the transformational creativity mechanism. The presented formulation is applied in two real cases, the first in the culinary field and the second in the musical context.

4.1 Introduction

Computational creativity is an emerging, multidisciplinary branch of Artificial Intelligence, closely related to Cognitive Science, whose goal is to model, simulate or serve as a support tool for creative tasks. In this chapter, we focus on systems for achieving the latter goal. Such systems are normally referred to as Creativity Support Tools or Creativity Support Systems (CSS). CSS can be defined as systems capable of enhancing human creativity without necessarily being creative themselves. They act as a creative collaborator with scientists, designers, artists and engineers by applying technology to help humans 'think outside the box' and expand their exploration boundaries by generating good ideas that have never been thought of before [Tho07]. They can help us to look farther and avoid dwelling on the obvious concepts. The great challenge for CSS is to enable more people to be more creative more of the time [Shn00].

Creativity can be found in painting, sculpture, music, literature, architecture but also in engineering, software development, scientific discoveries and almost all human activities. Many scientists and engineers have extended their discovery and innovation capabilities by applying computational tools able to perform fast calculations and useful simulations and visualization. For instance, genome researchers use specialized visual analysis tools to discover biological pathways, computer-aided design (CAD) is used in designing electronic, mechanical and architectural systems, and media artists are provided with powerful development environments that support animation, music and video editing tools. In fact, any tool that facilitates access to and revision of existing projects and performance, such as Web browsers, wikis and search engines, helps to enhance human creativity. However, like telescopes, microscopes and cameras, these computational applications are still only tools; the act of creation is actually carried out by the users [Shn07].

It is assumed that creativity is closely linked to the rational decision-making process. In the literature, decision-making processes normally comprise four steps: *Framing the decision*, *generating alternatives*, *evaluating the alternatives* and *choosing and implementing the chosen alternative* [LRJ12]. Creativity is mainly linked to the second step: generation of alternatives, but it is also associated to the third and fourth steps. Generating ideas (hypotheses for scientists, prototypes for engineers, models for architects, or sketches for artists) is often considered the key step in creativity. It is sometimes referred to as divergent thinking. Creating lists of questions or community brainstorming are activities which promote *divergent thinking*. The use of computer programs makes it easier to generate, collect, organize and present new ideas based on word combination, using hypertext databases and making different kinds of connections. However, once a new idea emerges, the creator must determine its suitability. The evaluation and selection stage is referred to as *convergent thinking*. This stage draws on large amounts of domain knowledge to assess novelty and quality.

Alternatives are normally generated by combining elements within and beyond the domain but one needs to choose potentially good alternatives if one is to avoid evaluation of a vast number of possible combinations. This is achieved by reviewing existing processes in the domain and other processes belonging to other domains with subtle common aspects. In this sense, creative people are skilled at both finding these apparently different domains with common characteristics and at pre-evaluating the alternatives, taking into account the relation between domains.

This chapter presents a new formulation of the central ideas of Boden's well-established theory on creativity [Bod91]. This new formulation redefines some terms and also reviews the formal mechanisms of exploratory and transformational creativity. It is based on the conceptual space proposed by Boden and formalized by other authors to facilitate implementation of these mechanisms. We consider transformational creativity to be a quest for concepts that fall outside the problem framework that involves weighing up the relationship (appropriateness and relevance) between concepts in different frameworks.

The remainder of the chapter is organized as follows: Section 2 provides a review of the literature on Computational Creativity. Section 3 covers the proposed CSS methodology and Section 4 gives conclusions and discusses future work.

4.2 Literature Review on Computational Creativity

Creativity should be regarded as one of the highest-level cognitive functions of the human mind. It is a phenomenon whereby something new and valuable is produced such as an idea, a problem solution, a marketing strategy, a literary work, a painting, a musical composition or a new cookery recipe. Authors have diverged in the precise definition of creativity beyond these two features: originality (new) and appropriateness (valuable) [Mum03].

One of the few attempts to address the problem of creative behavior and its relation with Artificial Intelligence was done by Margaret Boden [Bod91; Bod94]. She aimed to study creativity processes from a philosophical viewpoint focusing on understanding human creativity rather than trying to create a creative machine.

Boden distinguishes between creativity that is novel merely to the agent that produces it and creativity that is recognized as novel by the society. The first is usually known as *P-creativity* (or "psychological creativity") and the second is known as *H-creativity* (or "historical creativity"). All P-creative ideas are H-creative, but not all H-creative ideas are P-creative. What is valued by one person or social group may or may not be valued by another.

In order to understand these two concepts Boden gave the following example:

> If a person had never visited a museum, nor seen any work of art in any other way, and if he had painted a painting which is every detail is identical to Van Gogh's Sunflowers, this surely would count as a creative act. For the history of art his painting is of little relevance though, for the simple fact that the painting has already been made. So, from an art historical perspective his painting would would not count as very creative, but would rather be seen as a mere copy, and the Van Gogh Museum might even sue him. However, from a personal perspective, He really was being creative. This is one of the ways to distinguish between the H-creativity and P-creativity, or things that count as creative on a historical or on a more personal, or psychological level.

The most important contribution of Boden's study is the introduction of the idea of *conceptual space* composed of partial or complete concepts. She conceives of the process of creativity as the location and identification of a concept in this conceptual space.

The creative process can be performed by combining, exploring or transforming this conceptual space. According to Boden's theory, *combinational creativity* uses familiar ideas to generate a new idea in the form of unfamiliar juxtaposition. For instance, while making a collage, you could take parts of existing photographs and combine them into a new figure, which up until the moment you combined these images did not exist. Appreciation on the newly created image depends on the unexpectedness of the combination.

Exploration of a conceptual space is the second form of creativity giving rise to *exploratory creativity*. This term refers to the process of searching an area of conceptual space governed by certain rules. The purpose of exploratory creativity is not to break rules or to invent new rules but to invent a new concept following the existing rules. Media creation such as story authoring is largely exploratory creativity. The purpose of most story authoring is not to invent a new style or genre of story that will be accepted by the population but to invent a single narrative that is novel enough to be tellable.

Finally, another type of computational creativity in Boden's theory is *transformational creativity*. If the conceptual space is defined through a set of rules, when some of these rules change, then the process is called *transformational creativity*. The resulting change could lead to a new idea difficult to be accepted, or even understand. Sometimes, long time have to pass before it can be valued by the public. For instance, Picasso's pioneering cubist canvas of *Les Damoiselles d'Avignon* was initially spurned even by his close circle of fellow artists. He kept it hidden in his studio for several years before exhibiting it.

From Boden's study, it is not clear how the rules give rise to a particular conceptual space and, therefore, what is the true difference between exploring the space and transforming it. In order to clarify and to formalize the creative process, G. Wiggings [Wig06] presented several papers in which he emphasized the notion of search as the central mechanism for exploratory creativity and the notion of meta-level search related to transformational creativity. Wiggings posits a universe of possibilities $\mathcal{U}$ which is a superset of the conceptual space. The universe is a multidimensional space, whose dimensions are capable of representing all possible concepts which are relevant to the domain in which we wish to be creative. For transformational creativity to be meaningful, all conceptual spaces are required to be subsets of $\mathcal{U}$.

Wiggings conceives exploratory creativity as a search of concepts in a specific conceptual space. The process involves three sets of rules that can be denoted as *acceptability*, *appropriateness* and *strategy*. The first set of rules is linked with belonging to the conceptual space. Moreover, acceptability is related to style. On the other hand, appropriateness rules are related to the value of the concept. Valuable concepts may become successful regardless of being acceptable according to the rules associated to acceptability. This second set of rules (which defines the value of a concept) is much harder to define because it depends on cultural and aesthetic aspects, specific context, personal mood, etc. However, it is important to note that, in this context, appropriate means suitable to the task, but above all original and surprising. Finally, there exist a third set of rules linked to the search strategy. For instance, some people prefer to work "top-down", others "bottom-up", others rely on ad-hoc methodologies, using informed or uninformed heuristics and even at random. Wiggings points out that separating acceptability and strategy rules can be used to describe situations where different designers, each with a personal way of finding new ideas, are working within the same style (a shared notion of acceptability).

From Wiggins' perspective, the interaction of these three sets of rules (acceptability, appropriateness and strategy) leads to the exploratory creativity process. However, although working within three invariant sets of rules may produce interesting results, a higher form of creativity can result from making changes of these rules (transformational creativity). In other words, on the one hand, exploratory creativity consists of finding a concept in a specific conceptual space, following a specific strategy and assessing it by using a specific appropriateness set of rules. On the other hand, transformational creativity consists of the same process than exploratory creativity but changing the conceptual space, the search strategy or the appropriateness assessment.

Besides Wiggings work, there have been other formalizations of specific aspects of the computational creative process [Rit07; Rit12; CPC12]. Although these formalizations are very helpful in clarifying the nature of creative computation and have given rise to some applications in diverse domains including graphic design, creative language, video game design and visual arts [MRT12], the details of most of them are unspecified and the concepts they include are tricky to implement. The current chapter starts from the central ideas of Boden and Wiggings and redefines the formal mechanisms of exploratory and transformational creativity in a way which facilitates the implementation of these mechanisms.

4.3 The Proposed Formulation

As in Wiggins theory, let us start by considering a *universal set of all concepts*, $\mathcal{U}$. The idea is that $\mathcal{U}$ is universal enough to contain concepts for every type of complete or incomplete artifacts that might ever be dreamed up. In addition, we define the following terms:

Definitions (*framework, H-conceptual space, appropriateness, and relevance*). A *framework* F is the 3-tuple $(C, a(), r())$ where $C \subset \mathcal{U}$ and $a()$ and $r()$ are maps from $\mathcal{U}$ to $\mathcal{R}$.

- The subset C is the *H-conceptual space* (or 'historical conceptual space') formed by all concepts related to the framework F.
- $a()$ is the *appropriateness* map. In our formulation it is related to the success of considering a concept in this framework.
- $r()$ is the *relevance* map. It is a measure of the membership relation between the concept and the framework: $r() \neq 0$ if $y \in C$ and 0 otherwise.

A naïve relevance measure might be a $0/1$ value (1 if $x \in C$ and 0 otherwise), but it is possible to consider more complex measures containing more information about the relation between the concept and the framework.

In the proposed formulation, we separate originality and appropriateness. This separation is not clear in Wiggins formulation where appropriate means both suitable to the task and original and surprising. We consider that any agent can act as a *spectator* and can easily obtain the relevance measure for any concept given any framework. However, only *experts* on a framework know appropriateness for some concepts in the H-conceptual space.

Definitions (*expert and P-conceptual space*). An *expert* i on a given framework F is an agent that also knows value $a()$ for concepts from some subset C^i of C. Inspired by Boden's theory, we call C^i the *psychological* or *P-conceptual space*, that is, the concept space associated to the framework F and to the expert i

An *expert* only knows appropriateness for concepts from his/her P-conceptual space, but the values $a(y)$ for $y \notin C^i$ are unknown by the expert. However, an expert can also have expertise in others frameworks. We use the notation C_j as the H-conceptual space associated to framework F_j and C_j^i as the P-conceptual space associated to framework F_j and expert i. It is common that different frameworks share concepts but obviously appropriateness of the same concept can differ depending on the framework. Multi-expertise can be an advantage in the creative process.

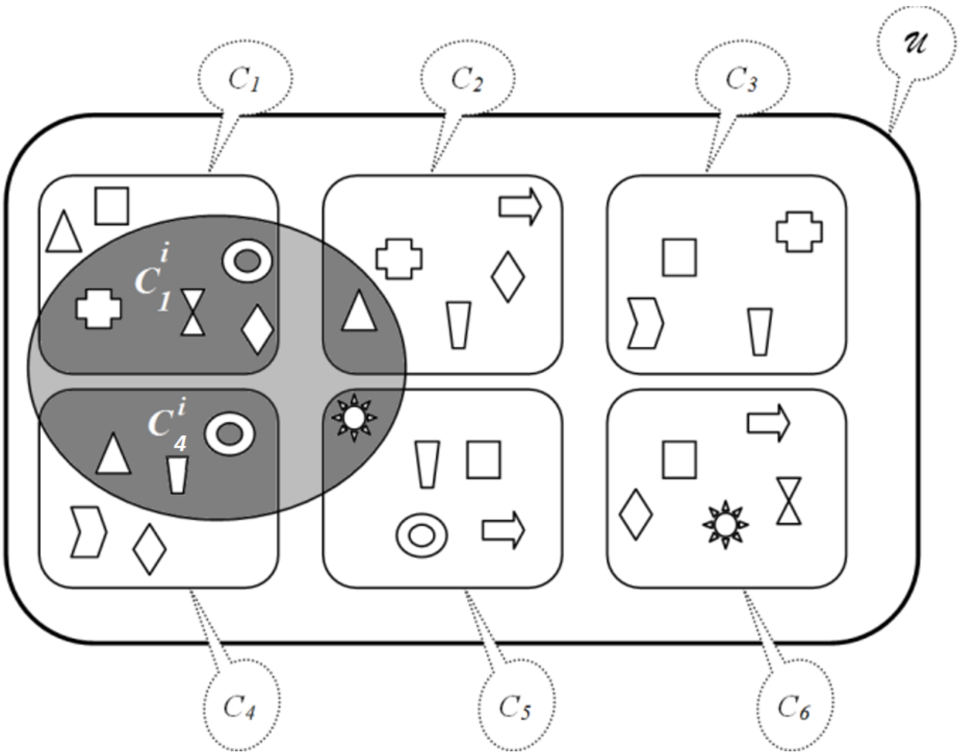

FIGURE 4.1: Universe of concepts. H-Conceptual spaces (associated to frameworks) and P-Conceptual spaces (associated to frameworks and one expert). The expert i is represented as a grey circle. He has knowledge on four frameworks. In the figure it can be seen that one concept can belong to different frameworks.

We consider that given a framework, the appropriateness of a concept is independent of the expert. The difference between experts of the same framework is related to the different P-conceptual spaces, all them subsets of the H-conceptual space.

In addition, we consider that both a framework and an expert can evolve and both the H-conceptual space and the P-conceptual space can grow because of the creative activity.

Definitions (*creative and strategy*) A *creative agent* on a given framework F, or just a *creative* (sic) (used as a noun), is an expert in this framework that has a *strategy* for obtaining concepts. A strategy is defined as a way to select a concept from $\mathcal{U}$ given all the knowledge that the creative has about the main framework but also about other frameworks. The strategy depends on the appropriateness and relevance values of concepts in different frameworks.

'Creatives' select concepts following their strategy. Once the concept is obtained, its relevance in the framework is modified and both the P-conceptual space and the H-conceptual space are extended to include this new concept.

The relevance is the result of creatives's activities. However, the appropriateness depends only on the concept and the framework considered. The underlying idea is that, although evaluating the appropriateness requires some kind of talent or expertise, relevance evaluation can be easily performed by any agent by means of an objective analysis of the framework. Thus a concept with high relevance in a framework is not necessarily highly appropriate. In fact, an original concept always has low relevance in the considered framework.

It is possible to simplify the model by avoiding the distinction between 'creatives' and experts but in some fields there are obviously two types of agents. For instance movie, painting or literature critics can be considered as experts who can assess concepts but they normally do not develop artistic skills.

4.3.1 CSS for Transformational Creativity

Among Boden's three kinds of creativity (combinational, exploratory and transformational), in this chapter, we have focused on the third one. As combinational and exploratory creativities delimit the search in the P-conceptual space, the best strategy seems to select the concept with the best combination of appropriateness and relevance values. Although the selection of a concept from the P-conceptual space may not be trivial and can be performed using other kind of CSS, this topic will not be consider in this work.

The main problem regarding transformational creativity is the lack of knowledge, from the expert's side, on the appropriateness values for concepts outside the P-conceptual space. The CSS cannot directly obtain this appropriateness value. However, computational intelligence can be used for obtaining relevance values for any concept with respect to any framework.

Definition (*relevance vector*). Let us consider a set $F_1, F_2, \ldots, F_m$ of different frameworks. Given a concept $x \in \mathcal{U}$, we consider the *relevance vector* of x with respect to the set of frameworks $F_1, F_2, \ldots, F_m$ as $\Phi(x) = (r_1(x), r_2(x), \ldots, r_m(x))$.

The relevance vector describes the membership relation of the concept $x \in \mathcal{U}$ to the set of frameworks $F_1, F_2, \ldots, F_m$. Given a framework F_0, the expert i and its P-conceptual space C_0^i, the utility of CSS in transformational creativity relies on proposing new concepts $y \in \mathcal{U}$, $y \notin C_0^i$ to the expert based on the relevance information of these concepts with respect to frameworks different to the one initially considered and from the relation among all these frameworks.

The system we consider is able to propose new concepts $y \in \mathcal{U}$, $y \notin C_0^i$ with likely high $a_0(y)$. In order to predict how valuable a new concept y is, i.e $a_0(y)$, our hypothesis is that no obvious relations between different frameworks exist, therefore the appropriateness $a_0(y)$ and the relevance vector $\Phi(y)$ are closely related. In this sense, it is considered that concepts with similar relevance vectors on the current framework should have similar appropriateness function. This hypothesis could not be true for a small set of frameworks but, from our preliminary experiments, seems to be true for larger ones.

Given the relation between appropriateness and relevance, our CSS will use the set C_0^i, or a subset of it, as a training set in a learning system in order to extract the relation between appropriateness in F_0 and the relevance vector in a set of frameworks $F_1, F_2, \ldots, F_m$. Once trained, we only have to feed the CSS with other concepts and the system will propose those concepts with expected high appropriateness.

4.4 Conclusions

In this chapter we use the idea of *conceptual space* introduced by Boden and redefine some properties such *appropriateness* and *relevance* that facilitate the computational implementation of the transformational creativity mechanism. While appropriateness can only be evaluated by an expert, relevance can be objectively measured for any spectator. Computational creativity is based on the relationship between appropriateness and relevance of a concept, and therefore a computational system can be used to support this task. To illustrate this formulation, the next chapter shows a computational system to support a creative chocolate designer and another computational system support capable of composing a single music melody.

Chapter 5

Applications

In this chapter, two different implementations of the theory developed in the previous chapter are presented. First (Section 1), we present the formulation applied to a real case of chocolate designing in which a novel and flavorful combination of chocolate and fruit is generated. The experimentation was conducted jointly with a Spanish chocolate chef. The second application (Section 2) is developed in the field of music. This second application analyses the relationship between appropriateness and relevance of a music concept in order to obtain a computer tool to support the musical composition task. Concretely, it describes the task of composing a single voice tune of a specific style, *reel* (a folk rhythm originated in Scotland) using ABC notation.

5.1 A Transformational Creativity Tool to Support Chocolate Designers

5.1.1 Background

Culinary design has long been seen as a highly creative domain within creativity research [Saw12]. Thus, CSS has a potential role in the food industry. Today, a significant portion of a food services or manufacturers' business focuses on coming up with new ingredient combinations and finding new flavors that may become a commercial success. With the availability of large-scale online recipe repositories in recent years, some recipe design principles have been formulated, inspiring creativity strategies [Ahn+11]. The flavor of a dish depends as much on how it is prepared as on the choice of particular ingredients. Furthermore, there are many ingredients whose main role in a recipe is not only flavoring but also to ensure mechanical stability, improve conservation or to add vivid colors a pleasing texture. However, some hypotheses ignore all these factors and focus solely on flavoring compounds in the ingredients. One of the main guiding principles in putting together two ingredients in a recipe is the so-called *food pairing hypothesis* [Ahn+11].

Food pairing is a relatively new method for identifying which ingredients go well together. It is based on the principle that some food combines well with one another when they share key flavor components. This flavor pairing hypothesis arose when Heston Blumenthal, the famous chef from the English restaurant The *Fat Duck*[1] , found caviar and white chocolate go well together. He contacted Firmenich, a Swiss perfume and flavor company, who found that both chocolate and caviar shares trimethylamine and other flavor compounds that contribute to the desirable flavors [Blu08]. In order to apply the food pairing hypothesis, flavor and aroma compounds of an ingredient should be obtained (with the aid of gas chromatography or mass spectrometry) and compared to the compounds of other ingredients. However, this hypothesis also makes it easy to come up with unexpected combinations since food pairing suggests that the binary relation *go well together* satisfies, to a certain degree, the transitive property, (that is to say, adequacy between two ingredients depends on the adequacy between these ingredients and other ingredients). The flavor pairing hypothesis has been scientifically studied for several modern cuisines and has been found to hold strongly for Western cuisine but not for Asian cuisine [Ahn+11].

5.1.2 Experimental Framework: Combining Chocolate with Fruits

To illustrate the implementation of the ideas presented in the previous chapter, let us consider the following creative situation: *coming up with a new chocolate cake by combining dark chocolate with a fruit* to obtain a highly accepted product. The 'creative' has a lot of experience in combining chocolate with many different ingredients –cheese, liqueurs, olive oil, nuts and, of course, fruits. Due to his experience, he knows whether several combinations of specific types of chocolates and fruits are suitable or not but, obviously, he does not know how well any kind of chocolate combines with all existing fruits. Thus, a CSS is going to be developed according to the methodology presented in the previous section in order to assist the expert in creating suitable new combination.

In our case, since we constrained the problem to combine fruit and dark chocolate, the universe $\mathcal{U}$ is formed by all fruits. The H-conceptual space, $C_0 \subset U$, contains all fruits that have ever been mixed with black chocolate. The P-conceptual space, C_0^i, which consists in all fruits for which the expert i knows whether they blend in well or

[1]The Fat Duck has been awarded three Michelin stars and was voted Best Restaurant in the world in 2005.

not with dark chocolate, is just a subset of C_0. Moreover, the expert is able to assign a value $a_0(x)$ for all $x \in C_0^i$, which, in our case, is represented in our case as a qualitative ordinal value (see Table 2). The objective of our CSS consists of suggesting other fruits $y \in \mathcal{U}$, $y \notin C_0^i$, with a high predicted value function $a_0(y)$, i.e. fruits valuable to the expert for the considered problem (combining with dark chocolate).

Following the CSS methodology introduced in the previous section, we can learn the value $a_0()$ of a fruit with respect to the dark chocolate (framework F_0) through the way it is related to other frameworks. In this example we are considering only frameworks related to recipes and ingredients, but other alternatives could also have been considered. To obtain the relevance value in regards to a framework, a large recipe database has been used. We counted the number of recipes containing both the fruit and each term associated to the framework.

Although the combination of fruits and dark chocolate could have nothing to do with, for instance, the combination of fruits and rice according to our assumption, given a new fruit that has a high value of a0 and has similar relevance vector than another unknown fruit with respect to others frameworks including rice, this new fruit could be considered as a good option to extend the search.

5.1.3 Data Collection

In order to validate our method, we used the data provided by the chocolate chef Oriol Balaguer who assessed, according to his expertise, the combinations of 28 different fruits and their suitability in combination with dark chocolate [Age+13]. In addition we considered 14 frameworks aside from the main framework (dark chocolate). All considered frameworks consisted in ingredients used in cooking, but not necessarily in pastry making. In this implementation of the CSS, we are not focusing on the frameworks selection problem. Instead, we think that the *ad-hoc* selection for this example is enough for illustrating how the formulation presented can be implemented and we leave framework selection as work to be undertaken in the near future.

In order to obtain the relevance vector for each fruit we used the online database of recipes *www.allrecipes.com*. Allrecipes.com is a food-focused social media website where millions of home and professional cooks find and share food experiences. Founded in 1997, Allrecipes.com has grown to become the world # 1 food site with over 450 million visits annually. In addition to the US based site, Allrecipes has 16 international sites around the world.

Table 5.1 gives the list of the 23 fruits (rows) and some of the frameworks (columns). The last column of this table shows the qualitative assessment provided by the expert considering the qualitative labels detailed in Table 5.2. Values in Table 5.1 are obtained by searching both terms simultaneously (fruit and framework). This value represents the number of recipes of the database containing both terms. Table 5.3 gives the complete list of frameworks considered in this study.

This list of 23 fruits constitutes a subset of the P-conceptual space of the expert. This subset is employed to obtain the relation between the appropriateness value given by the expert and the relevance vector given by the website. Once this relation is captured, the CSS can be used to predict the appropriateness of new fruits whose relevance vectors were obtained from the website.

TABLE 5.1: List of the 23 fruits assessed by the expert (last column) and a list of first 12 frameworks considered in this example. The last column contains expert assessment of the suitability of this fruit.

	Almond	**Bacon**	**Beef**	**Beans**	**Beer**	**Bread**	**Butter**	**Cabbage**	**Caramel**	**Cheese**	**Chicken**	**Chilli**	...	**a()**
Apple	188	119	155	133	23	565	1309	99	154	601	522	168	...	**1**
Pear	28	5	10	11	0	44	116	3	15	82	30	12	...	**1**
Quince	0	0	0	0	0	0	3	0	0	0	0	0	...	**2**
Apricot	63	4	13	8	2	52	156	2	5	54	73	8	...	**4**
Peach	49	6	10	18	4	57	210	7	3	64	43	13	...	**3**
Plum	16	33	48	16	5	90	114	13	2	187	118	58	...	**5**
Blackberry	6	2	2	3	2	11	89	0	5	24	6	0	...	**4**
Strawberry	89	7	6	30	3	121	323	5	9	257	40		...	**4**
Raspberry	72	3	3	14	5	54	213	2	2	127	32	4	...	**5**
Grape	44	31	20	17	2	48	61	9	6	171	115	18	...	**1**
Pineapple	66	29	57	65	5	138	321	21	12	280	215		...	**5**
Orange	201	29	78	92	24	274	684	23	16	272	342	89	...	**5**
Banana	103	13	15	44	7	361	425	4	29	125	32	23	...	**5**
Pomegranate	7	0	0	0	0	11	13	2	0	10	0	4	...	**4**
Grapefruit	3	0	2	2	0	5	7	0	0	8	7	0	...	**5**
Kiwi	5	0	4	0	0	3	18	0	0	20	9	2	...	**3**
Lime	36	27	132	51	63	110	264	63	9	289	514	322	...	**4**
Mandarine	34	6	0	9	0	7	22	8	0	36	32	2	...	**5**
Mango	21	4	7	7	0	43	66	6	0	50	119	31	...	**5**
Olive	204	386	995	202	90	1560	1321	160	112	3403	2327	1081	...	**2**
Papaya	5	0	0	0	0	3	8	0	0	7	11	2	...	**1**
Watermelon	2	3	0	0	0	3	5	0	0	25	4	5	...	**1**
Citron	15	0	0	2	0	6	24	0	0	3	0	0	...	**3**

TABLE 5.2: Labels and linguistic meaning in the fruit assessment by the expert.

Labels	**Linguistic labels**
1	It does not combine at all
2	It does not combine well
3	Combines well
4	Combines very well
5	It makes an excellent combination

TABLE 5.3: Complete list of frameworks considered in the study

#	Framework	#	Framework	#	Framework	#	Framework
1	Almond	16	Fish	31	Nuts	46	Spinach
2	Bacon	17	Flour	32	Onion	47	Sugar
3	Beef	18	Garlic	33	Pasta	48	Tabasco
4	Beans	19	Honey	34	Peanut	49	Tea
5	Beer	20	Hummus	35	Pepper	50	Tofu
6	Bread	21	Jam	36	Pie	51	Tomato
7	Butter	22	Ketchup	37	Pizza	52	Tuna
8	Cabbage	23	Kidney	38	Potato	53	Turkey
9	Caramel	24	Lettuce	39	Prawn	54	Vanilla
10	Cheese	25	Liqueur	40	Rice	55	Veal
11	Chicken	26	Lobster	41	Salad	56	Vinegar
12	Chilli	27	Mayonnaise	42	Salmon	57	Wine
13	Coffee	28	Milk	43	Salt	58	Yoghurt
14	Curry	29	Mint	44	Soda		
15	Eggs	30	Mustard	45	Soup		

5.1.4 CSS Training and Results

As said in Section 3, our proposal is based on the existing relation between the appropriateness of a concept with respect to a framework and the relevance vector of this concept with regard to a set of other frameworks. To validate this hypothesis, we used data from Table 5.1 to obtain this relation and assess its significance. This validation is performed twice by using, on the one hand, the complete range of expert's valuation shown in Table 5.2 and, on the other hand, using just a binary valuation (suitable or not suitable) that simplifies the expert's assessment. We used a multiclass and a two-class support vector machines (SVM) and we validated through 'leave one out' cross-validation process. If the SVM can correctly estimate the appropriateness of a fruit from the relevance vector, it can be used to propose new fruits with high predicted appropriateness.

TABLE 5.4: Best parameter values and results of binary and multi-class SVM.

	Five classes	Two classes
C	10	10^5
γ	100	0.1
Accuracy (%)	34.78	85.00

Parameters of the SVM were tuned by optimizing the geometric mean of sensitivity and specificity because data are imbalanced [Gon+14]. In the first case, we employed a multiclass SVM (5 classes) with a Gaussian kernel. The best parameters obtained were C=10 (regularization cost) and γ=100 (Gaussian kernel parameter). Software R and LibSVM library were used to train the datasets and predict accuracy of classifying [R D08],[CC]. The total accuracy obtained was 34.78%. This value means that 34.78% of the time, the predicted value matches with the expert assessment. Taking into account that there are 5 classes and the expected accuracy in the case of random values is $\sum_{i=1}^{5}(N_i/N)^2\%$ (N_i is the number of examples of class i and N the total of examples), the accuracy value obtained reaffirms our hypothesis. In the second case, pattern labels are changed in order to maximize CSS utility. Instead of using the labels shown in Table 5.2, a binary classification when employed in which the first class contains those combinations that were suitable to the expert, and the second class those were not. Patterns corresponding to values 3 and less are considered to the first class and the rest of patterns are considered to belong to the second class. In this case, the best parameters obtained by the tuning process were C=100,000 and γ= 0.1. The total accuracy obtained was 85%.

In order to show that the relationship between the appropriateness and the relevance vector increases with the dimension of the relevance vector, subsets of the set of frameworks have been considered instead of the whole set. Figure 5.1 shows the mean accuracy according to the number of frameworks considered in each trial. For each k from 1 to 58, thirty different subsets of k elements have been considered. The mean accuracy among these thirty subsets of k elements is calculated when the SVM is applied considering leave one out cross validation. Figure 5.1 supports our hypothesis and, in addition, it can be noted that this accuracy stabilizes from the value 30.

5.1.5 Conclusions

In this section, the formalization presented in the previous chapter has been implemented in a real example conducted with a Spanish chocolate chef. The CSS obtained proved capable of proposing new, unknown fruits that were predicted to combine well with dark chocolate. The validation of the method was performed using both a bi-class and a multi-classs SVM. The results allowed us to conclude that the assumptions on which the method is based were satisfied in this example.

Finally, it is important to note that in this implementation, we are not aiming at the frameworks' selection problem. However, this is an important issue to be analyzed in future work.

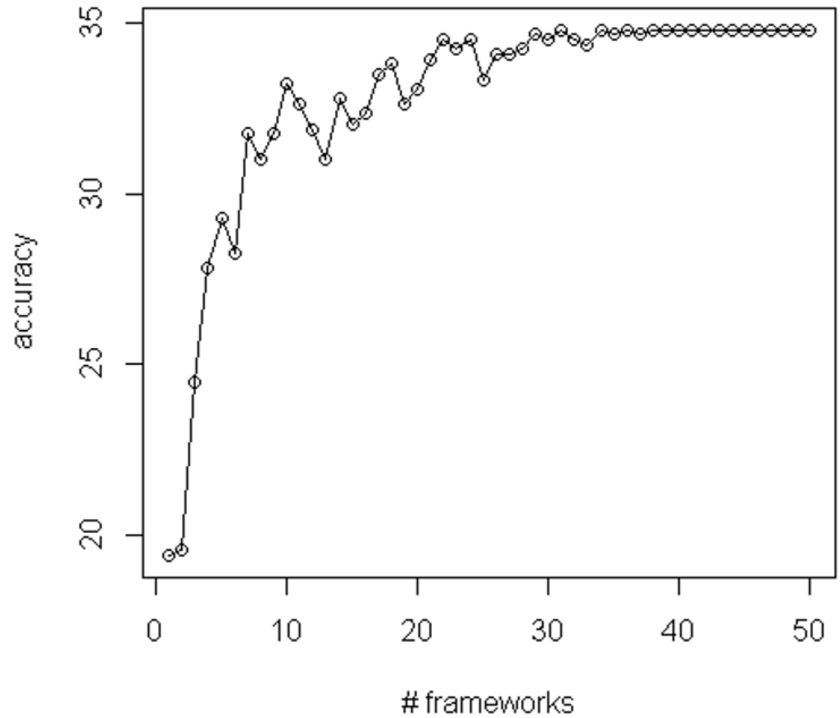

FIGURE 5.1: Mean accuracy of the SVM with respect to the number of frameworks considered.

5.2 A Transformational Creativity Tool to Support Musical Composition

The formulation presented in the previous chapter is also powerful enough to be applied to other creative fields as music composition. The formulation enables us to focus on the selective step in creativity, evaluating alternatives from the relationship between appropriateness and relevance. We can even use concepts from different frameworks, that is, apply transformational creativity.

5.2.1 Background

The first creative computational systems were designed based on probabilities of note transitions and Markov-based techniques. The concept of probability transitions and Markov models was used to model musical styles by simply computing the note transition probabilities. Given a musical database corpus, new music can then be produced by generating notes using inferred probability distributions.

The ILLIAC (Hiller and Isaacson) (*Illinois Automatic computer*) was a series of computers that pioneered music composition based on Markov models. *Illiac Suite* is a 1957 composition for string quarter which is generally agreed to be the first score composed by a computer.

One of the most well-known applications of Markov chains for music generation is probably the Experiments in Musical Intelligence (EMI) designed by David Cope [CM96] although his musical results are not produced entirely automatically.

Not all the early work on composition relies on probabilistic approaches. Other approaches rely on simulating human composition processes using heuristic techniques. In [Lóp13] a more extensive list of previous works on computational creativity in music can be found.

5.2.2 Experiment Description

To illustrate the implementation of the approach presented, let us consider the task of composing a single voice tune of a specific style, for example a *reel* (a folk rhythm originated in Scotland).

We have considered single voice folk songs written using ABC notation and our goal is to substitute part of one song by other compatible sequence of notes with similar relevance vectors.

We start with an already existing reel and we extract a small part (a sequence of notes) of this reel. We then substitute this sequence of notes by another compatible sequence (that follows some structural rules of harmony and style) and which has a similar relevance vector as the original part. To this end, we considered that the position of the extracted sequence, and the type of tune to be composed (reel, in this example) is the framework. To obtain the relevance vector, we consider other frameworks (other styles of tunes such as 'jig', 'waltz' or 'polka'). The hypothesis is that substituting the musical element (concept) by another with similar relevance vector, the appropriateness measure will be similar.

5.2.3 ABC Notation

ABC notation is a text-based music notation system popular for transcribing, publishing, and sharing music, particularly on the internet. It was formalized (and named) by Chris Walshaw in the early 90s with help and input from others.[2] Since then, ABC has

[2]http://abcnotation.com/contact

gone from strength to strength and is widely used by folk musicians, especially from Western European origin, e.g. English, Irish, Scottish, and which typically produce single-voice melodies. The most recent standard for ABC is v2.1, released in 2011.[3]

Each ABC tune consists on a tune header and a tune body (it may also contain comment lines or stylesheet directives). The tune header is composed of several information field lines containing the reference number, title, tempo, default note length, rhythm, key, etc. The tune body contains the notes, duration, bar lines and other musical symbols.

5.2.4 The Notes in ABC Notation

Starting at middle C, the notes in that octave are shown as CDEFGAB. The next octave is shown in lowercase and the next one using apostrophes. The octave immediately below middle C is shown by a comma immediately following the note name (see Figure 5.2).

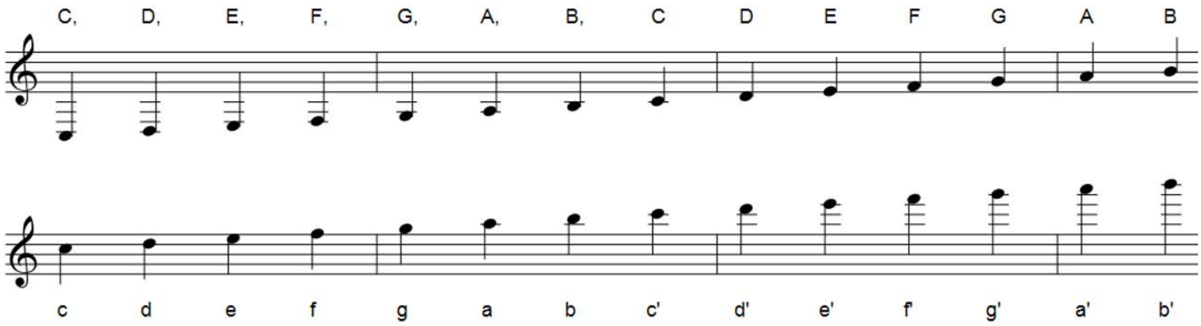

FIGURE 5.2: A scale in standard notation, with the equivalent abc note names shown.

The range can be extended further by adding more commas or apostrophes. Sharps (♯) and flats (♭) are shown using circumflex (ˆ) and underscore (_) before the note name. Different key signatures enables sharpening or flattening all notes of the same name. The equal sign (=) is used to naturalise (♮) a note.

ABC enable us to set the ’default note length’ for each tune. If the particular note length is a divisor of the default length, then it is shown as ’/n’ following the note name. If it is a multiple of the default length it is shown as ’n’ following the note name. The symbols ’>’ and ’<’ are a shorthand notation for dotting. They transfer half the value of the note on one side to the other side.

[3]http://abcnotation.com/wiki/abc:standard:v2.1

In the tune body, spaces and bars are used to facilitate the reading, double quotes indicate some information such as accompaniment chords and other symbols such as tilde or curly brackets indicate the presence of an ornament.

In this experiment we only have considered single voice tuned without accompaniment chords and we have dispensed with all note information from a tune except pitch and length. This means that, for instance, from this ABC code:

$$K : D$$
$$| : "G"ABc2|A > AA2|GAdc : |$$

we extract the following information:

$$\left(\begin{array}{ccc|ccc|cccc} A & B & c\# & A & A & A & G & A & d & c\# \\ 1 & 1 & 2 & 1.5 & 0.5 & 2 & 1 & 1 & 1 & 1 \end{array}\right)$$

where the first row of the matrix corresponds to the pitch notes and the second row to the respective lengths. Vertical lines separate sequences of four default times (default=eighth note)

5.2.5 Database Description

The database is formed by 2386 tunes classifying in 16 different rhythms: (reel: 1002, jig: 484, polka: 164, song: 152, hornpipe: 138, slide: 98, slip jig: 76, waltz: 65, march: 35, carolan: 31, slow air: 29, highland: 24, strathspey: 21, hop jig: 20, set dance: 20). This database is extracted from databases:
http://www.folktunefinder.com/tunes
http://abcnotation.com/
http://www.norbeck.nu/abc/
all of the tunes are single-voice melodies in different key signatures.

5.2.6 Procedure Description

The *concepts* in our experiments are composed by two sequences: a sequence of pitches and a sequence of note lengths that add up to four. The idea is to substitute this sequence of notes by another with similar relevance vector. By repeating this step with different sequences, we can obtain a completely different song starting from an original song.

As we have 16 different types of rhythms, we consider relevance vector of dimension 16. Each component of the relevance vector for a sequence of pitches and lengths is calculated by counting the percentage of sequence occurrences in the collection of tunes of a specific rhythm. In this calculus, we give different value weights if all pitches and lengths occur, or only the sequence of pitches or the sequence of note lengths appear. Although it is a parameter of the method, in the preliminary experiments we have obtained good results using the following scores:

$$\begin{pmatrix} A & A & A \\ 1.5 & 0.5 & 2 \end{pmatrix} \rightarrow 100 \; points$$

$$\begin{pmatrix} A & A & A \\ . & . & . \end{pmatrix} \rightarrow 20 \; points$$

$$\begin{pmatrix} . & . & . \\ 1.5 & 0.5 & 2 \end{pmatrix} \rightarrow 10 \; points$$

If the sequence of pitches and lengths is found in a specific tune of a certain style, we add 100 points to the respective relevance coordinate, if the sequence of pitches is found but with different note length, only 20 points are added. Finally, if the sequence of note length is found with different pitches, only 10 points are added. Only one of the four scores (100, 20, 10 or 0) is considered for each song, and the sum of all scores for all songs belonging to the same style is normalized by the number of songs of this style. This calculus performed for all styles produces the relevance vector of this sequence of pitches and lengths.

The next step is to consider different sequences of pitches and lengths to replace the previous one. We consider sequences of different pitches and lengths (almost one hundred of them) that satisfy some harmony constraints (related to the key) and rhythmic constraint (related to the style). At the moment, this step is performed manually. For each of the sequences, the relevance vector is obtained using exactly the same algorithm explained in the previous paragraph.

After all relevance vectors are obtained, the Euclidean distance between each and the relevance vector of the original sequence of pitches and lengths is computed. The generated sequences are sorted by distances, and those with a shorter distance can be selected to replace the original one. The more sequences replaced, the more the resulting tune will differ from the original.

5.2.7 Conclusions

Our goal is not to create a computational system capable of composing a creative piece ready to be interpreted in a concert, or to be included in an album for sale. Conversely, we want to test the relation between the concepts of appropriateness and relevance in this field. To better understand the scope of our formalization we have chosen a simple musical environment and eliminating complex ornaments.

It is difficult to measure the quality of the melodies obtained. We are working on creating a website to publish some of these melodies and also a web application that can change some of the parameters such as the sequence length replaced, score system, the harmonic and rhythmic constraints).

Finally, we are working on automating the generated sequences step since it is the most onerous part of the whole process.

Chapter 6

Conclusions

Among all those human qualities that are added to the objectives of Artificial Intelligence, this thesis deals with two of them: *socialization* and *creativity*. In both cases, the empathy machine is in the core of the research about the development of devices and systems that are able to detect and respond to human emotions.

6.1 Social Robotics

First, the thesis discuses about the work completed by the PhD candidate in the research project PATRICIA. In this case, the main aim is to develop a social assistant robot architecture for improving the children experience when they are hospitalized. The architecture proposed, based on the paradigm of cloud robotics, aims to address the problem of human-robot interaction based on a significantly high volume of information to be monitored in real time. The learning phase is based on a semi-supervised learning paradigm with a Michigan-style Learning Classifier System approach. This framework consists of an online cognitive-inspired system that combines a credit-apportionment algorithm with Genetic Algorithms. The system was divided into two layers: in the lower cloud layer, each robot has a children assistant agent (CAA) that gathers data which is then aggregated by the local Information Management Agents (IMA) to obtain valuable information. The intelligent agent is implemented by a self-training version of the Supervised Classifier System (UCS). The robot follows the schedule given by the IMA via the CAA. On the other hand, the upper cloud layer allows the information exchange between the local IMA through the global IMA to further improve the results. Experts can monitor, manage and control the scenario though this layer.

We expect results can foresee cause-effect reactions between the robotic pets and the children in cooperative environments between one child and his or her owned pet or even between several children and their pets. These results should help the therapists and clinical professionals to determine possible relations between the anxiety of the patients and the interaction with their robots in comparison with classical video analyses.

Talking about technological aspects of this project, the first one of the objectives, the Bluetooth communication with Pleo, has been achieved completely. Using a PCB with extensible pins, we can supply Bluetooth communication to any Pleo, even those without UART connection. The second objective, to modify Pleo's states from an Android device, or any of their possible actions, has been successfully achieved too, so helping the coordinator to understand and to control the robot using an easy app. The third objective, to assemble a Bluetooth+Batteries package has not been fully completed. Pleo will work using 3 (not 2) AA cells and it will fit to the designed package in this work, but it was not be completely developed, since 3D cage was built for two AA cells. However, it should be possible to build this assembly.

6.2 Creativity Tools

The second part of the thesis was devoted to applications of the new formalization proposed for the mechanism of creativity. This formalization, based on Boden's notions of conceptual space and transformational creativity allowed us to be applied on two real cases: the first of chocolate designing in which a novel and flavorful combination of chocolate and fruit is generated and the second of the composition of a single voice tune of reel using ABC notation.

In the first case, the CSS obtained proved capable of proposing new, unknown fruits that were predicted to combine well with dark chocolate. The validation of the method was performed using both a bi-class and a multi-class SVM. The results allowed us to conclude that the assumption on which the method is based were satisfied in the example.

In the second case, the CSS was able to help to compose a creative piece of music. In this case, our goal was not to create a computational system capable of composing a piece ready to be interpreted in a concert, or to be included in an album for sale. Conversely, we wanted to test the relation between the concepts of appropriateness and relevance in this field. On the other hand, we believe that the applications considered allow to better understand the formulation presented assigning to each theoretical concept a concrete meaning in this context.

6.3 Future Work

As far as Pleo is a commercial closed platform, alternative platforms should be considered in the near future. In this sense, two technical research lines are opened. The first one is either to consider commercial platforms as Pleo's alternative or to develop a pilot robotic platform to be certified for commercial use. The second line is working in the possibility to certify the employed device as a medical device for therapeutic purposes.

Talking about creativity, it is important to note that in the implementation performed, we are not aiming at the frameworks' selection problem. However, this is an important issue to be analyzed in future work. In addition, two different topics will be considered in future research. First, the inclusion of both complete and incomplete concepts in the formalization. Second, consideration of a new real case, where it could be demonstrated that creativity enhanced by introducing the methodology described in this work.

We are sure that the application presented in this thesis will serve as a guide to apply the formulation of transformational creativity to other fields.

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