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TANGIBLE COLLABORATION APPLIED INTO SPACE SYSTEMS CONCURRENT ENGINEERING CONCEPT STUDIES

Christopher Shneider Cerqueira

Doctorate Thesis of the Graduate Course in Space Engineering and Technology/Space Systems of Management and Engineering, guided by Drs. Ana Maria Ambrosio, and Claudio Kirner, approved in February 28, 2018.

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"With the passage of time, the psychology of people stays the same, but the tools and objects in the world change. Cultures change. Technologies change. The principles of design still hold, but the way they get applied needs to be modified to account for new activities, new technologies, new methods of communication and interaction".

Don Norman
in *"The Design of Everyday Things"*, 2013

ABSTRACT

The first development phase of a Space Mission consists of the Space System Concept Studies, in which system concepts are broadly defined, as a set of feasible System Conceptual Solutions to accomplish the mission needs. Nowadays, this phase involves the practices of System Engineering (SE) and Concurrent Engineering (CE), which respectively: (i) organizes the systems investigation/documentation methodology, and (ii) speed-up the process into parallelization of disciplines studies and successions of convergence sessions (CE Sessions). The CE Sessions for Space System Concept Studies are highly interactive activities, which require: (i) specialists of a given discipline (thermal, operation, electrical, etc.) to describe to the team their System Element solution models, showing its parts and required parameters, and (ii) facilities to handle the CE activities streamlining the work toward the System Concept Solutions. Either in document-centric or model-centric approaches, the model collaborations occur by: projection of the models, within a sequential order, and accordingly to the number of the projectors, which shows the discipline's models. This virtualization of information undermined the physical collaboration through artefacts, in preference to virtual-only metaphor collaborations, where, for instance, a person bringing together two physical peons means that a new representation is obtained, was replaced by drag-n-drop tree branches in Graphical User Interface (GUI). This thesis proposes and demonstrates the viability to use Tangible User Interfaces (TUI) constructed with physical electronic artefacts and Spatial Augmented Reality to reintroduce tangible collaboration into CE Session. A tangible interaction vocabulary was defined in order to use real artefacts to control CE data. In a pragmatic aspect for the Space Engineering sector, this thesis brings cognitive aid tools back to the design workspace.

Keywords: Tangible User Interface. Concurrent Engineering. Model Based System Engineering. Space Systems Concept Design. Collaborative Environments.

COLABORAÇÃO TANGÍVEL APLICADA PARA ESTUDOS CONCEITUAIS DE SISTEMAS ESPACIAIS REALIZADOS ATRAVÉS DA ENGENHARIA SIMULTÂNEA

RESUMO

A primeira fase de desenvolvimento de uma Missão Espacial consiste dos Estudos Conceituais de Sistemas Espaciais, na qual os conceitos do sistema são definidos, como um conjunto de Soluções de Sistemas viáveis para atender às necessidades da missão. Hoje em dia, esta fase envolve as práticas de Engenharia de Sistemas (*System Engineering - SE*) e Engenharia Simultânea (*Concurrent Engineering - CE*), que respectivamente: (i) organiza a metodologia de investigação e documentação de sistemas e (ii) agiliza o processo em paralelização de estudos das disciplinas e sucessões de sessões de convergência (*CE Sessions*). As sessões para os Estudos Conceituais de Sistemas Espaciais são atividades altamente interativas, que requerem: (i) especialistas de uma determinada disciplina (térmica, operacional, elétrica, etc.) para descreverem ao grupo de especialistas seus modelos com as Soluções dos Elemento do Sistema, mostrando suas partes e parâmetros necessários, e (ii) instalações para realizar as atividades durante as sessões, acelerando o trabalho para as soluções dos conceitos dos sistemas. Ou abordagens centradas no documento ou nas centradas no modelo, as colaborações de modelos ocorrem por: projeção dos modelos, dentro de uma ordem sequencial, e de acordo com o número do projetores, que mostram os modelos da disciplina. A virtualização da informação diminuiu a colaboração física usando artefatos, dando preferência às colaborações de metáforas apenas virtuais, deixando de lado, por exemplo, uma pessoa que reúne dois peões físicos significa que uma nova representação foi obtida, estas representações foram substituídas por arrastar e soltar de ramos de informação em interface usuário gráficas. Este trabalho propõe e demonstra a viabilidade de utilizar Interfaces Tangíveis construídas com artefatos eletrônicos físicos e Realidade Aumentada Espacial para reintroduzir interações físicas colaborativas nas sessões de Engenharia Simultânea. Foi definido um vocabulário de interação tangível para uso de artefatos reais capazes de controlar os dados dos modelos. Em um aspecto pragmático na engenharia, esta tese traz para o espaço de trabalho de design as ferramentas cognitivas.

Palavras-chave: Interfaces-Usuário Tangíveis. Engenharia Simultânea. Engenharia de Sistemas Baseada em Modelos. Design de Conceitos de Sistemas Espaciais. Ambientes Colaborativos.

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LIST OF ABBREVIATIONS

3D	–	Three Dimensional
AI	–	Artificial Intelligence
AR	–	Augmented Reality
ARToolKit	–	Augmented Reality Tool Kit
ARToolKitPlus	–	Augmented Reality Tool Kit Plus
BYOD	–	Bring your Own Device
CAD	–	Computer Aided Design
CAF	–	Computer Aided Facility
CDF	–	Concurrent Design Facilities
CDSC	–	Concurrent Design and Simulation Center
CE	–	Concurrent Engineering
ConOps	–	Concept of Operations
CPRIME	–	*Centro de Projeto Integrado de Missões Espaciais*
CR	–	Cross Reality
CV	–	Computer Vision
CVE	–	Collaborative Virtual Environments
DB	–	Data Base
DC	–	Direct Current
DCT	–	Document-Centric Tool-set
DLR	–	*Deutsches Zentrum für Luft-und Raumfahrt*
DSM	–	Design Structure Matrix
ECSS	–	European Cooperation for Space Standardization
EMF	–	Eclipse Modelling Framework
EQ	–	Equipment
ESA	–	European Space Agency
ESP	–	EspressIf
GUI	–	Graphical User Interfaces
H2D	–	Human-Data
H2F	–	Human-Facility
H2H	–	Human-Human
HAI	–	Human-Artefact Interaction
HCI	–	Human Computer Interaction
HR	–	Hyper Reality
HI	–	Human Intelligence
HTML	–	Hypertext Markup Language
I/O	–	Input and Output
I2C	–	Inter-Integrated Circuit
IAV	–	Intelligent Augmented Virtuality
IDM	–	Integrated Design Model
IMDC	–	Integrated Mission Design Center

INCOSE	–	International Council on Systems Engineering
INPE	–	*Instituto Nacional de Pesquisas Espaciais*
IoT	–	Internet of Things
IR	–	Infra-Red
ISO	–	International Organization for Standardization
IVE	–	Intelligent Virtual
JAXA	–	Japan Aerospace Exploration Agency
LED	–	Light Emitting Diode
MBSE	–	Model Based Concurrent Engineering
MCRpd	–	Model, Control, Physical Representation, and Digital Representation
MCT	–	Model-Centric Tool-Set
MVC	–	Model View Controller
NASA	–	National Aeronautics and Space Administration
OCD	–	Operational Concept Description
OCDT	–	Open Concurrent Design Tool
OPM	–	Object Process Methodology
PDC	–	Project Design Center
PoC	–	Proof of Concept
PR	–	Physical Reality
SD	–	System Design
SE	–	System Engineering
SECESA	–	System Engineering and Concurrent Engineering to Space Applications
SoC	–	System on Chip
SS	–	Subsystem
STL	–	STereoLithography File
SysML	–	System Modelling Language
TTL	–	Transistor-Transistor Logic
TUI	–	Tangible User Interfaces
UI	–	User Interface
UW	–	Ubiquitous World
UX	–	User Experience
VGA	–	Video Graphics Array
VR	–	Virtual Reality

CONTENTS

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1 INTRODUCTION

1.1 Context

The engineering activities are done, primarily, by human beings that iterate using their cognitive and intellectual background to transform problems into buildable solution.

Complex, Coupled and Multidisciplinary Engineering consists of technology arrangements, optimized by its function, cost, schedule and performance, in a multidisciplinary convergence that involve the engineered product itself and the people who develop it. Examples are the products of the Space Engineering, which requires great effort within a very controlled life cycle through the development decomposition, the realization, use/operation and disposal.

Space Engineering has historically used passive tangible artefacts to aid the development. Mock-ups are created to represent, with higher or low fidelity, the context and elements required by the engineers to understand the domain. In Space Engineering the most common tangible artefacts are the Earth, and-or, Earth-Moon, globes which allows the engineers to discuss their disciplines and the influences from the orbit position. Discussing how they may suffer from where the Space Product will operate.

At early 50's at the Mercury Program, the NASA's Space Task Group (NASA, 1969) was responsible to study and explore man-made missions. The Task Group was represented in the movie "Hidden Figures" (FOX, 2016), which shown exactly the work facility. Figure 1.2a depicts the main view of such facility, where, a tangible artefact to orient discussions regarding orbit is located in the center of the room.

The NASA's Space Task Group was focused in the conceptual study before the first main review of the Space Engineering product. This study is now structured and named as Space Systems Concept Studies (Phase 0 - Mission Concepts, to ESA (ECSS, 2008) and/or Phase Pre-A / Concepts Studies, to NASA (KAPURCH, 2010)). The Space Systems Concept Analysis aims to: (i) identify mission needs, (ii) propose possible space system concepts, (iii) do a preliminary assessment of programmatic (cost, schedule) and risk aspects and (iv) early requirements. The Space Mission Concept Definition and Exploration, to Wertz et al. (2011), is an iterative approach that evaluates the multidisciplinary needs of subjects, and states:

> "*To explore a concept successfully, we must remove the walls between the sponsor, space operators, users, and developers and become a team.*"(WERTZ et al., 2011)

Nowadays, the community body of knowledge of successful missions, systems, and equipment increased, so the Concept Studies can reuse decisions with superior confidence, speeding up the process. New approaches in evidence in these context are: (i) Concurrent Engineering (CE) and (ii) Model Based System Engineering (MBSE).

CE organises the engineering work into three parts: pre-study (definition of the involved disciplines, time, cost, etc.), and cycles of (i) concurrent studies and (ii) sessions for information convergence. In CE, the various subsystems and designers involved in the process demand to integrate multidisciplinary perspectives to resolve their trades to create designs or to fulfil requirements of all stakeholders. The canonical Bandecchi's paper (BANDECCHI et al., 2000) defines Concurrent Engineering (CE) as:

> "*a systematic approach to integrated product development that emphasizes the response to customer expectations. It embodies team values of co-operation, trust and sharing in such a manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life-cycle.*"

The literature (BRAUKHANE et al., 2012) (BRAUKHANE; BIELER, 2014) (DENIER-GÉGU et al., 2014) (SCHUMANN et al., 2010) (BIESBROEK, 2012) (RICHARDSON et al., 2012) and real cases observations indicate that a common situation among the specialists (engineers, scientists and/or Principle Investigators) is the exchange of shared knowledge at collaborative CE sessions. Even though the existing practices in collaboration are relatively well mapped into spreadsheet-based software infrastructures, this is not true when considering collaboration using Model Based System Engineering modelling tools.

In Model Based System Engineering - MBSE there is a systematic adoption of explicit modelling aided by software, with the benefits of (i) significant advantage to project performance, (ii) improvements in engineering efficiency, and (iii) further prevention of costly rework (CARROLL; MALINS, 2016) (HAUSE; HUMMELL, 2015). According to Watson et al. (2015) the term MBSE means:

> ”*the formalized application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. MBSE is part of a long-term trend toward model-centric approaches adopted by other engineering disciplines, including mechanical, electrical and software. In particular, MBSE is expected to replace the document-centric approach that has been practiced by systems engineers in the past and to influence the future practice of systems engineering by being fully integrated into the definition of systems engineering processes.*”

The tendency in System Engineering, and its increasing momentum, is towards model-centric approaches. Even though, modelling is in the core of SE, as well it is in all other engineering disciplines (HARVEY et al., 2012), the role of the tools that support modelling, processes, viewpoints and ways to connect the data from multiple developers, still does not have a standardized language and/or approach to allow continuous use of model-centric tools by organizations (SAMPSON; FRIEDENTHAL, 2015) (OMG, 2014) (ECSS, 2010).

Particularly, in Space Systems Concept Studies, which is traditionally Document-Centric, two Model-Centric methodologies are just now being researched, the Arcadia (POLARYS, 2017) and the Object Process Methodology - OPM (DORI et al., 2016). These methodologies help modelling from brainstorming of first phases, through architectures designs and deliverable work-package distribution to next decomposition phases. But, even with the available systemic methodologies and tools, manipulating models during collaborative CE sessions is still not as dynamic as drag-and-drop building boxes into GUI (Graphical User Interface), and tools have not converged into a systemic collaborative representation.

Despite the tendency towards Model-Centric approaches, as far as was researched, there are none researches about human-to-data collaboration related to Space Systems Concept Studies regarding physical artefacts aiming at improving knowledge aggregation of the whole team (Figure 1.2b exemplifies the ESA’s Concurrent Design Facility, which has no physical artefact available to the team).

Interfaces with physical artefacts rely on the Natural User Interfaces, that aims to augment the facility and objects, creating interactive surfaces and/or tangible artefacts, expanding the applications to tools to other than keyboard and mouse. These extensions of the virtual world enable tangible explicit interaction with the otherwise hidden data (ISHII et al., 2012). Those environments are described in interaction trends reported in The New Media Consortium Horizon Report NMC (2017) as a four to five years' time-to-adoption in daily activities (Figure 1.1).

Figure 1.1 - Horizon Report indication of future technological adoptions.

SOURCE: extracted from NMC (2017).

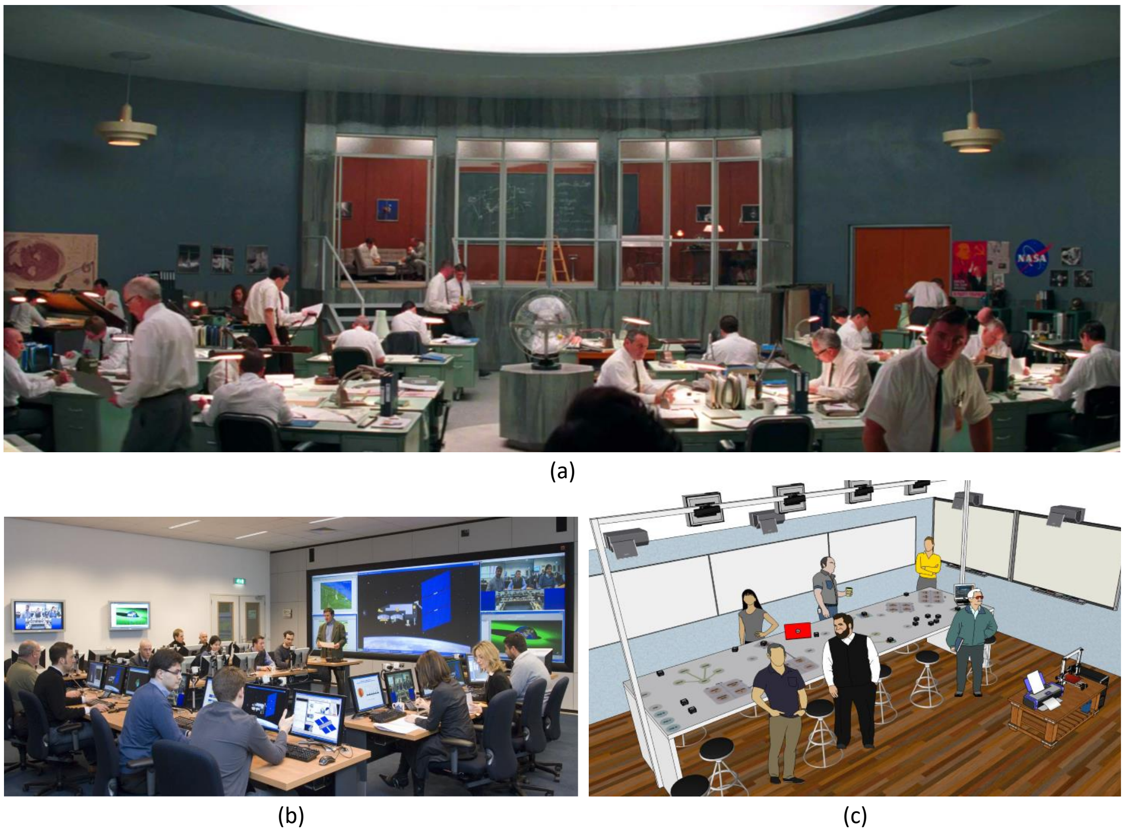
In the Human-Computer Interaction research of the Computer Engineering, the user-interfaces which the users interact with data through physical arterfacts is the Tangible User Interface (TUI).Ullmer and Ishii (2000) defines that Tangible User Interface:

> "*gives physical form to digital information, employing physical artefacts both as representations and controls for computational media. TUIs couple physical representations (e.g., spatially manipulable physical objects) with digital representations (e.g., graphics and audio)*"

The later aspect that contextualize the TUI reintroduction as an user-interface with smart and integrated tools connected to a source of data (models) to perform a given task is the 4th Industrial Revolution - Industry 4.0 (GILCHRIST, 2016). The Industry 4.0 relates the integration of computational tools and services (Artificial Intelligence, Big Data, Machine Learning, Internet-of-Things - IoT, Augmented Reality, so on) with the industrial tools and processes. This integration is driven by the rising complexity of the engineered products, that also demands speed/quality to keep the time-to-market need (SMITH, 1997). The Industry 4.0 in the Space field is addressed in Space 4.0 (ESA, 2016b). Space 4.0 integrates the space into a toolset framework that provide the connectivity services to enables Industry 4.0 potentials (ESA, 2016a).

In this context, this thesis investigates the shift giving by the tendency towards moving from implicit modelling to explicit modelling ongoing in the Concurrent Engineering (SCHUMANN et al., 2010) added with TUI in the Space Systems Concept Studies scenarios. Figure 1.2c exemplifies the facility arrangement proposed in this thesis, where data and models are handled via TUI over a single collaborative table rounded by the engineeries in a given design session..

Figure 1.2 - Facilities example regarding the physical artefacts to aid Space System Concept Studies.



(a) Scene of the movie Hidden Figures containing the NASA's Space Task Group work facility with the physical artefacts to help into design. (b) ESA's Concurrent Design Facility illustrating the nonexistent physical artefacts. (c) example of a Facility with TUI artefacts proposed in this thesis.

SOURCE: (a) was extracted from the movie Hidden Figures from FOX (2016), (b) from Pickering (2017), (c) from the author.

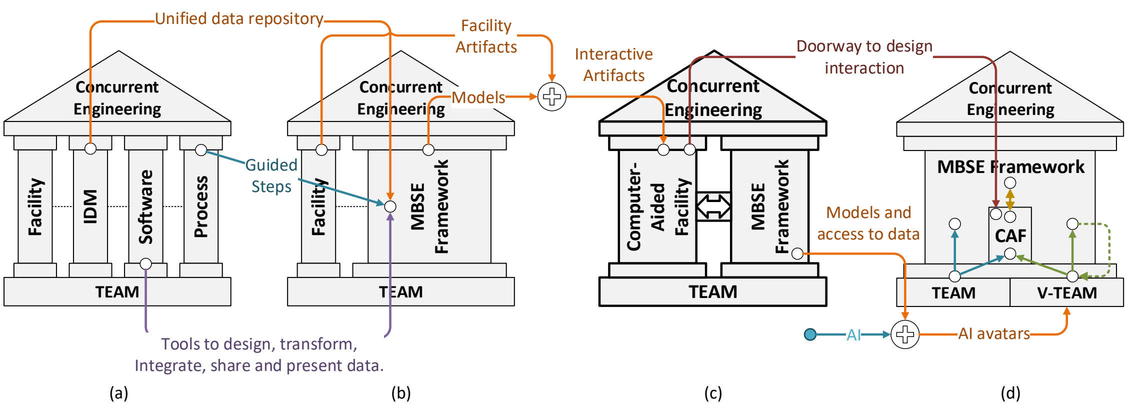
The Space System Concept Studies, after being performed with Concurrent Engineering practices and supported by computational tools (since the 90's), may be described through five elements: the team, the facility, the software, the Integrated Design Model (IDM) and the process (Figure 1.3a). The current CE approach formalizes and collaborates the information in Sessions mainly through Office Software medium representations, as charts and presentations, and 3D models in specific cases.

Over the 2010's, MBSE methodologies, containing tools with Systemic Modelling languages, are being researched as the main format to formalize and collaborate information in System Engineering. These tools porsue a medium with a common language to all specialists. MBSE combines: the IDM, the set of software and a process that is embedded in the methodology (Figure 1.3b) of the MBSE Framework. MBSE still requires some steps to be fully adopted as CE standard medium. The focus of the MBSE Framework is toward the creation of a model, rather than a document.

(BRAUKHANE; BIELER, 2014) noted that despite the virtual tools to create models, facility artefacts were being used to create physical model representations. However, such models only contributed to aid mental models and in fact, does not cater into the MBSE Framework. This thesis illustrates the inclusion of such artefacts, creating an artefact medium to manipulate the models to promoting meaningful collaborations in a Computer-Aided Facility (Figure 1.3c).

This work discusses, for the future, a basis for the ongoing tendency related to Industry 4.0 (and Space 4.0) where a real team collaborates and is assisted by a virtual team (V-Team) made from artificial intelligent agents, as well as the use of software user-interface modalities such as Augmented Reality and Tangible User Interfaces, to create a Computer Aided Facility which will enable to manipulate the models through natural languages (Figure 1.3d).

Figure 1.3 - Concurrent Engineering medium changes.



SOURCE: from the author.

CE applied to Space Systems Concept Studies regarding computer-aided cognitive physical artefacts handled by the engineers during sessions, shows an opportune starting point in developing computational tools and experiment interaction methods to: explore the nature of sharing model information among the engineers using physical artefacts. Once the literature review did not indicate any study on that.

Exchange models addresses challenges that come with MBSE and CE combined. The way interaction happens can ease or difficult communication among engineers, interfering into the resulting solution. So, the following question drives this thesis:

Can Tangible User Interfaces be integrated to handle models in CE Sessions?[1]

That driven question leads to other three questions for previews analysis:

- Question 1 - How does the team of a CE Session **manipulate models**?
- Question 2 - How **adapted are the current tools** to collaborate during a CE Session?
- Question 3 - How does the **collaboration** among the members occur during a CE Session?

1.2 Thesis Objective

This thesis objective is to propose (and show the feasibility of the use of) **TUI artefact vocabulary as the medium to engineers collaborate models during Space Systems Concurrent Engineering Concept Studies Sessions**. The idea is to reintroduce physical cognitive artefacts to represent the study data and collaborative interactions.

Taking into account the existing Space Missions Integrated Design Center (*Centro de Projeto Integrado de Missões Espaciais* - CPRIME) at INPE, this thesis intend to contribute with new ideas towards a model collaboration and a new way of interaction for the work being developed in CPRIME according to the current practices on MBSE and CE applied to Space sector.

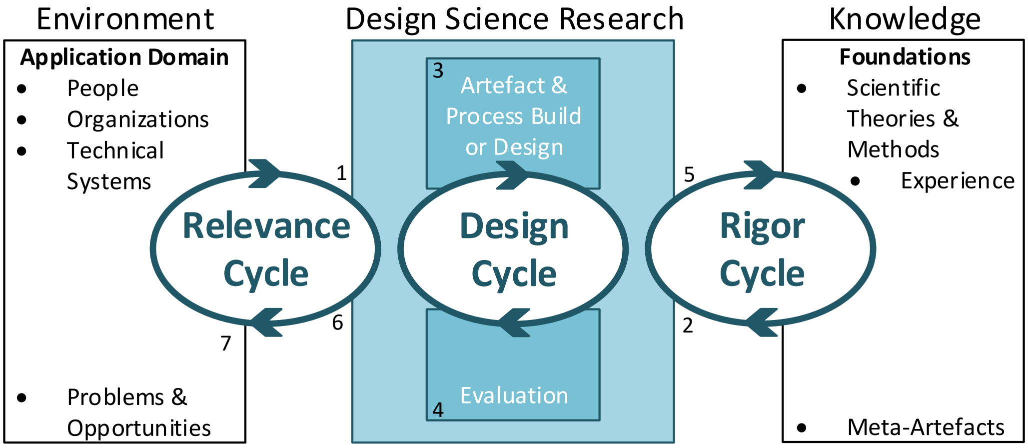
[1]From now on, we name collaborative sessions of Concurrent Engineering performed for the Space Systems Concept Studies only as **CE sessions**

1.3 Research Paradigm

We adopted the Design Science Research Paradigm (DRESCH et al., 2015) in order to structure and preset this research. This paradigm comprises three activity cycles (Figure 1.4) (HEVNER et al., 2004) (HEVNER, 2007):

- **The Relevance Cycle**: relates to the application domain environment which is desired to introduce a new/innovative artefact or process. The Cycle addresses the identification and representation of the opportunities and problems (presented in the Context of this Thesis), to improve practices, or identify the problem before it is broadly recognized. The Relevance Cycle provides the context, that not only describes the requirements for the research, but also the **acceptance criteria** (see Section 1.4).
- **The Rigor Cycle**: relates to the experience and expertise knowledge that defines the state of the art foundations that will be applied into the application domain. The cycle collects existing artefacts/processes found in Scientific Theories and Methods, so the research project can use them as innovative meta-artefacts. The Rigor Cycle includes any extension to the original theory made during the research, as a feedback to the Body of Knowledge.
- **The Design Cycle**: generates design alternatives matching knowledge foundations with application domain environment. It contains the evaluation of the design against acceptance criteria requirements until a satisfactory design is achieved.

Figure 1.4 - Design Science Research Paradigm.



SOURCE: adapted from Hevner (2007).

In this thesis we consider as (the numbers of the items are indicated in Figure 1.4):

1. **Relevance Cycle Inputs**: The inputs come from the thesis background environment, containing the Facility, Information Exchange and Collaborations used in the CE Sessions.

2. **Rigor Cycle Inputs**: The inputs are the Related Technologies, including Collaborative Environments, Tangible User Interfaces and Ergonomics.

3. **Artefact & Process Build or Design**: The development description of the interactive facility as well as the artefacts, and the interaction vocabulary.

4. **Evaluation**: The evaluation is against the proposed questions realized through a comparison of the CE Session Collaborations and an evaluation regarding the Collaborative Environment attributes.

5. **Rigor Cycle Feedback**: It is given by the outputs of the design that contributes to the Body of Knowledge, in this case a proposal of Tangible Artefact Elements Taxonomy.

6. **Relevance Cycle Feedback**: It means the outputs of the design that contributes to the background environment, in the case a proposal of CE Session Model Taxonomy and the CE Sessions contributions.

7. **Relevance Cycle Revisiting**: The further opportunities after the Design Cycle. It considers the inclusion of other technologies that extend the development and presents other problems and opportunities.

1.4 Evaluation Criteria Propositions

The evaluation criteria of this thesis that can be used to demonstrate the design relevance follow two of the Design Science Evaluation Methods, listed by Hevner et al. (2004):

- **The Analytical Architecture Analysis**: uses a study fit of the designed artefact into the technical propositions. We demonstrate through a comparison with the CE Session Collaborations;
- **The Descriptive Informed Argument**: uses the information from The Body of Knowledge to build a convincing argument for the artefact's utility. We demonstrate through arguing about this thesis's questions.

1.5 Thesis Outline

The next Chapters of this thesis are organized as follows:

- **Chapter 2 - Space Systems Concurrent Engineering Concept Studies - CE Sessions**: This Chapter describes the current state of the practice of the Space Systems Concurrent Engineering Concept Studies, within the research towards how data is modelled, how the information is exchanged, the physical aspect of the facility and the collaborations. This Chapter relates to the Relevance Cycle of the Design Science Research.
- **Chapter 3 - Tangible User Interfaces**: This chapter describes the current state of the art of the computational technologies regarding the design opportunity of introducing Tangible User Interfaces in CE Sessions, with the research towards the Collaborative Virtual Environments (CVE), the Tangible User Interfaces, and the relative ergonomics of using physical artefacts. This Chapter relates to the Rigor Cycle of the Design Science Research.
- **Chapter 4 - Concurrent Engineering Collaboration with Tangible Cognitive Artefacts**: This Chapter presents the design solution regarding the background and the related technologies. The chapter describes the data entities, the way the data is represented, the Computer Aided Facility, and the interaction vocabulary. This Chapter relates to the Design Cycle of the Design Science Research.

- **Chapter 5 - Implementation**: This chapter presents the implementation of the tangible artefact, the Computer-Aided Facility Interaction Elements to track the artefact and project the intangible representations, and the viability proof demonstration. This Chapter relates to the Design Cycle of the Design Science Research.

- **Chapter 6 - Evaluations and further discussions about the Future Works Opportunities**: This chapter presents the Evaluation Criteria to demonstrate the thesis' design relevance, as well as further development opportunities to create a Hyper-Reality CE Facility, describing some foreseen research opportunities including Cognitive Artificial Intelligence, Big Data & Analytics, Augmented Reality, and Modelling & Simulation. This Chapter relates to the Design Cycle Evaluation, and Rigor and Relevance Cycles Feedback.

- **Chapter 7 - Related Works**: This chapter presents this thesis' related works. The topics cover the technology, use of tangible user interfaces in engineering, use of systemic modelling to collaboration in Concurrent Engineering Sessions and Concurrent Design Facilities collaborations.

- **Chapter 8 - Conclusion**: This Chapter discuss the contributions and summarizes this thesis findings.

The Appendixes brings more specific related information:

- **Appendix A** describes the intangible representations (auras) created to exhibit the Concurrent Engineering Session context.

- **Appendix B** contains a Tangible User Interface Elements Taxonomy proposal.

- **Appendix C** contains the first page of all publications done by the author during this thesis.

2 SPACE SYSTEMS CONCURRENT ENGINEERING CONCEPT STUDIES - CE SESSIONS

This chapter presents the information about the application domain background within the state of the art, focusing on the practices of the Phase 0 - Concept Studies using Concurrent Engineering. This Chapter supports the Relevance Cycle of The Design Science Research showing the application context of collaboration in CE Sessions. We divided this chapter in:

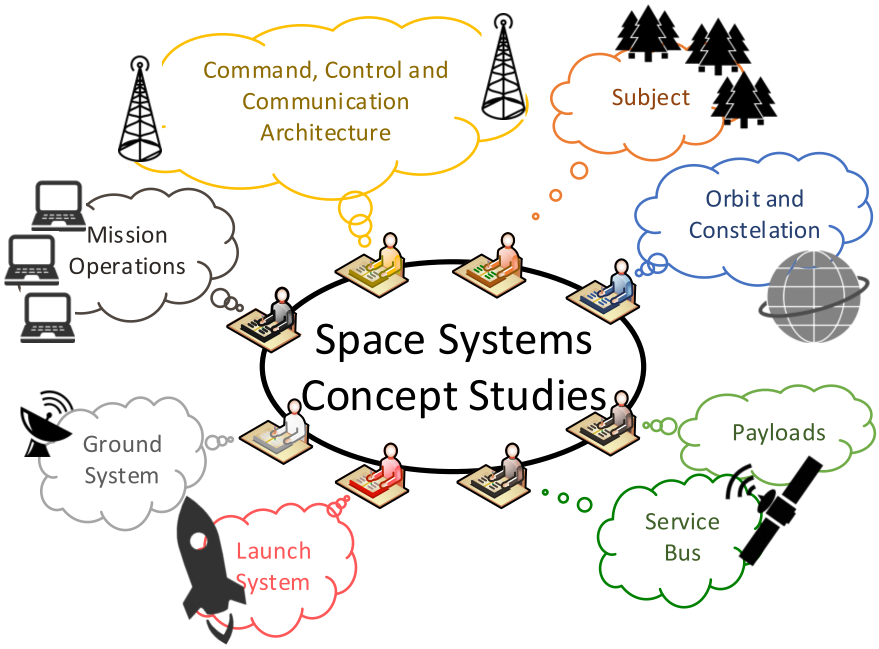
- **Space Systems Concept Studies**: describes the System Engineering life cycle phase in consideration of this thesis;
- **Concurrent Engineering**: describes the CE approach that speeds-up the assessments of Concept Studies;
- **Data Modelling Approaches**: describes the document and model centricity vs. basis approach towards the data modelling tool possibilities;
- **Information Exchange**: describes the media to system concept information exchanging during sessions collaboration;
- **Concurrent Design Facilities**: describes the facilities broad types found through the literature and observations;
- **Collaborations**: describes the collaboration of the main data entities.

2.1 Space Systems Concept Studies

The purpose of the Concepts Studies is to provide a feasible spectrum of concept alternatives and ideas from which system solutions can be selected.

Wertz et al. (2011) states a common set of disciplines that are necessary to concept a Space Mission Architecture, as illustrated in Figure 2.1. The space mission defines the density and amount of depth of each discipline exploration. The common disciplines are: (i) the **subject**, which consists of the end reason for the system, (ii) the **payload and service bus**, which consists of the subsystems which are part of the aircraft, where the payload fulfils the reason of the system and the service bus provides the infrastructure to it (as power, pointing, etc.), (iii) the **launch system**, which consist of the elements to place the aircraft in orbit, as launch facility, launch vehicle, etc.; (iv) the **orbit and constellation**, which consist of the spacecraft's, or group of spacecraft, movement description necessary to fulfils the system mission; (v) the **ground systems**, which consist of the arrangement of subsystems to communicate with the spacecraft and distribute data; (vi) the **mission operations**, which consist of people, facilities and resources to execute the mission and the (vii) **command, control and communication architecture**, which consist of the spacecraft, ground segment and the mission operational elements.

Figure 2.1 - Space Systems Concept Study Main Disciplines.



SOURCE: adapted from Wertz et al. (2011).

The first phase of a Space mission development, as described into NASA's System Engineering Handbook (KAPURCH, 2010), is named "Concept Studies". It describes the study of the stakeholders needs and potential opportunities consistent with the organization, demonstrate the feasibility of the desirable mission, and/or system that will need some programmatic estimates, analysis and future allocation of resources. These concept studies aim to stablish mission goals, high-level requirements and functional descriptions, and Concept of Operations - ConOps (or Operational Concept Description - OCDs).

Similarly, ECSS's ECSS-M-ST-10C - Project Planning and Implementation (ECSS, 2009), calls the Concept Studies as "Mission Analysis/Needs Identification" states that the primary objective is to release the mission statement and assess the preliminary technical requirement specification and programmatic aspects. The main tasks are: (i) **decompose** the mission statement in terms of mission needs, expected performance, dependability, goals and operations constraints, (ii) **establish** a preliminary technical requirements specification; (iii) **identify** possible mission concepts, and (iv) **evaluate** a preliminary programmatic and risk assessment.

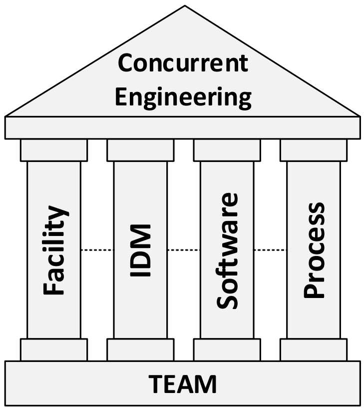
2.2 Concurrent Engineering

Since the 80's, the importance of a quicker Space System Assessment lead to find ways to speed-up the process to create Space System architectures (REDDY et al., 2013) (BANDECCHI et al., 2000) (KARPATI et al., 2013) (COFFEE, 2006). These studies postulate, in general, that a product design and its manufacturing process are thought simultaneously, with multidisciplinary groups to accomplish the multi-modality coverage and convergence of complex coupled products. Even though this approach is not new, as pointed by (HARVEY et al., 2012), it gained momentum using different names: Concurrent Design, Simultaneous Engineering, Simultaneous Design or Integrated Design.

CE is characterized by five key dimensions (Figure 2.2 illustrate the dimensions): (BANDECCHI et al., 2000)

- **Team**: the most important factor, it must be a well-chosen, and integrated, group of specialists to study the system. The team is the base of any development, and they are accompanied of four following pillars.
- **Process**: the sequence of steps that the study needs to accomplish the desired deepness and results.
- **Software infrastructure**: the group of domain specific tools (the specialist tools).
- **Integrated Design Model (IDM)**: the centralization of the specialists results into a single repository, usually spreadsheets.
- **Work Facility**: the place where the studies occur.

Figure 2.2 - Concurrent Engineering dimensions.



SOURCE: adapted from Bandecchi et al. (2000).

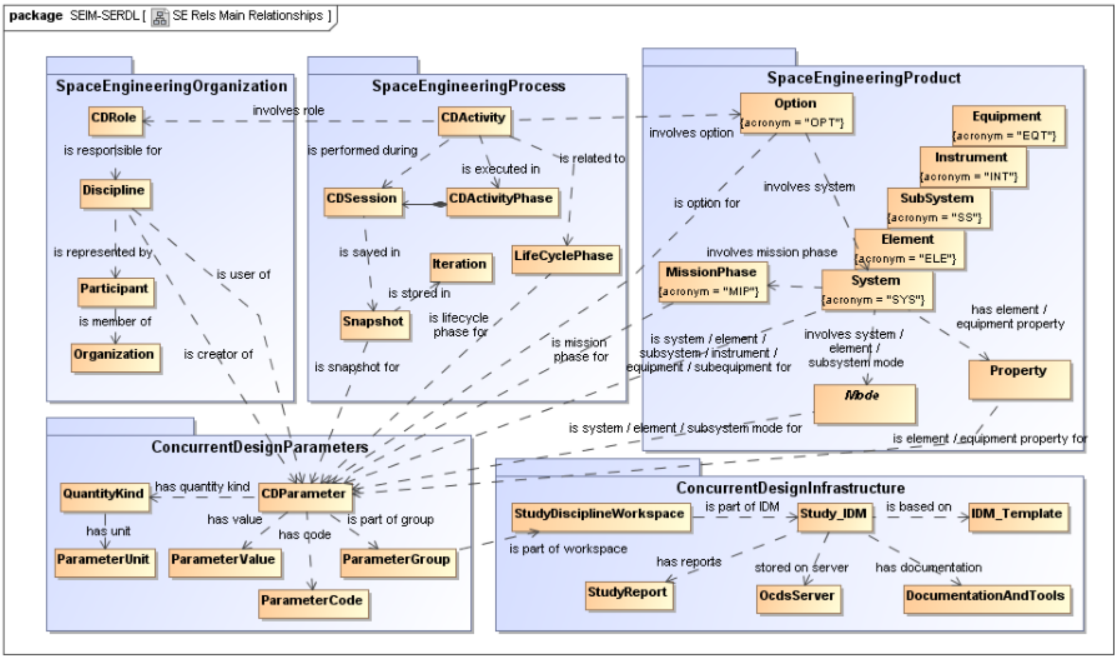
Smith (1997) notes that CE dates from 19th century and become organized and popularized as Concurrent engineering in recent years. The post 90's CE initiatives based in computational tools have a strong resemblance with the Software Engineering Agile Methods (SOMMERVILLE, 2011). The Agile Methods are best suited to applications still gathering requirements, that are intended to deliver fast answers to customer, which can propose, or remove, delivered elements in further iterations - just as CE.

2.3 Data Modelling Approaches

In Concept Studies Phase are described in models the characteristics that are important to the final system's description, and further viability analysis (FLEETER et al., 2014). To those models, performance and other choosing criteria are done by catalogue comparison or by the discipline specialist "feeling".

In data modelling an important aspect is the information model that describes the relations, constraints, rules and operations of a data semantics for a chosen domain. One of the information model elements are the **entities**. The entity is the fundamental building blocks which describes the data structure of information model (MICROSOFT, 2017). The ECSS (2010) (Illustrate in Figure 2.3) exemplifies the hierarchies of an Information Model: the organization, the process, the product, the parameters, and the infrastructure.

Figure 2.3 - Space Engineering Information Model main object types.



SOURCE: extracted from ECSS (2010).

The Space Engineering Product and Concurrent Design Parameters (Figure 2.3) contains the spacecraft types of parameter grouping, from which are abstracted the main entities: models, system elements, and parameters.

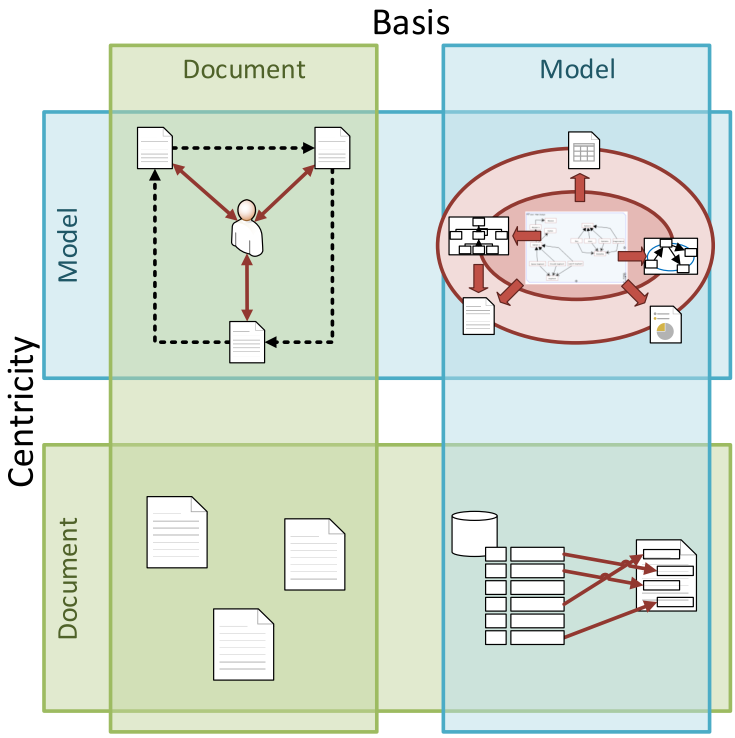
- **Models**: the file, the project, the abstract representation that contains one, or a set of system elements.

- **System Elements**: the abstract reunion of system parameters that the specialists use to describe parts of the system. The system elements are the object things which the solutions are made of, and can be further specialized (if required) into: mission, option, discipline, segment, satellite, subsystem, equipment, ground station, ground function, launcher. System elements are coupled to each other, as building blocks, to create the concept alternatives.

- **Parameters**: the actual data, from where the specialists retrieve information to their decisions. The parameters are exposed system elements data that describe inner information. ECSS (2010) describes several sub types of parameters used in CE, thus they can be summarized in three types: (i) discrete, (ii) continuous, and (iii) textual.

Different tools approaches can handle these entities. Harvey et al. (2012) describes a historic process of System Engineering tools technology evolution, which keeps changing the way to represent the design entities. From documents to specific modelling tools. He proposes a taxonomy, summarized in Figure 2.4, to characterize the tools.

Figure 2.4 - Correlation between basis and centricity.



Spectrum representation of tooling considering the combinations of model or document basis vs. model or document centric.

SOURCE: adapted from Harvey et al. (2012).

The taxonomy combines two aspects: (i) the **centricity** - which describes the user interface approach to the tools; versus the (ii) **basis** - which describes the information's nature in:

- **Document-centric & document-based approach** (in the bottom-left): does not have a central model of the system, and loosely allows descriptions of the system as the documents are unconnected.

- **Model-centric & document-based approach** (in the top-left): the model is in the head of the systemic engineer, and it populates a set of documents with the views of the system, the data interconnection among documents is implicit (in dashed black), only the engineer knows the interconnection (in red).

- **Model-centric & model-based approach** (in the top-right): a full model approach, where the model is the integration of engineering, technical and documentation. The model can be refined, transformed and redrawn, as required, in any level.

- **Document-centric & model-based approach** (in the bottom-right): the user handles model elements that correspond to document parts (paragraphs, sections, and diagrams) and the tool output a whole document when required.

To summarize the categories, (HARVEY et al., 2012), (KONING et al., 2012) and (FRIEDENTHAL et al., 2008) describe the shared tool-set that the specialists agree to use in:

- **Document-Centric Tool-set (DCT)**: approach when the organization documents the information directly on the end-media artefacts, being either a physical or virtual document artefact.

- **Model-Centric Tool-set (MCT)** approach when the organization documents the information that represents the system in model artefacts which will them be transformed in the end media interface, with representations and formats adequate to the context of the author.

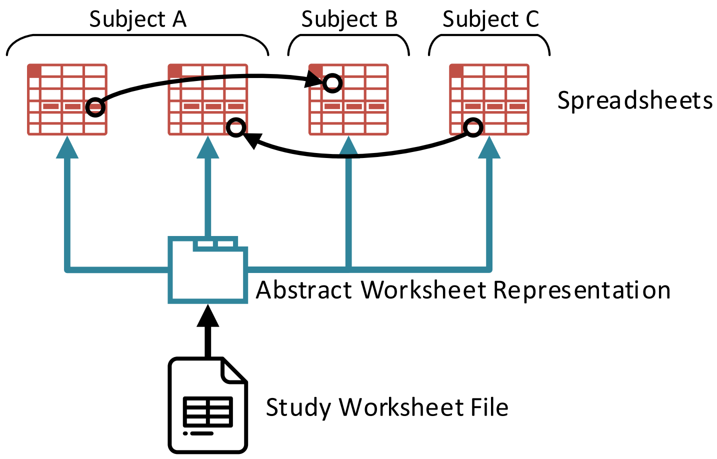
2.4 Information Exchange

The model-based information exchange, in both document-centric and model-centric, in CE Sessions are the way that the specialists exhibit their design entities data. The literature points to four possibilities: (i) via a single worksheet, (ii) via multiple linked worksheets, (iii) via multiple worksheets linked by databases and (iv) via modelling tools.

2.4.1 Via Single Worksheet:

Using a single worksheet, as depicted in Figure 2.5, the CE study uses only one worksheet file that contains all system parametrized aspects. Each tab, or group of tabs, of the worksheet has spreadsheets that relates to one discipline. The disciplines are interconnected by links through the cells of two tabs (in the case of external context parameters). (GAUDENZI, 2006)

Figure 2.5 - Data connection among the spreadsheets of a single worksheet.



The connection among the spreadsheets can be done through cell links that relates the interconnection through the subject domains.

SOURCE: by the author.

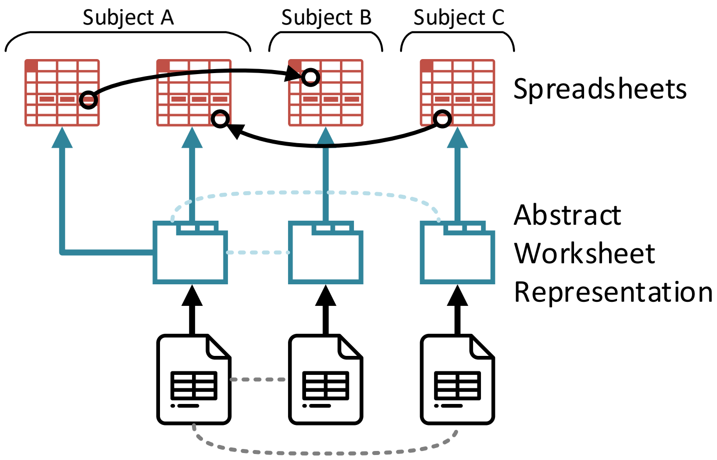
In earlier implementations, the use of this single worksheet as a data source was not concurrent *per se* (ROSER, 2006). Each specialist had a moment of the study sequence to place the study result meeting the specified process - and free access to only examine. They shared the worksheet through a file server, e-mail, and/or diskette (and later flash drives). Nowadays within the collaborative cloud documents a single worksheet can be filled and manipulated by multiple users concurrently, as Quip[1], Mindmeister[2], the Google Suite[3] and the Microsoft Office Online[4].

2.4.2 Via Multiple Linked Worksheets:

As the worksheet software evolved in, it allows interconnection among files, as multiple linked worksheets. With multiple worksheets, each worksheet file can represent one discipline. The separation of the disciplines provides better organization and work parallelization (PORTELLI et al., 2008). The parameters are linked through cells of different worksheets files. Figure 2.6 shows the organization.

[1]Quip - available at https://quip.com/
[2]Mindmeister - available at https://www.mindmeister.com
[3]G Suite - available at https://gsuite.google.com.br
[4]Office Online - available at https://www.office.com/

Figure 2.6 - Data connection among spreadsheets of multiple worksheets.



The connection among the worksheets can be done through cell links that relates the interconnection through the subject domains.

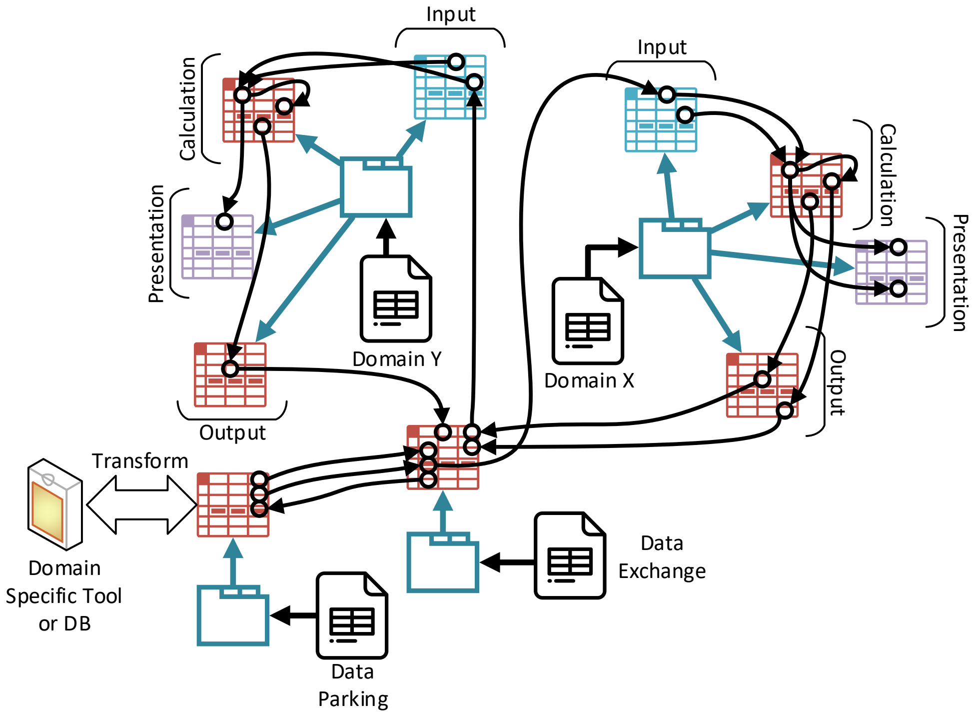
SOURCE: by the author.

One worksheet per discipline, allows: structured worksheets and template workbooks. (MATTHYSEN; HENDERSON, 2012)

- **Structured worksheets**, illustrated in Figure 2.7, contains the IDMs five main parts: (i) **subsystems workbooks** - containing the discipline's models in four sheets dimensions: input sheets, calculation sheets, presentation sheets, and output; (ii) **systemic workbooks** - containing the main activities control, storing the requirements, trades, options and budgets included in all other workbooks, (iii) **data exchange workbook** - containing all the output parameter from the output sheets, as a snapshot repository of all outputs at every moment, (iv) **data parking workbooks** - containing the links between specific tools, with the large amounts of raw data that need to be formatted to the proper workbook, and the (v) **domain specific tools / databases** - containing the specific software/databases that are part of the engineer software repertoire, to some authors this is described as the Software infrastructure.

- **Template workbooks** are earlier created discipline's workbook, which are handled to each engineer at the beginning of a new study. The templates are result of the know-how of common used parameters, and successful data organization.

Figure 2.7 - Template sheets on multiple worksheets.



Having one domain per worksheet allows to create: (i) a sheet to each group of parameters - reusing in later studies, (ii) data parking, and (iii) data exchange sheets with data conversions.

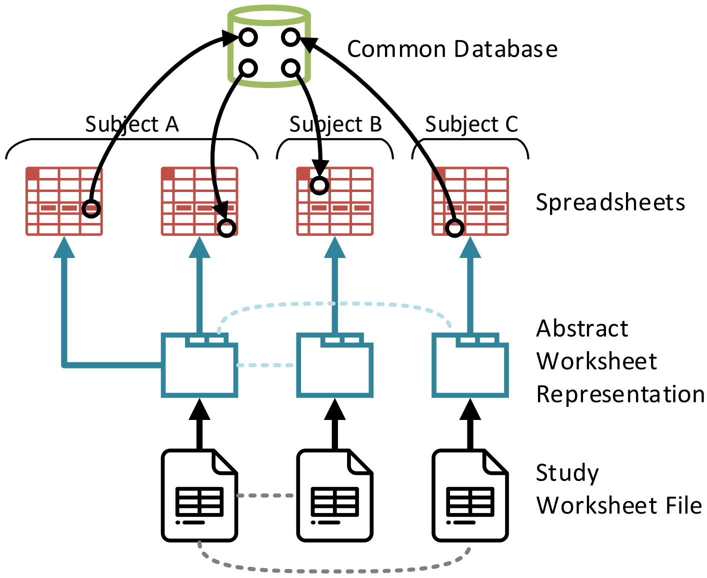
SOURCE: by the author.

2.4.3 Via Multiple Data Base Linked Worksheets:

The third approach found in the literature is the Multiple Data Base Linked Worksheets, realized by the Open Concurrent Design Tool (OCDT), which implements the ECSS-E-TM-10-25 - System Engineering - Engineering Design Model Data Exchange (CDF) (ECSS, 2010) definitions to create a European size collaborative server to share information among: agencies, industries, and academia. This modality is similar to the multiple linked worksheet. But, instead of direct links, the information flows through a remote database which tracks all sheets cells (as the data exchange and data parking worksheets of the structured worksheets). Figure 2.8 shows the organization.

NASA's Fredrik work environment has a similar approach, interconnecting tools with a remote data base (VOLK et al., 2000). The Team Xc is also implementing a DB based Trade Space Tool to provide continuity, adaptability and reuse of the different types of models (MURPHY et al., 2016).

Figure 2.8 - Data connection among the spreadsheets via remote database.



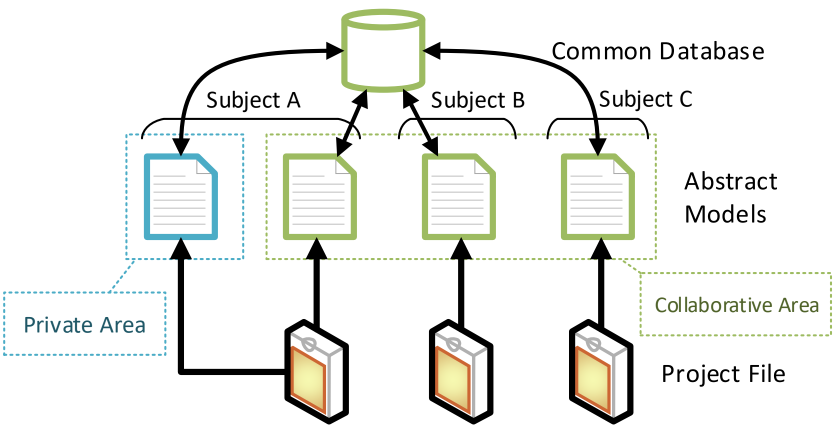
Using a Database as an exchange middle-ware among the spreadsheets allows to scale locally and remotely the implementations.

SOURCE: by the author.

2.4.4 Via Model Based System Engineering Tools

Using MBSE Tools moves from **direct cell linked through the DB** to a **linked model** done by the modelling infrastructure. The modelling infrastructure must allow to: remotely save and retrieve in case of a collaborative use, and locally edit models in design studies. Figure 2.9 shows the data architecture organization.

Figure 2.9 - Data connection among models.



SOURCE: by the author.

Those SE implementations vary from the use of modelling environments, as Simulink

[5] and Enterprise Architect [6], to specific designed implementations. Including tailored strategies underneath methodologies to support the SE processes. Some convergence of methodologies was researched by INCOSE, resulting into a suggestion list of MBSE Methodologies. (WATSON et al., 2015)

The two MBSE that are gaining momentum in Space CE Community as possible common modelling standards, are: (i) the **Arcadia** from Polarsys Group (GIORGIO et al., 2012) (POLARYS, 2017); and (ii) the **Object Process Methodology (OPM)** from the Enterprise Systems Modelling Laboratory of the Technion Israel Institute of Technology (DORI, 2016), which recently become an ISO[7] standard under the name: ISO/PAS 19450:2015 - Automation systems and integration – Object-Process Methodology.

OPM is based on the minimal universal ontology paradigm, which states the minimal number of symbols and semantics that can describe any system. The Object-Process Theorem defines fundamental principles that organize the system concept design: (DORI, 2016)

- **Function-as-seed**: every design starts by defining the high-level function that defines, names and depicts the main function of the system.
- **Model Fact Representations**: a fact in the model needs to appear at least in one diagram to be represented in the all model.
- **Element Representation**: a model element appearing in one diagram may appear in any other diagram of the same element.
- **Timeline**: processes, inside a zoomed process, sequence must be described from top-bottom, and left-right direction.
- **Thing Importance**: the most important things are the one that appear on the highest levels of the models.
- **Singular Name**: all things must be single named, plurals must be convert to "group of" and "set of" naming.
- **Graphic-Text Equivalence**: every fact on the OPD must have a textual representation.

[5]Simulink - available at https://www.mathworks.com/products/simulink.html
[6]Enterprise Architect - available at http://sparxsystems.com/products/ea/
[7]Available at: https://www.iso.org/standard/62274.html

- **Thing Name Uniqueness**: different things must have different names; in case of feature names they are distinguished by the reserved word "of" and the name of their exhibitor.

- **Procedural Link Uniqueness**: a process shall have at least one object or state connected by a transforming link.

- **Detail Hierarchy**: every time the diagram becomes with an excessive amount of details, a new, descendant diagram shall be created.

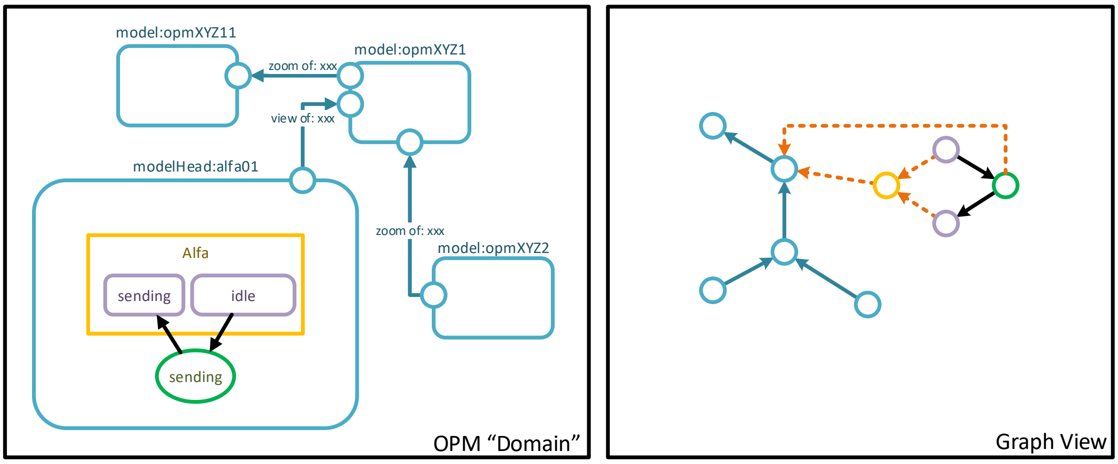
- **View Creation**: *this is not a principle* but is an important refining mechanism, the detail hierarchy zooms the model vertically, adding internal details into the refinable model; the views mechanism adds horizontal specific aspects which improves the description or addresses different scenarios.

To support OPM, the Prof. Dov Dori developed the OPCat tool[8]. OPCat is a custom-made tool, written in Java that implements OPM. The software incorporates additional functionalities created by the prof. Dori alumni. OPCat uses the semantics defined by Object-Process Theorem defining: (i) **stateful objects**: things that exist, (ii) **processes**: things that happens, and (iii) **links**: relationship characteristics between two things. Both structure and behaviour are described into a single diagram. The elements are interconnected through the name of the things to provide traceability and consistency through the complete model.

Underneath the OPM models, the methodology (and tool) uses graphs (WILSON, 1986) that relates the things (nodes), through links (edges). System Designs are also nodes, with things connected. System Designs nodes also interconnect with other designs through: zooms-in and views nodes. Figure 2.10 exemplifies the one-to-one graph representation of the OPM elements: (i) in blue the system designs models, and its relations, (ii) in yellow the object things, (iii) in purple the object states, (iv) in green the process things, (v) in black the things links, and (vi) in dashed orange the containing relations.

[8] http://esml.iem.technion.ac.il/opcat-installation/

Figure 2.10 - OPM Graph Representation.



Left: Example Model with the relation among System Design. Right: Graph Representation of the relations.

SOURCE: from the author.

The user of a modelling tool does not need to know if the tool has a graphs underneath. The information of this structure presents opportunities to implementations of graph-based data-bases to manipulate the models, as well as graph-based artificial intelligence strategies to optimize and manipulate OPM models through Design Languages (GROSS; RUDOLPH, 2012).

2.5 Concurrent Design Facilities

Concurrent Engineering Facility is the physical accommodation where the team of specialist meets and collaborates to converge the concept designs. The facility receives different names, accordingly to the organization: ESA calls it as Concurrent Design Facilities (CDF), NASA's Team X calls it as Project Design Center (PDC), NASA's Goddard calls it as Integrated Mission Design Center (IMDC). Chinese National Space Science Center calls it as Concurrent Design and Simulation Center (CDSC), and Brazilian National Institute for Space Research calls it as Space Missions Integrated Project Center.

The key role of the facility is to create an environment which fulfil the operational needs of the specialist team, dealing with: (SIMONINI et al., 2008) (PICKERING, 2017) (NAKAJIMA et al., 2016)

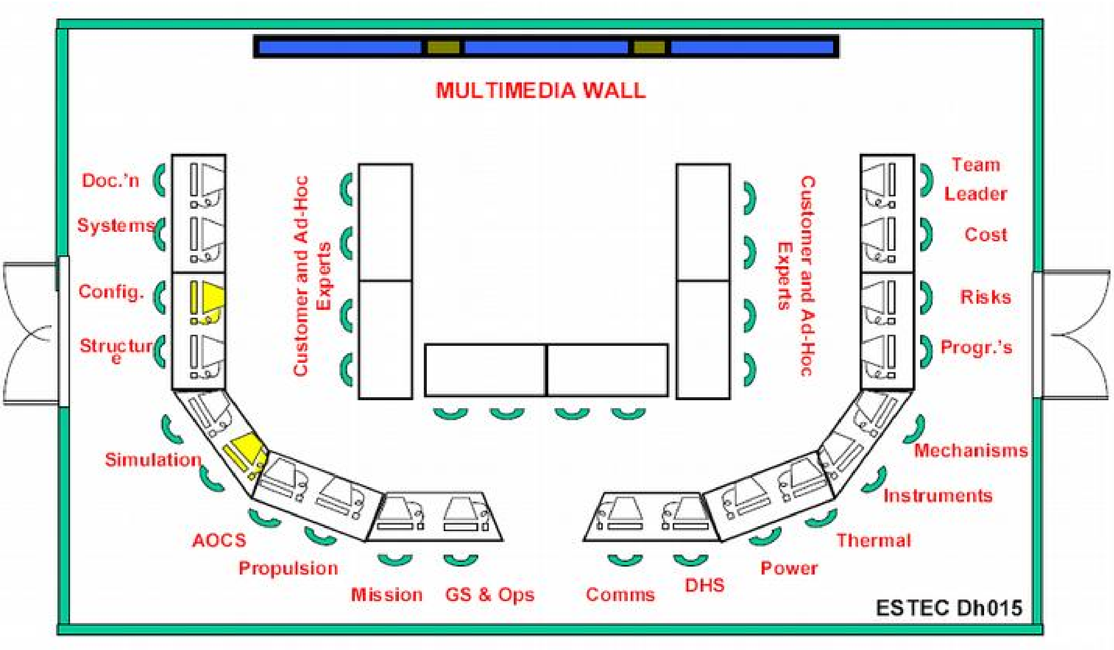
- table placements,
- positioning of the people by discipline's relationship,

- ergonomics of the participates,
- ”free” design spaces,
- meeting equipment positioning,
- study/research material,
- table space to draw sketches and notes,
- communication among study sprints,
- relax zones,
- breakout rooms,
- archives,
- data centres, and
- office material storage.

The baseline facility layout, illustrated in Figure 2.11, presented by (BANDECCHI et al., 2000) set-up a standard to the facilities layout. Even though they already changed their layout concepts[9], it keeps the original as a baseline (PICKERING, 2017). This layout is formed by a large “U” shape table distribution containing the disciplines. The disciplines’ positions are related with the amount of interaction between disciplines. Discipline with strong coupling, which will lead to more collaborations, are close to each other. The inner U usually contains the customers and other invited experts. The U’s are facing a multimedia wall, that the literature refers as containing: projectors, monitors, and/or interactive whiteboards.

[9]http://www.esa.int/Our_Activities/Space_Engineering_Technology/CDF/The_Facility

Figure 2.11 - Standard Concurrent Design Facility Layout.

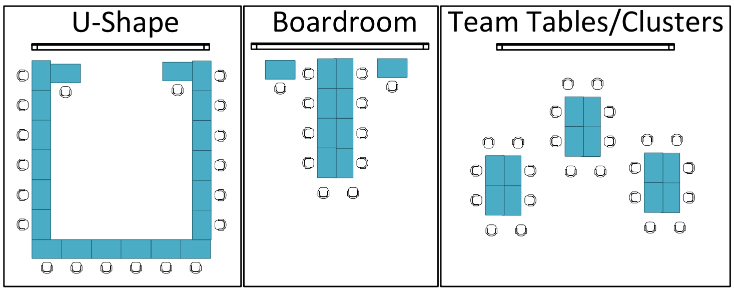


The U shape layout facing a multimedia wall is the most common approach to organize the team.

SOURCE: from Bandecchi et al. (2000).

Collins (2004) and Thorne (2014) list some of other possible meeting rooms' layouts, discussing the ideal number of participants, the discussion format, the sense of freedom, and some psychology issues, as diminished feelings. Figure 2.12 exhibits some of the rooms which are found on the SECESA's Community literature: (i) the standard "U" shape found in the majority of the facilities, followed by the (ii) Boardroom, then by the (iii) Clusters.

Figure 2.12 - Meeting room layouts.



SOURCE: adapted from Collins (2004).

CE Facilities, regarding modelling, only servers as housing places. Models are handled at computer stations, and projection/TV screens, as exemplified at Figure 2.13, of the ESA's CDF. The facility itself does not cater any modelling in-formation, it does not have any meaningful apparatus other than the desktop/laptop interfaces, to change and/or interact with digital data.

Figure 2.13 - ESA's Concurrent Design Facility.

SOURCE: from Pickering (2017).

As a different approach, JAXA CE Facility (NAKAJIMA et al., 2016) shows an arrangement where no computers are available to the team (Figure 2.14a) and if required they should bring their own devices. In this facility, the team is encouraged to make stand-up meetings (STRAY et al., 2016) (Figure 2.14b) and share design data through small whiteboards, magnetic-attached into a facility wall (Figure 2.14c). In discussion, the team can move the boards and rearrange as required. To the Japanese culture, CE is very related to creativity, and thus, is important provide talking rooms. To relax and discuss (Figures 2.14d and 2.14e), and the opportunity to bring personal artefacts (Figure 2.14f).

Figure 2.15 illustrates the arrangement of the Goddard's ICMD, the tables are placed around the facility, and an empty meeting table close to the presentation place to Customer Collaborative Meetings. Note that this organization requires specialists' movement to assume different positions during study sprints and converging sessions. (KARPATI et al., 2013) (KARPATI; PANEK, 2012)

JPL's Team Xc's facility, illustrated in Figure 2.16, uses the two parallel table desks, with a clean meeting table in the back of the photo. Note in the Right, a drawing white board to make scribes. (Jet Propulsion Laboratory, 2018)

Each facility reflects their own country cultural approaches and desires towards collaboration and team work. (SIMONINI et al., 2008) (BIESBROEK, 2012) (BIESBROEK, 2016)

Figure 2.14 - JAXA's Concurrent Design Facility.

SOURCE: adapted from Nakajima et al. (2016).

Figure 2.15 - Goddard's ICMD Facility.

SOURCE: from Karpati and Panek (2012).

2.6 Collaborations

Collaborations are the information exchange interactions among CE specialists. Table 2.1 lists some of the common collaborations in environments based on Document-Centric Tools (DCT) and Model-Centric Tools (MCT) found on literature. DCTs and MCT are described at Section 2.4.

The collaborations cater the entities presented in Section 2.3, summarizing the

Figure 2.16 - Team Xc Facility.

SOURCE: from Jet Propulsion Laboratory (2018).

ECSS-E-TM-10-25 - System Engineering - Engineering Design Model Data Exchange (CDF) (ECSS, 2010), which are the main data that are exchanged: **Models**, **System Elements** and **Parameters**.

During the CE sessions, the specialists use two workspaces: a Specialist Workspace and a Collaborative Workspace. Into the Specialist Workspace the specialists can manipulate their models with the better suited tools, that contains the domain vocabulary proper to the discipline - this thesis did not enter in the Domain Specific Model Design Tool. Regarding the **Collaborative Workspace**, the SECESA's Workshop papers indicates macro collaboration related to the workplace itself, and interactions among the models.

Table 2.1 - Collaborations in MCT and DCT.

Topic	Category	Type	Description
Collaborative Workspaces	**Style**		**The style is how the information is presented to the specialist team.**
		DCT	This style uses a common database at a file server (local or cloud) to store and share all worksheets and files that the specialists can use (MATTHYSSEN et al., 2014). Using a transparent single worksheet is possible via a cloud service that allows collaborative access (MURPHY et al., 2016). The Collaboration Interaction are through sheets shown into projections.
		MCT	This style uses a drag-n-drop GUI interfaces within models shared through concurrent design models (CALIO et al., 2016).The Collaboration Interaction are through models in the Computer, concurrently, and into projections.
	Big Picture		**The big picture is how the specialist team have the perception of the all design during collaboration.**
		DCT	Matthysen and Henderson (2012) describes the template sheets with the four contexts, one of them is to the presentation sheet. The Collaboration Interactions are through sheets observations as there is no full data sheet other than the Data Parking worksheet, or the final simulation.
		MCT	Both MBSE tools Capella and OPM, allows to create graphical diagrams with the big picture of a given design. The Collaboration Interactions are directly into the Modelling GUI, seen and manipulating the big picture elements.
	Detail Level		**The detail level is how to control the amount of information seen during the collaboration.**

(Continue)

Table 2.1 - Continuation

Topic	Category	Type	Description
		DCT	The details are controlled by which sheet is currently in use, as each one has the description of the: Inputs, Outputs, Computations and Presentations (MATTHYSEN; HENDERSON, 2012). Hiding lines/rows allows to control the amount of seen data. The Collaboration Interactions are directly on the sheet during the presentation.
		MCT	Each modelling tool has its approach. Capella controls the detail level through different views. OPM despite the views has the possibility to create zoomed models to describe inner parts. Both are navigated with tree views. The Collaboration Interactions does not change the models, only switching the visible model in the presentation controls the detail level.
	Design Exploration		**The design exploration is how to find the designs into the design collaborative space.**
		DCT	The exploration is done through search the file server folder. The Collaboration Interaction does not cater the design exploration other than exhibit it into the projection.
		MCT	The exploration, in both Capella and OPM, are done through model search into the tool workspace. If connected to the server they can show the models into the tree navigation view. Collaboration Interaction does not cater the design exploration other than exhibit it into the projection.
	Design Selection		**The design selection is how the specialist team decide which parts are worth to compose the baseline.**
		DCT	The design selection process is done by moving the correspondent model to a baseline snapshot folder, or committing the worksheet to the database (MATTHYSSEN et al., 2014). Collaboration Interactions does not exist, the decision is taken and all commit/move to the destination.
		MCT	The design selection process implicates to move the model container symbol to the correspondent container or to the tree navigation view (LIU et al., 2017). Collaboration Interactions are the virtual drag-n-drop the selected design into the main tree branch.

(Continue)

Table 2.1 - Continuation

Topic	**Category**	**Type**	**Description**
	Sharing Conduct		**The sharing conduct is how the specialists notice the other specialists that provided a design to collaboration.**
		DCT	This conduct requires the specialist to leave the data on the common storage and verbally tell that the information is available. Collaboration Interactions are the verbal communication to indicate the model localization.
		MCT	This conduct requires the drag-n-drop, the modelling tool yields that the data is available (COMBEMALE et al., 2016). Collaboration Interactions are through visual identification of readiness.
	Remote Design		**The remote design is the format that remote specialists collaborate during sessions.**
		DCT	Using local file server prohibits remote collaborations of the data, only the usual video-conference. Through OCDT, remote users can connect and monitor remotely their data (KONING et al., 2014). Collaboration Interaction, in OCDT, is similar to local collaboration as the specialist has access to data.
		MCT	The remote design depends of where is located the sharing service. Into a cloud the collaboration is transparent of the geography location (LIU et al., 2017). Collaboration Interaction is similar to local collaboration as the specialists already collaborate through a remote sharing service.
Model	**Send/Retrieve to Collaborative Workspace**		**The exchange between workspaces is the way to place the models into the shareable common area.**
		DCT	The exchange between the specialist workspace area and the collaborative workspace is through drag-and-drop files or through OCDT, the specialist can commit/retrieve directly via the Concorde Interface (KONING et al., 2014). Collaboration Interaction is not visible, unless the screen is been shared.

(Continue)

Table 2.1 - Continuation

Topic	Category	Type	Description
		MCT	The exchange between a private design area and the collaborative workspace is through drag-and-drop and selecting the sharing property, it is also possible through drag-n-drop the model containers (LIU et al., 2017). Collaboration Interaction is visual as the new available designs appear into the tree navigation view.
	Manipulation		**The model manipulation is how the specialists can manipulate the internal data.**
		DCT	The model manipulation is through file substituting/replacing, to the same linked model name. This changes and reflects the all set of new data. Collaboration Interaction can be done in collaborative Smarboards®, but one file each time.
		MCT	The model manipulation is through the project file that is connected into the sharing server. It can have multiple branches that can be dragged, deleted, copied, so on. Collaboration Interaction is in the specialist computer and reflected by the sharing server.
	Visual Appearance		**The visual appearance is how the model is shown in collaboration.**
		DCT	The model visual appearance is done in the spreadsheet formatting or using embedded programming language visual user interface components (MATTHYSEN; HENDERSON, 2012).
		MCT	The model visual appearance is given by the diagrammatic language repertoire. Capella is SysML based, so the visual appearance resembles the SysML. OPM has its own set of symbols. Figure X (after this table) contains a catalogued set of representations found through SECESA's Community literature.
	Navigation		**The navigation is how the specialist search the model for information to show in the collaboration.**
		DCT	The structure hierarchy is hard coded by the visual appearance. Spreadsheets are steady representations - moving cells can change the data cohesion (SCHUMANN et al., 2010). Collaboration Interaction is done in presentation changing the and moving the sheets to show the described data.

(Continue)

Table 2.1 - Continuation

Topic	Category	Type	Description
		MCT	The structure hierarchy is achievable by the tree panel navigations and through symbols that represent elements that allow to click and zoom-in (OPM Case) or show a connected diagram (Capella Case). Collaboration Interaction is done in showing the elements and hierarchy, only one can navigate on collaboration.
	Inspection		**The inspection is how the specialist open the model to read its contents.**
		DCT	The inspection is done by opening the file. It shows all cells directly. There is no collaboration.
		MCT	The inspection is done through clicking on the model symbol, that will show information or open a connected view/zoom. There is no collaboration.
	Coupling - Attaching / Detaching		**The coupling is how the models can be connected to make a model group.**
		DCT	The models are connected through the inputs/outputs data. To perform the all calculation the model interface must be settle prior the design sessions (MATTHYSEN; HENDERSON, 2012). Collaboration Interaction is only viewing the model "interfaces".
		MCT	The models are not attachable. The model is imported into the project file and its components stay available to use. Collaboration Interaction is only to pick/inspect the imported models.
	Explicit handle System Elements		**The explicit representation of a System Element entity by the model.**
		DCT	This is partially implemented by the row/column types that explicit in the title a System Element entity. The System Element abstraction is a group of parameters that represent a context (ECSS, 2010).
		MCT	This is not implemented by any (general) modelling tool, requiring the definition of stereotypes. Specific tools as the VirSat implements the System Elements (SCHUMANN et al., 2010).
System Element	**Manipulation**		**The model manipulation is how the specialists can manipulate the internal System Element data.**

(Continue)

Table 2.1 - Continuation

Topic	Category	Type	Description
		DCT	The specialist can change cell values, or swap the model (which will change its internal System Elements). Collaboration Interaction is done through cell value changes, that will reflect into inputs of other System Elements.
		MCT	The graphical modelling tools componentize the design in boxes that can be moved, deleted, created, so on. Collaboration Interaction is through building blocks manipulation.
	Interface Inspection		**The interface inspection is how the specialist inspect the exhibited System Element ports.**
		DCT	The interface inspection is done by opening the sheets that describe the input/output parameters (MATTHYSEN; HENDERSON, 2012). Collaboration Interaction is to show the parameters that interconnect the system elements.
		MCT	Each modelling tool has its approach. Capella represents the interfaces as clickable "ports". OPM represents the interfaces as "environmental things". Collaboration Interaction is to show the interfaces and drag-n-drop the interconnection links.
	Explicit Structure		**The explicit structure is how the System Element organize the inner System Elements and allow collaboration to visualize the structure.**
		DCT	Unless it is described the inner structure (within "contain" or "part" lists), there is no explicit internal structure. Collaboration Interaction to show and choose to inspect inner parts non exist.
		MCT	The structure symbols are organized across the diagrams. The building blocks induces the structure arrangement. Collaboration Interaction can move and rearrange structure.
	Behaviour		**The behaviour is how the System Element organize the behaviours.**
		DCT	The behaviour is implemented on the calculation sheet, embedded script codes, or third-party applications. Collaboration Interaction are done by changing values and recalculating the connected sheets in avalanche.

(Continue)

Table 2.1 - Continuation

Topic	**Category**	**Type**	**Description**
		MCT	Each modelling tool implemented an strategy to describe the behaviour. Capella derives from SysML, so it implements Sequence, State-Machine, and other diagrams. OPM uses procedural links and process things to describe the time-variant events.
	Explicit handle Parameters		**The explicit representation of a Parameter entity by the System Element.**
		DCT	The parameters are the spreadsheet cell values. Changing the cell value changes the parameter. According to the organization, via multiple linked workbooks (MATTHYSEN; HENDERSON, 2012) or via data base (MURPHY et al., 2016), will execute the cascade changes.
		MCT	The parameters are the building blocks that are organized to expose the system's characteristics. Changing a parameter is through block clicking and proprieties menus.
Parameter	**Visual Appearance**		**The visual appearance is how the parameter is shown in collaboration.**
		DCT	The parameters are cells, textboxes, and labels.
		MCT	The parameters in Capella have different symbols, according with the diagram type. In OPM the parameters is represented by an "object" thing.
	Navigation		**The navigation is how the specialist searches the parameters.**
		DCT	The parameters are spread to the corresponding sheets of the model. Changing the sheet or rolling the sheet shows the parameter. Collaboration Interaction occurs within the Presentation Sheet that contains the summary of the parameters.

(Continue)

Table 2.1 - Continuation

Topic	**Category**	**Type**	**Description**
		MCT	The parameters are represented by drawings, the parameters are achievable by the navigation of the all model parts that compose the model. The parameters are exhibited, and can be navigated, as building blocks inside the model parts (system elements), both in Capella and in OPM. Collaboration Interaction occurs changing the model views/zooms.

Informations about DCT relates to the ECSS Technical Memorandum, SECESA Literature Review, NASA's available Technical Documents and Rhea's CDP (Concurrent Design Platform) documentation. MCT only relates to collaborations in Capella and OPM tool. Even though the implementation only considers OPM models, Capella complements the collaboration possibilities.

3 TANGIBLE USER INTERFACES

This Chapter presents the information of the Body of Knowledge about Tangible User Interfaces to define the tangible artefacts.

We divided this Chapter in:

- **User Interface Style**: describes the user interface styles and the evolution to include tangible artefacts;
- **Human-Artefact Interactions**: presents the interaction types of a tangible artefact available to the users;
- **Tangible User Interface Interaction Model**: describes the interaction model and the feedback loops related to the use of tangible active artefacts;
- **Peripheral Interaction**: describes the attention sharing due to multiple tangible artefacts and collaboration;
- **Collaborative Virtual Environments**: describes metrics to evaluate computer based collaborative environments;
- **Ergonomics**: discusses the human factors needed to develop tangible artefacts.

This information supports the Rigor Cycle of the Design Science Research showing the meta-artefact descriptions of the Body of Knowledge to introduce in the CE Sessions Relevance Cycle.

3.1 User-Interface Styles

Using a software, the user has an earlier knowledge that indicates the possible meanings of the resources available at the user interfaces (UI). To Hix and Hartson (1993) a user-interface is "*The medium through which the communication between users and computers takes place. The UI translates a user's actions and state (inputs) into a representation the computer can understand and act upon, and it translates the computer's actions and state (outputs) into a representation the human user can understand and act upon*".

If the UI shows a piece of paper that can be edited to a user that has never used a computer system, two memories are remembered: the possibility to type (write) and the automatic persistence, assuming it automatically saves itself - as within a physical piece of paper. These expected behaviours of the instinctiveness of user interfaces are called **user-interface models**. All software user interfaces, especially the graphic ones, tries to mimic real physical behaviours, to provide a pre-conceived idea of the expected behaviours of the user-interface models. This copy-cat representation is called in Software Engineering as **metaphors**. (SPOLSKY, 2001)

Software metaphors need to obey the same rules; so, choosing a suitable user interface metaphor requires the design of: **symbols**: the user must recognize the diagrammatic and textual representations of the mimicked context in the interface, **actions**: the user must recognize and pre-empt the interface behaviour based in the mimicked rules and **aesthetics**: the user must recognize light, colours, pattern and motion perceptions and associate it to states of the symbols and actions events. (NOBLE, 2009) (CARD et al., 1983) (SPOLSKY, 2001) (NORMAN, 1991)

Rekimoto and Nagao (1995) addressed four user-interface styles regarding the relation among user, computer and real world:

- **Graphical User Interfaces (GUI)**: the humans interact with the computational artefact or with the real-world artefacts, not both in the same time. (THE LINUX INFORMATION PROJECT, 2005)
- **Virtual Reality (VR)**: the user interacts with a computer simulated environment where a projection of part of him to a virtualized avatar can interact with virtual artefacts. (BURDEA; COIFFET, 2003) (KIRNER, 2011)
- **Augmented Reality (AR)**: the humans interact with real world artefacts mediated by a computer interface that changes the perception of the real artefacts by virtual elements. (AZUMA, 1997) (KIRNER, 2011)
- **Ubiquitous World (UW)**: the humans interact with several interconnected computational artefacts and with the real world in the same time. The computational artefacts may interact with the real world as well, to collect data and actuate with the world. (WEISER, 1993)

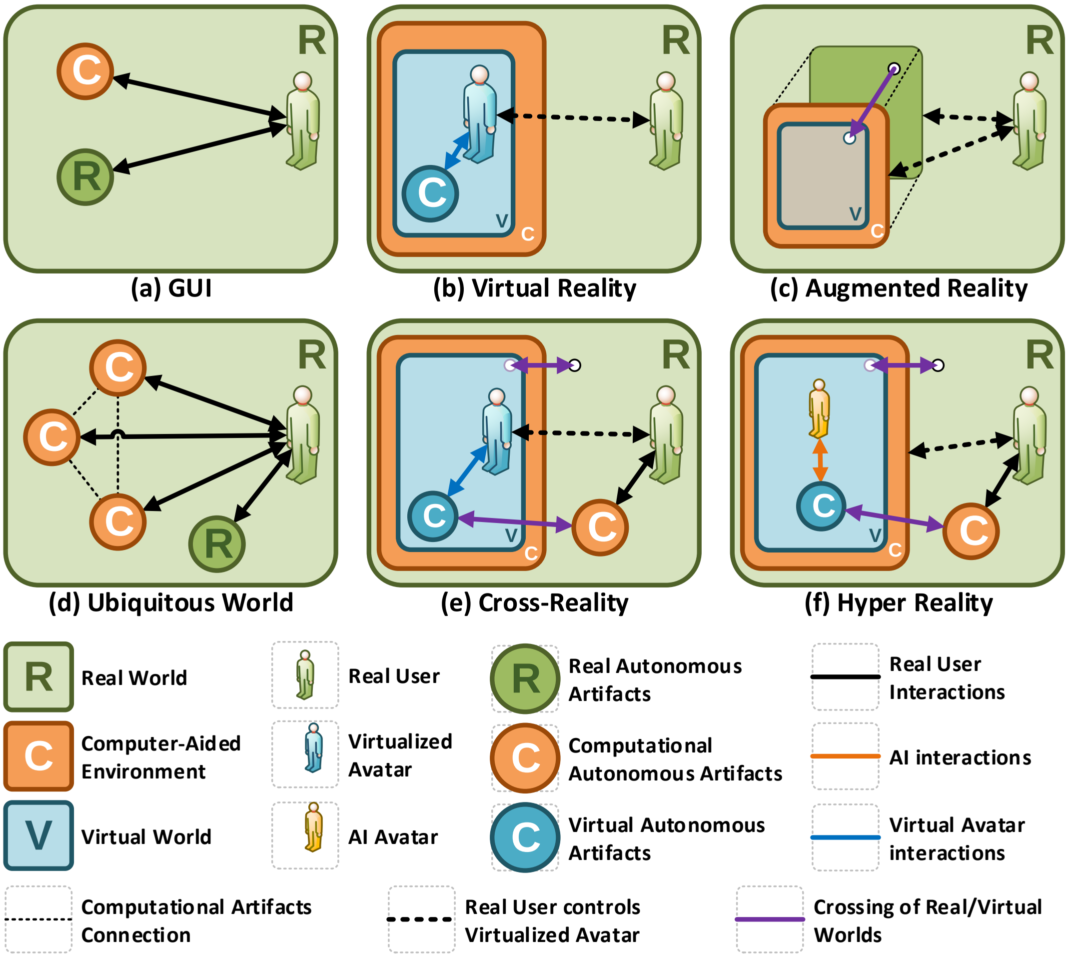
Kirner et al. (2012) added a fifth and sixth user interface styles:

- **Cross-Reality (CR)**: the humans interact either directly with computational artefacts, or Internet of Things enabled artefacts, that has its interfaces connected with a virtual artefact or by a virtualized avatar that can interact with the virtual artefacts. (PARADISO; LANDAY, 2009)

- **Hyper Reality (HR)**: the humans have the same interactions as a Cross-Reality added with (Artificial Intelligent) AI avatars that can either interact with the virtualized avatars or interact the virtual artefacts. (TIFFIN; TERASHIMA, 2001)

In Figure 3.1 we summarized all the user interface styles.

Figure 3.1 - Interaction Styles.



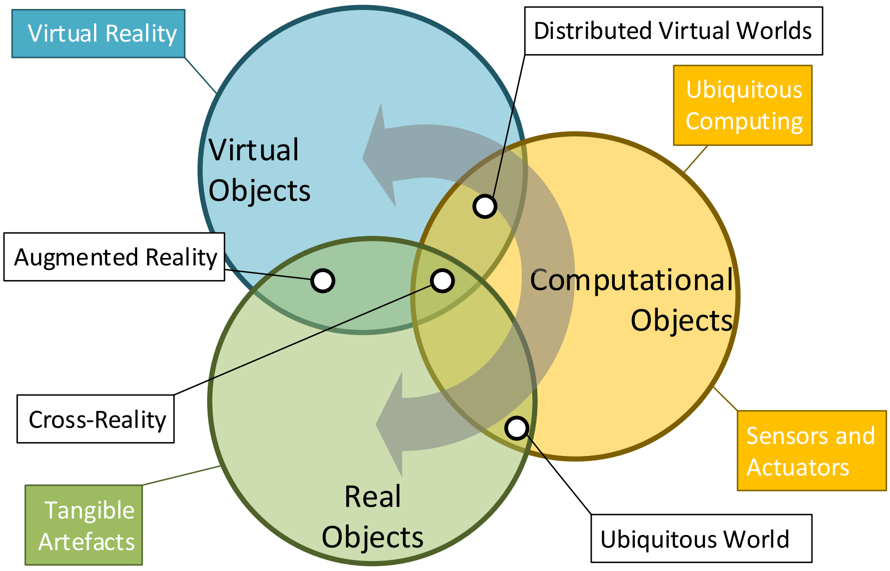
SOURCE: adapted from Rekimoto and Nagao (1995) and Kirner et al. (2012).

Milgram et al. (1994) attempted to interconnect the user-interface styles in what he called **Reality-Virtuality Continuum**. Milgran described the environments from a Real Environment, to a full-immersive Virtual Environment. The Continuum states that the real environment is gradually added by virtual content, making the Mixed Reality. From the Real-World view, creating Augmented Reality. On the other side, the Virtual Reality, is gradually added by real content, making also a Mixed Reality called Augmented Virtuality.

Looking from the artefacts point of view, Kirner et al. (2012) redraws the continuum as interrelated relation of: (Figure 3.2)

- Pure Virtual Objects leads to Virtual Reality.
- Pure Real Objects leads to Passive Tangible User Interfaces.
- Pure Computational Elements leads to Ubiquitous Worlds.
- Virtual Objects and Virtual Elements leads to Distributed Virtual Worlds.
- Virtual and Real Objects leads to Augmented Reality.
- Real Objects and Computational Elements leads to Active Tangible User Interfaces.
- And the Crossing of all, leads to Cross Reality. With further additions of artificial intelligence avatars, it leads to the Hyper Reality.

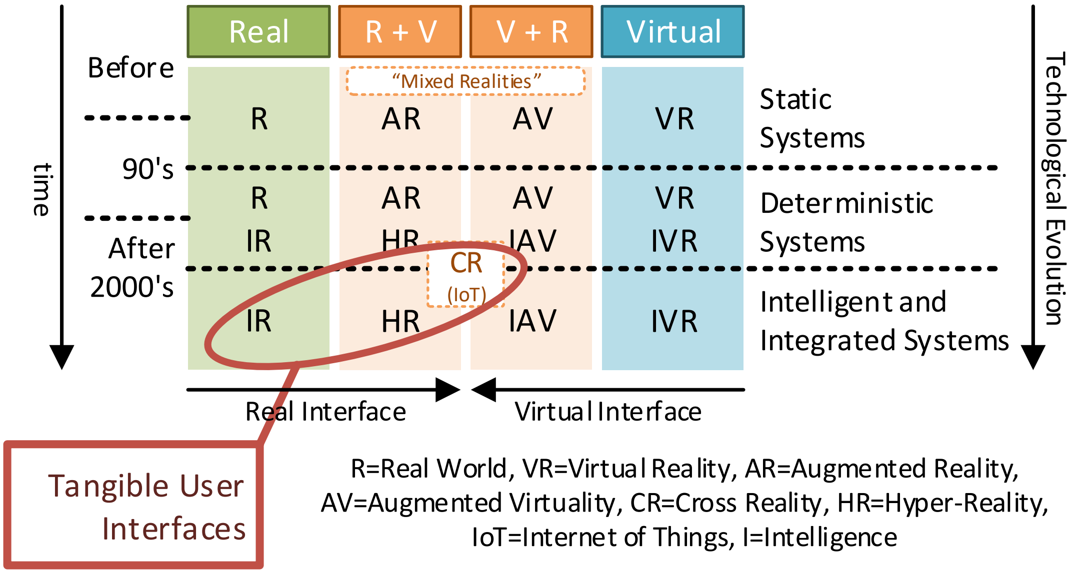
Figure 3.2 - Realities by Cognitive Artefacts Composition.



SOURCE: adapted from Kirner et al. (2012).

According to KIRNER (2008), Milgram's Continuum was a representation that considered the systems available at the time, and thus, to nowadays technologies it is a misrepresentation. The shift from Augmented Reality to Augmented Virtuality is

Figure 3.3 - Evolution of Realities.



SOURCE: adapted from KIRNER (2008).

not gradual, they: (i) are different user interface styles paradigms, (ii) have strongly different equipment to create the environment and (iii) include other emergent technologies that are now under consideration. So, KIRNER (2008) proposed, as shown in Figure 3.3, that the user-interface (within real and virtual) are increasingly gaining, two dimensions: the amount of artificial intelligence and computational elements. So, both are becoming more intelligent and integrated.

3.2 Human-Artefact Interactions (HAI)

Humans interact all the time with its surrounds. The artefacts that compose the environment provides way to understand it and interact with it. Norman (1991) describes the artefacts as cognitive tools that allows the humans to suppress the limitations of the body and mind, augmenting strength and world understanding. Interactions with artefacts proper the following interactions: (SHMORGUN; LAMAS, 2015) (HEIBECK et al., 2015)

- **Material Reaction**: Reaction is the immediate feedback that an artefact can give, the intuitive response that the human sights provides as an understanding of the artefact behaviour. It's the natural propriety that emerges from the material that the artefact was built.

- **Translation**: Adding movable parts in the artefact introduces the translation possibility. It emerges from the movement of the artefact pieces, as, gears and pulleys, or others that convert a translation movement into other new movements.

- **Amplification**: Amplification introduces mechanical systems, with motor actuation, that amplify human actions - allowing less human work.

- **Computation**: Although amplification introduces an improvement into human artefacts, it lacks possible interactions due its physical constructions. Electronics and computation liberates those limitations that used to tie the form with the function. Electronics replaces physical translation and reaction with electrical power, signals. Computation enables complexity of connections and rules.

- **Transformation**: From the miniaturization of the electro mechanical systems, and cyber-physical systems, the computational elements can change back the material reaction feedback, form, and thus translations. New dynamics can arise from these material modes.

The artefact interactions repertoire can follow one, to all, of these possibilities. The combination defines the tracking and feedbacks that the tangible interaction vocabulary possesses. (DIEFENBACH et al., 2013)

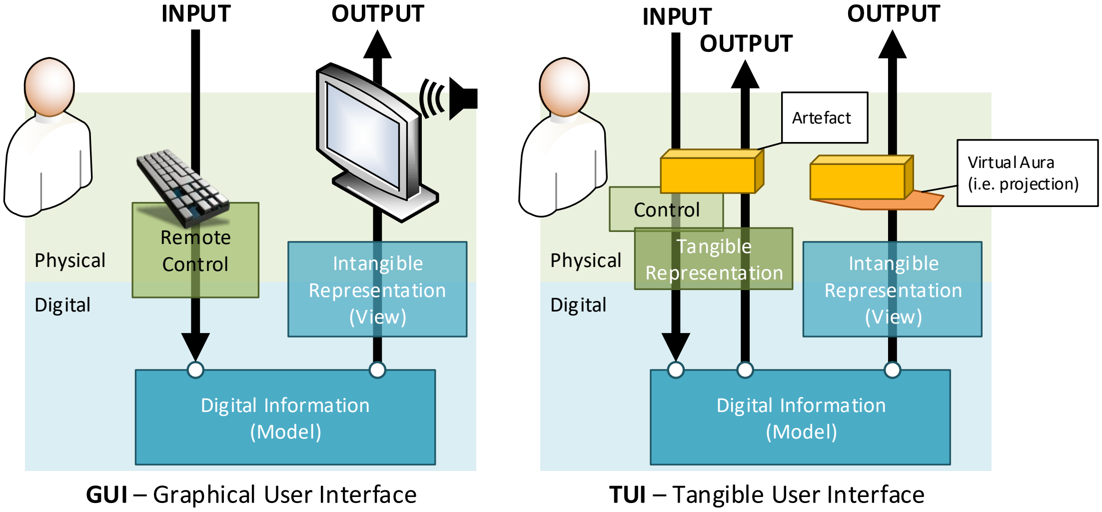
3.3 Tangible User Interface Interaction Model

GUI interactions define the interaction format with the computer artefact in terms of input/output streams. Output is delivered by screens, printers, while input is obtained by devices such mouse and keyboard. The most common relation between input/output and the data is the MVC (Model View Controller) architecture (REENSKAUG, 1979) (seen in Figure 3.4). Into MVC the control of the application is connected into the input devices, acting as a remote control, which manipulate the model - digital information, and the view which is composed by output devices (as video or audio) and exhibits the intangible representation of the user-interface itself.

The TUI interaction model, represented in the Figure 3.4, is based on the MVC model, adding a physical representation that acts as both input and output, allowing tangible[1] interactions. This integration is not on concept level, as touchscreen that overlap input/output. TUI physical representations physically allows control manipulation, as well as it keeps as the representation of the model itself. Ishii (2008)

[1]It is worth noting that the "tangible" term derives from the Latin words "tangibilis" and "tangere", meaning "to touch" - Source: http://www.dictionary.com/browse/tangible

Figure 3.4 - GUI and TUI interaction models.



SOURCE: adapted from Ishii (2008).

defines the TUI interaction model as MCRpd (Model, Control, Physical Representation, and Digital Representation), with later changing the physical and digital to, respectively, tangible and intangible. (ULLMER; ISHII, 2000)

The TUI interaction model addresses:

- **Tangible Representations coupled with the data**: this is the main TUI characteristic, which exposes physically the underlying digital information of computational models.
- **Tangible Representations with mechanisms for control**: the tangible representation also works as an interaction control, where movements, rotations, insertions, attachments or any other manipulation severs as a tangible input.
- **Tangible Representations coupled with Intangible Representations**: this allows to expose inner data and behaviours offering dynamic information that overcome the limitations of the physical elements of the tangible artefacts.[2]
- **Physical State of the artefacts and the digital state of the system**: physical artefacts are persistent into the design space (they don't disappear), and their state together generate a state into the digital model, as well as to the user's mind model.

[2]The intangible representation is often called "aura" as it exposed the digital self of the tangible artefact.

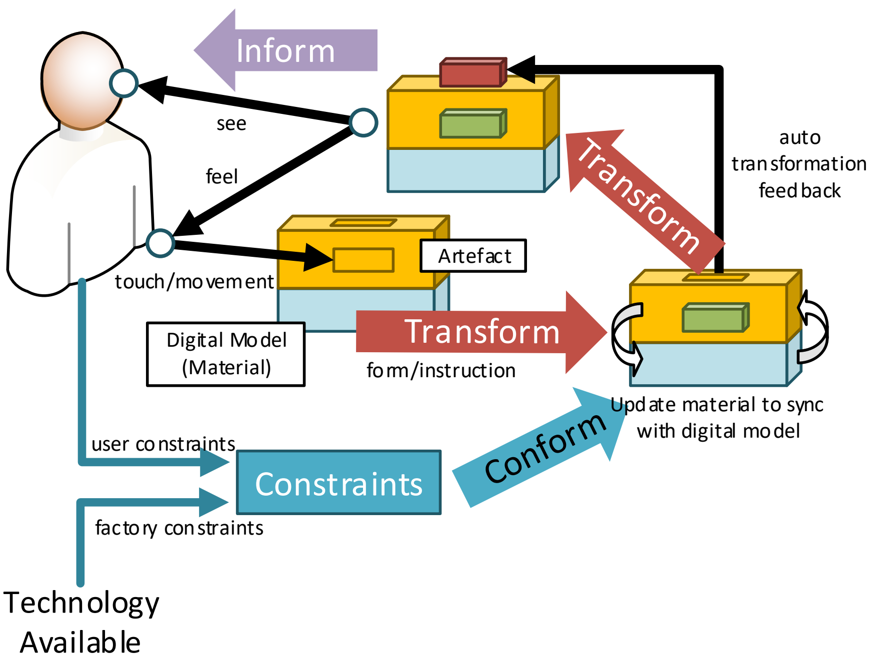
Ishii et al. (2012) revised the TUI concepts to what he named **Radical Atoms**. Where he considers artefacts containing all five human-artefact interactions interconnected, defining TUI as:

> "*leap beyond tangible interfaces by assuming a hypothetical generation of materials that can change form and appearance dynamically, so they are as reconfigurable as pixels on screens. Radical Atoms is a vision for the future of human-material interactions, in which all digital information has physical manifestation so that we can interact directly with it*"

The, still theoretical, Radical Atoms interaction model follows three concepts (Figure 3.5):

- **Transform** the shape to reflect the data model state and allow the user control input;
- **Conform** to constraints imposed by the environment, domain, and user control input; and
- **Inform** users about the effects and resulting dynamics.

Figure 3.5 - Radical Atoms interaction model.



SOURCE: adapted Ishii et al. (2012).

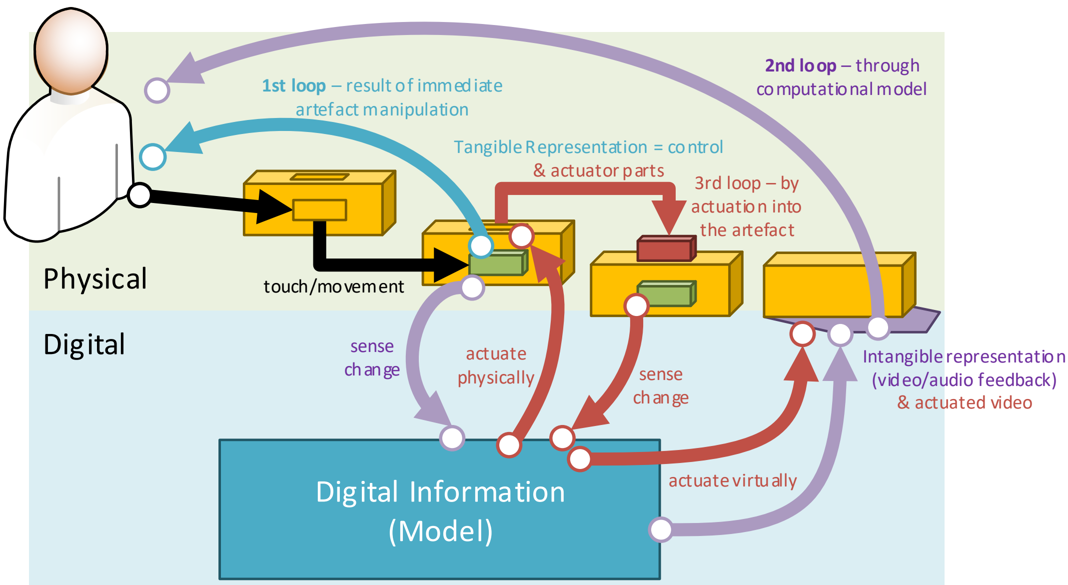
Intelligent tangible objects are usually connected to an environment grid network, allowing its sensed data to be shared: (i) among the user, (ii) with other user-interfaces and (iii) through other tangible objects; and thus, reacting to the stimulus through its actuators. (ISHII et al., 2012) (KIRNER et al., 2012)

The process of an entity communication with the user while checking for changes into the user-interface is called feedback loop. While GUI applications have one single feedback loop: the user interacts with input, the controller process and interacts with the model, which exhibits the changes into the output views, feedbacking the behaviour to the user (NOBLE, 2009). TUIs may have double and/or triple simultaneous interaction feedback loops (Figure 3.6): (ISHII, 2008)

- **Double interaction feedback loop**: the 1st loop is provided by the immediate response of a physical artefact manipulation, this does not require sensing or processing other than of the artefact. As this is a real manipulation, there is no computational delay. The 2nd loop is the digital feedback from the digital layer sensing the artefact manipulation and creating the intangible representation, which feedbacks to the user.

- **Triple interaction feedback loop**: the artefacts are empowered by actuators, it answers do to the 1st and 2nd loop interactions, as well as external physical control requests. The third loop can feedback the tangible representation, which re-feedbacks into the intangible representation.

Figure 3.6 - TUI interaction Loops.



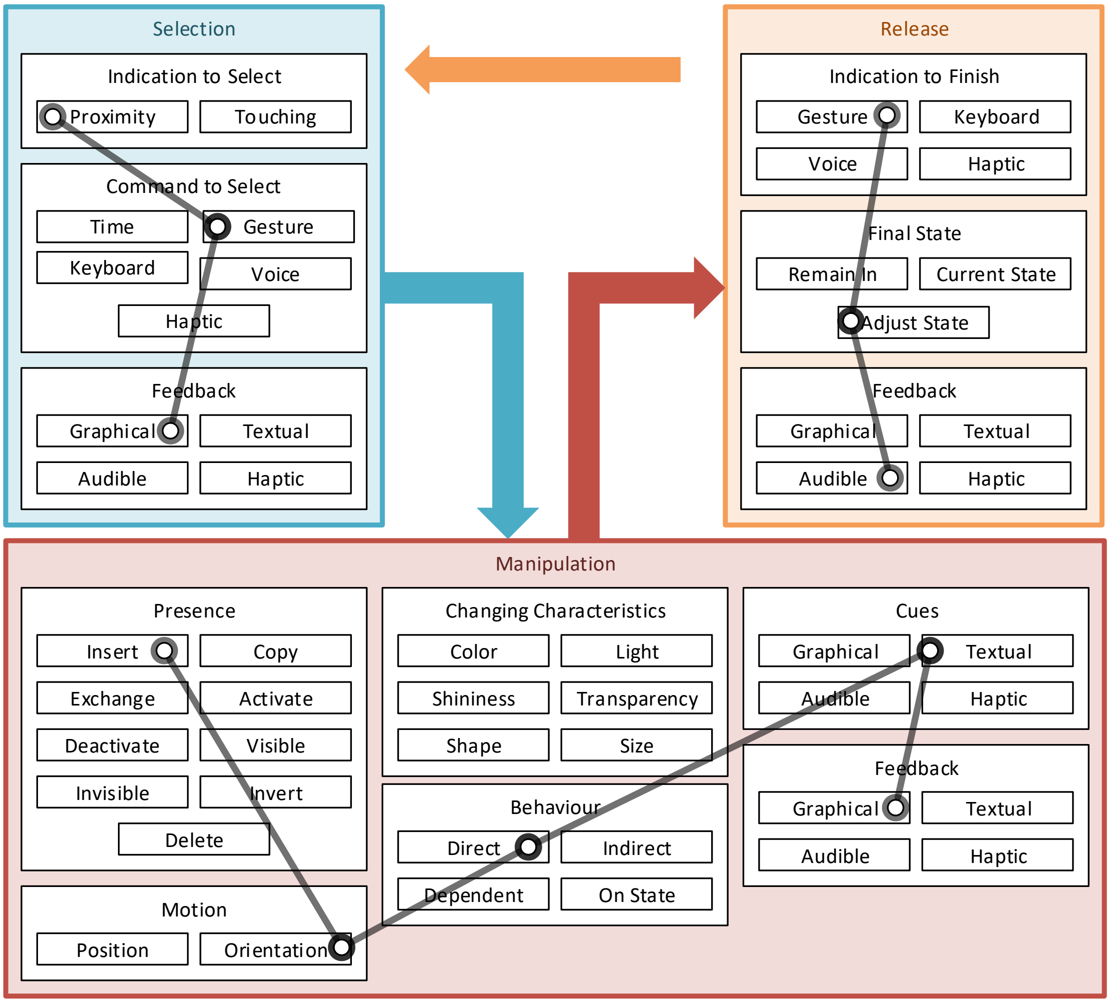
SOURCE: adapted Ishii et al. (2012).

Artefacts with three interaction loops can change themselves accordingly to the interactions or can change the environment. Those physical feedbacks are inherent with the expected physical feedback behaviour, prior presented (in **Subsection 3.2 - Human-Artefact Interactions**) in **material reaction** and **translation** interactions.

3.3.1 A Point about Interaction

Interaction, on the point of view of the interaction system, can be described by a three-stage model, containing: selection, manipulation and release. Bowman (BOWMAN et al., 1999) (BOWMAN et al., 2004) presented a taxonomy specific to interaction in virtual reality environments, where he tested a series of selection and manipulation interaction techniques. Later KIRNER and SANTIN (2009) described a taxonomy of the selection, manipulation, and release for Augmented Reality Environments, as illustrated in Figure 3.7.

Figure 3.7 - Interaction taxonomy example.



SOURCE: adapted from KIRNER and SANTIN (2009).

In AR, the selection is simple, because it uses direct and tangible actions. Manipulations are more complex and relates to more combinations of actions. Release needs to consider the state of the application release position.

Interactions can be created using different selection-manipulation-release combinations. Even using the same strategy, each element can have inner states that differentiates the interactions of an application.

3.3.2 General vs. Specific Appearance

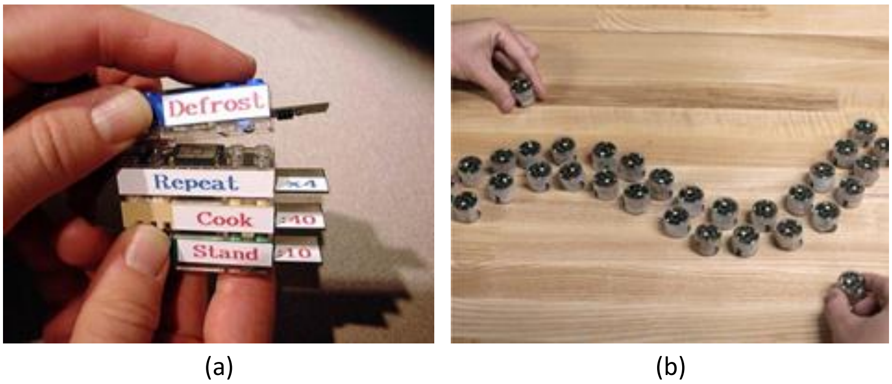
TUIs are software and hardware hybrids which are constraint by the physical impossibility to change the material shape, on run time, in the opposite of GUIs. GUIs as pure software-based user-interfaces are transient to the myriad of possible domains.

The GUI displays a user model metaphor, thus, in the same way, TUI also needs to correct represent the domain appearance. TUIs can have five approaches towards the metaphor: (i) none - it does not use hints of pre-conceivable behaviours, (ii) noun - it uses hints that represent interactable things (usually constructive TUIs), (iii) verbs - it use hints that represent actions (usually relational TUIs), (iv) nouns and verbs - it uses both things and actions metaphors, and (v) full - it is a direct representation of the controlled model (FISHKIN, 2004). The correct correspondence between the physical appearance of a TUI and its user interface model aims to improve the directness and intuitiveness of interaction, and take advantage of pre-existing skills and work practices. (HORNECKER, 2016)

The TUI artefacts designs are important as its forms and actions (noun and verbs) will indicate the available repertoire of functions (the vocabulary). However, a balance discussion between specific/generic visual and concrete/abstract model representation must consider the extremes:

- that a very specific purpose artefact is highly related to the domain, and a big disadvantage if the requirements include reuse in other applications. (Figure 3.8a)
- that very abstract artefacts lose the directness of the tangible representation, relying on intangible representations to feedback the domain data. (Figure 3.8b)

Figure 3.8 - Specific x General Appearance.



(a) Example of a very specific artefact where each brick has a special meaning, and purpose, given by the context. (b) Example of a very abstract artefact where each drone is a general-purpose artefact, that needs a meaning given: (i) the object that represent or (ii) action that makes.

SOURCE: (a) from (MCNERNEY, 2004). (b) from (GOC et al., 2016).

The decision is domain and resource oriented, but the reuse of artefacts must be considered to prevent the accumulation of single use artefacts.

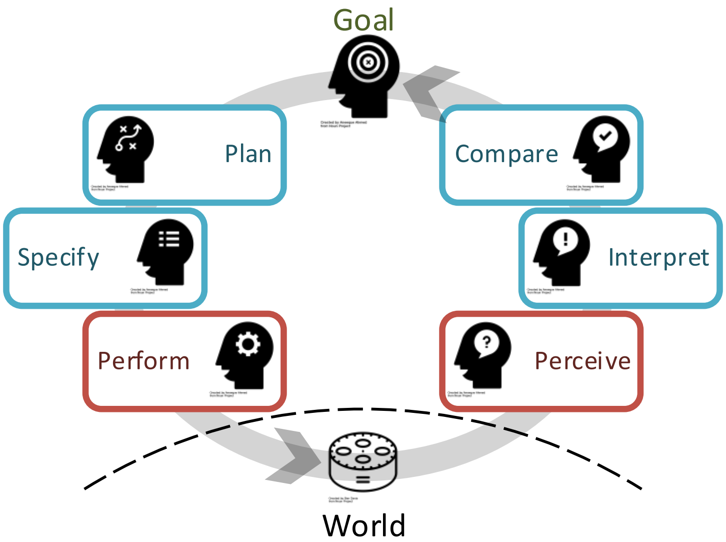
3.4 Peripheral Interaction

Considering the use of tangible devices collaboratively, TUIs are becoming ubiquitous systems (WEISER, 1993). Weiser recognized that traditional GUI methods of human-computer interaction demands focused attention into a display (or set of displays), and in a ubiquitous user-interface, hidden, and integrated through the environments, the interactions would be also taken outside of the attention focus - calling the technologies that can migrate from the central to periphery attention as **Calm Technologies** (WEISER; BROWN, 1997).

Peripheral Interaction is the interaction with technological artefacts that occur in periphery attention, and if relevant, may shift to the central attention. Physical interactions are naturally peripheral. We can look to one direction and simultaneously grab and move something that is not at our focus sight. The central attention is the one activity to which most mental resources are allocated, and the periphery attention consists of all potential remaining activities, regardless of the number of sensory and cognitive resources allocated to them. (BAKKER et al., 2016)

To Norman (NORMAN, 2013), the interactions consist in cycles of seven stages (Figure 3.9). Starting with a (i) cognitive decision of the desired goal (what do I want to accomplish?), (ii) the decision/intention planning to act into something (what are the alternative action sequences?), (iii) the thought of specify a sequence of steps to achieve the goal (what action can I do now?), (iv) the execution of the steps (how do I do it?), the world/plant/artefact responds, the state is then (v) perceived (what happened?), (vi) interpreted (what does it mean?), and (viii) compared (is it okay? Have I accomplished my goal?), to provide insights to restart, if necessary, the cycle.

Figure 3.9 - Norman's Interaction and Decision Cycle.



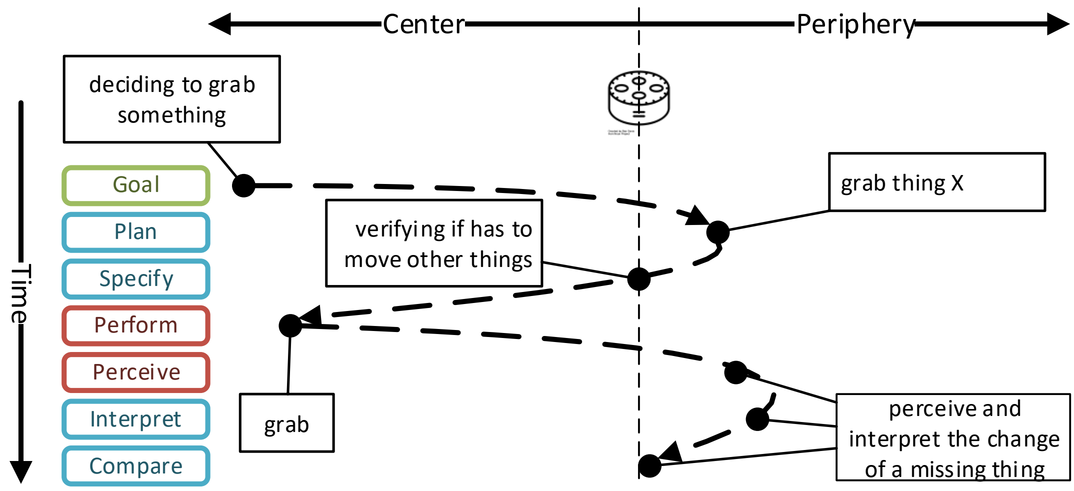
SOURCE: adapted from Norman (2013).

In multiple collaborations, at a common shared collaborative workspace, we focus into our activities, and monitor the others peripheral activities. As Illustrate in Figure 3.10, apart from temporary activities that have an understood objective, our attention also finds temporary side attentions, creating micro-interactions (ASHBROOK; STARNER, 2010), that does not necessary serves to the objective but helps understand the all context. (BAKKER et al., 2016) (WICKENS, 2008) (HEIDEGGER, 1967)

Not all stages are at the central attention of multiple ongoing interactions. And in fact, they can shift all the times for many reasons, as: (i) **habituation**: the stage is a well established habit, (ii) **difficulty**: the stage is difficulty and requires focused attention, (iii) **significance**: the stage has abstract importance, (iv) **salience**: the stage causes some stimuli that attracts attention, and (v) **affection**: the stage has potential reasons that affect the user emotions. (BAKKER et al., 2016)

Norman (2013) further states seven fundamentals insights from the stages: (i) **discoverability**: determine what actions are possible at a given state, (ii) **feedback**:

Figure 3.10 - Ongoing activities attention changes.



SOURCE: adapted from Norman (2013).

determine the current state after an action, (iii) **conceptual model**: create a pre-vision of the behaviour, (iv) **affordance**: exist elements to make de desired action possible, (v) **signifiers**: ensure that the correct meaning is well communicated and intelligible, (vi) **mappings**: map the relationship between controls and expected actions, (vii) **constraints**: provide physical, logical, semantic and cultural guides actions and eases interpretation.

3.5 Collaborative Virtual Environments

Define collaboration is not a straightforward activity, it depends of the understanding of the context and cultural factors. Transversally to the definitions, there are common characteristics, where essentially, collaboration means: "to co-labour, to co-operate to achieve common goals, working across boundaries in multi sector relationships" (O'LEARY et al., 2006). By collaborating, the group wants to reduce the difference among them in terms of knowledge, skills, and resources, to develop synergistic solutions to complex systems (HARDY et al., 2005).

Collaborative Environments are working places (real, virtual, or mixed) that are designed to prior collaboration over individual work. The introduction of Virtual Reality in Collaborative Environments, introduced the concept of Collaborative Virtual Environments (CVE). CVEs represent a shift in interacting with computers in that they provide a medium that mix data representations and users, which: (SNOWDON; MUNRO, 2001)

> "*CVEs represent the computer as a malleable space, a space in which to build and utilize shared places for work and leisure. CVEs provide a terrain or digital landscape that can be 'inhabited' or 'populated' by individuals and data, encouraging a sense of shared space or place. Users, in the form of embodiments or avatars, are free to navigate through the space, encountering each other, artefacts and data objects are free to communicate with each using verbal and non-verbal communication through visual and auditory channels.*"

Germani et al. (2010) proposes a set of heuristics to estimate collaboration performance of a Collaborative Virtual Environment: Teamwork, Communication, Human involvement and Cognitive Reaction. For each heuristic, he defined a set of metrics to highlight critical issues of multidisciplinary teamwork. Where:

- **Teamwork**: **Decision Making Process Stage**: measures the distribution of design activity and the communication among participants. (presentations, discussions, solving, evaluations), **Design Content**: refers to the correct relation of discussion and shown content. (usability, aesthetical, features, functionalities) and **Actor Skills**: measures the confidence in adopting the tool.

- **Communication**: **Interaction Style**: measures the directness of interaction. (referring to, interacting with, simulating on), **Verbal Communication Style**: refers to the verbal communication used to describe the contents. (referential, descriptive, emotional or reflective languages) and **Nonverbal Communication Style**: refers to the non-verbal communication used to describe the contents. (gestures, graphical-marked).

- **Human Involvement**: **Mutual Engagement**: measures the preferred interaction modality. (spatial, temporal, conceptual), **Collective Creativity**: measures the ability of creating and merging creative ideas. (seeking, giving, reframing, reinforcing) and **Stimulate Integration**: measures the ability of forecasting solutions (linked only to physical artefacts, virtual models, extract hints from elements, use to imagine new concepts).

- **Cognitive Reaction**: **Cognitive Reaction to Model**: measures the physical operations (selection, placement, reallocation, assembly, etc) on data, **Cognitive Perception of Model**: measures the attention of model's elements. (model elements, relations, locations) and **Cognitive Decision Making**: measures the decision-making process (new solutions, reuse solutions).

Properties of TUIs that support collaboration include: (i) increased familiarity with real-world interactions; (i) more known interface given the natural interaction; and (iii) physical embodiment, as they can guide and filter collaboration options. (SHAER; HORNECKER, 2010)

As far as physical objects multi-user manipulability, tangible artefacts / TUI are collaborative by design (ISHII et al., 2012). Different users can interact with the content at the same time, as it is done with physical artefacts. Physical-only artefacts cannot change information and properties through interactions - eventually it is possible to change its characteristics by modifying its body, and its physics, but cannot add an intelligent property only by manipulation.

3.6 Ergonomics

The implications from Calm Technologies and Collaborative Virtual Environments into design of TUIs reflect in the human-factors (ergonomics) decisions of the artefact and the environment of use. (BØDKER; KLOKMOSE, 2011)

According to Bowman et al. (2004), to design a novel 3D interaction it is important to consider the human factors that affects the usability and the performance of the tasks. The human-factors refers to the physical capabilities, characteristics, and limitations that includes the body, senses and cognition.

Tilley and Associates (2002) presents anthropometric data related to humans' perceptions, reachability, tolerances, so on. From the data, three points are the most important and relates to TUI: (i) the Visual Data Perception: addressing the field of view of the capabilities to discriminate visual elements, (ii) the Hand Measurements: addressing the mean grasping and clicking capabilities, and (iii) the Workstation Measurements: addressing the reaching distances, and comfort zones, of the working area.

The anthropometric data describes that the focus attentions are on the +/- 30° in the horizontal and vertical. From 30° to 60° there are severe degradation to the symbol and word recognition. After 60° we have limited colour and light discrimination.

Considering the graspable point of view, the mean measurements of hands, indicates a maximum graspable sphere of 2,75 inches (7 cm) of diameter, where the thumb natural position is slightly below the hand line. The reachability is different from a seating and standing position, in the standing position allows with 30° bending an extra 400mm from the mean 650mm of arm reach.

Shaer and Hornecker (2010) indicate that the effects of size and weight of tangible artefacts should not be underestimated. The artefact must consider ergonomics and long-term strain of manual activity needed to perform the tangible interactions. Ullmer (2002) exemplifies that TUI pucks are constantly lifted and moved around, and a block with width of 10cm grip requires the entire hand width open. Also, TUIs tends to require more body movements, needing to stretch out over a surface, straining more body parts.

4 CONCURRENT ENGINEERING COLLABORATION WITH TANGIBLE COGNITIVE ARTEFACTS

To tie the CE Session context with the TUI technology and create the interaction vocabulary, this thesis analysed the collaborative behaviour - identifying the elements towards the models and the collaboration formality, extracted the entities and what the specialists want to do with them to define use scenarios of how the entities could be used in collaboration. Then, listed the available artefact and facility interactive elements to create the vocabulary metaphors: the nouns and verbs.

The vocabulary metaphor defines the semantic of the interaction in terms of nouns, and verbs. The noun-metaphors represent the things that are being handled: a satellite, a rocket, a piece of equipment, a discipline, etc. The nouns define the structure among the interaction elements to create the intuitiveness of the handled models. The verb-metaphors represent the actions that can be used to: select, choose, share, expose, remove, edit, and so on. The verbs define the behaviours that are enabled by the user-interface to give the formality to collaborate the models.

This Chapter is the Design Cycle's Artefact & Process Build or Design of the Design Science Research, it shows the coupling of the Relevance Cycle : CE Sessions, with the Rigor Cycle : Tangible User Interfaces. Sections 4.1, 4.2 and 4.3 refers to the Inputs from the Cycles. Section 4.4 describes the Cycle Artefact Design.

This Chapter is divided into the following sections:

- **Section 4.1 - Collaborative Behaviour**: describes the collaborative CE Sessions characteristics towards models and facility.
- **Section 4.2 - The Entities**: describes the entities that are manipulated in CE Sessions, mapping them in OPM and Graph to be handled by artefacts.
- **Section 4.3 - The Use Scenarios of the Entities**: presents the use scenarios of each entity.
- **Section 4.4 - TUI Design**: describes the user interface design associating collaborations activities, properties and TUI.
- **Section 4.5 - Computer Aided Facility**: describes the user perceptions, enabling control mechanisms, and the facility to track and project the intangible representation.

- **Section 4.6 - Tangible Interaction Vocabulary**: presents one of the five generated tangible vocabulary set of noun-verbs (the remaining are in Appendix).

4.1 Collaborative Behaviour

This section presents an analysis of "models and facility" CE Session elements related to collaboration. Both describe the collaboration behaviour format of the CE Sessions.

4.1.1 Model Type

Reviewing SECESA's workshop papers (from ESA, NASA, JAXA Agencies) and observing CPRIME works, was catalogued in Section 2.4 the model-based information exchange among CE specialists. The model-based tools identified has two natures: Document-Centric Tool-set (DCT) and Model-Centric Tool-set (MCT).

DCT are mainly spreadsheet based, so the models representations are in forms (in the spreadsheet or in scripts GUI) within connectable Data-Base. Despite the variations (single, multiple and data-base linked).

MCT may be divided in two categories: (i) the tools that represent a specific context, and (ii) generic modelling tools that are context-free (despite having its own language repertoire).

Out of the two tool-sets, we found a myriad of other "models" that does not use computation tools. These models are totally free representations in boards, cognitive mockups, schemes, etc. Which as stated by (NORMAN, 1991) are powerful reality mappings and signifiers (described in Section 3.4).

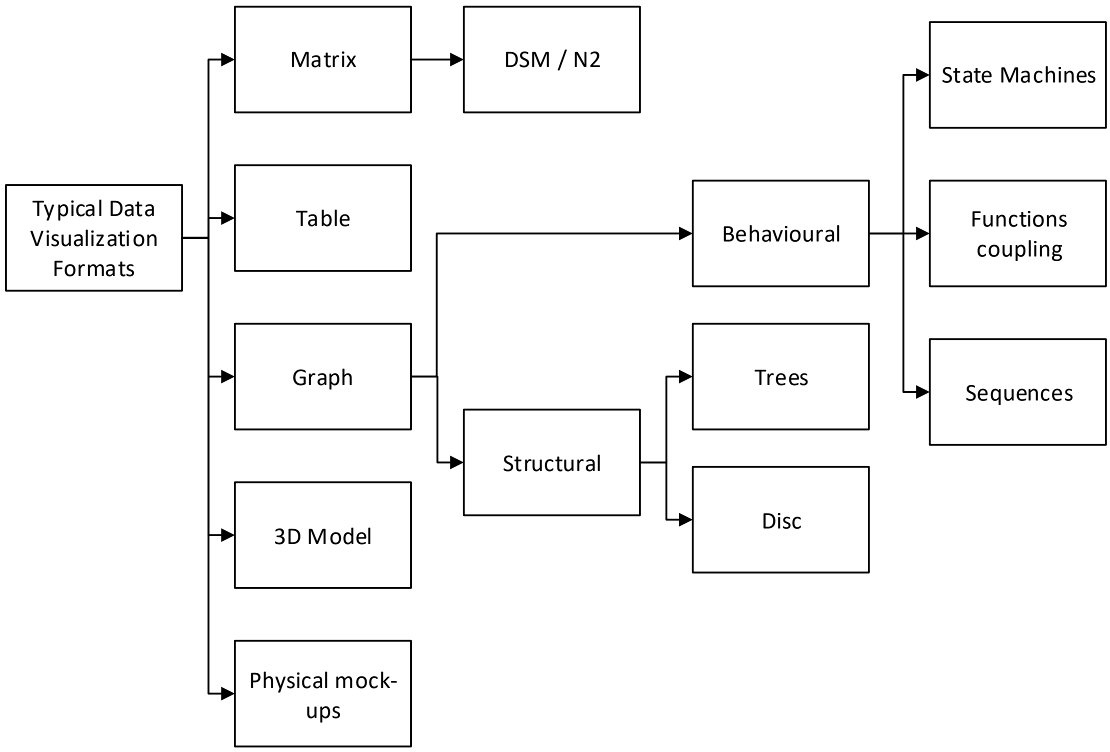
The SECESA papers also points to three visual representation natures to describe information in building blocks (despite specific context of 3D visualizations - virtual / real):

- Matrices: building blocks organized in two dimensional correlation of parameters, the typical use found was in DSM (Design Structure Matrix) and N2 Charts.
- Tables: building blocks organized in one dimensional, the typical use found was in single field or lists.

- Graphs: building blocks with n-m relations, the typical use found was to describe behaviour (state machines, function-entity coupling, sequences) and structure (trees and discs).

Figure 4.1 summarizes the main data visualization pointed by the SECESA papers.

Figure 4.1 - Data visualizations found through SECESA papers.



SOURCE: from the author.

From this review, we propose a taxonomy of the model used in collaboration in four broad types: (i) Free, (ii) Loose, (iii) Context Specific, and (iv) Context Independent. These categories were created by the grouping of five characteristics: [1] **formalism** - if the model has any subset of metamodels that limits the form to express the information, where can be from a totally free description from no formalism, to a rigid formalized fixed repertoire; [2] **specialist use** - if the model language/tool requires training to use, where can be from a no training to a course requirement to understand the model; [3] **computational interpretation** - if the model is difficult to be interpreted by a computational system, where can be from an impossible to interpret situation to a fully controlled language; [4] **collaboration** - the way the collaboration intra/inter models happen, where can be from a scribe within all domains drawn together to a collaborative domain filterable modelling; and [5]

storage method - the way the model is saved, where can be from camera pictures to a centralized data sharing.

The four proposed collaboration models types are characterized as:

- **Free Models** are paper and pen, chalkboard, or even Smartboard drawings, schemes, free textual descriptions (handwritten). Free models do not have a formalism neither requires preview model syllabus learning, this makes computational interpretation extremely hard, as without a set of rules, any symbol can be used. Collaboration using free model scribes are very collaborative, as the physical media naturally allows collaboration, and to save those physical artefacts the common way is by picture taking, which does not include a centralized data sharing approach.

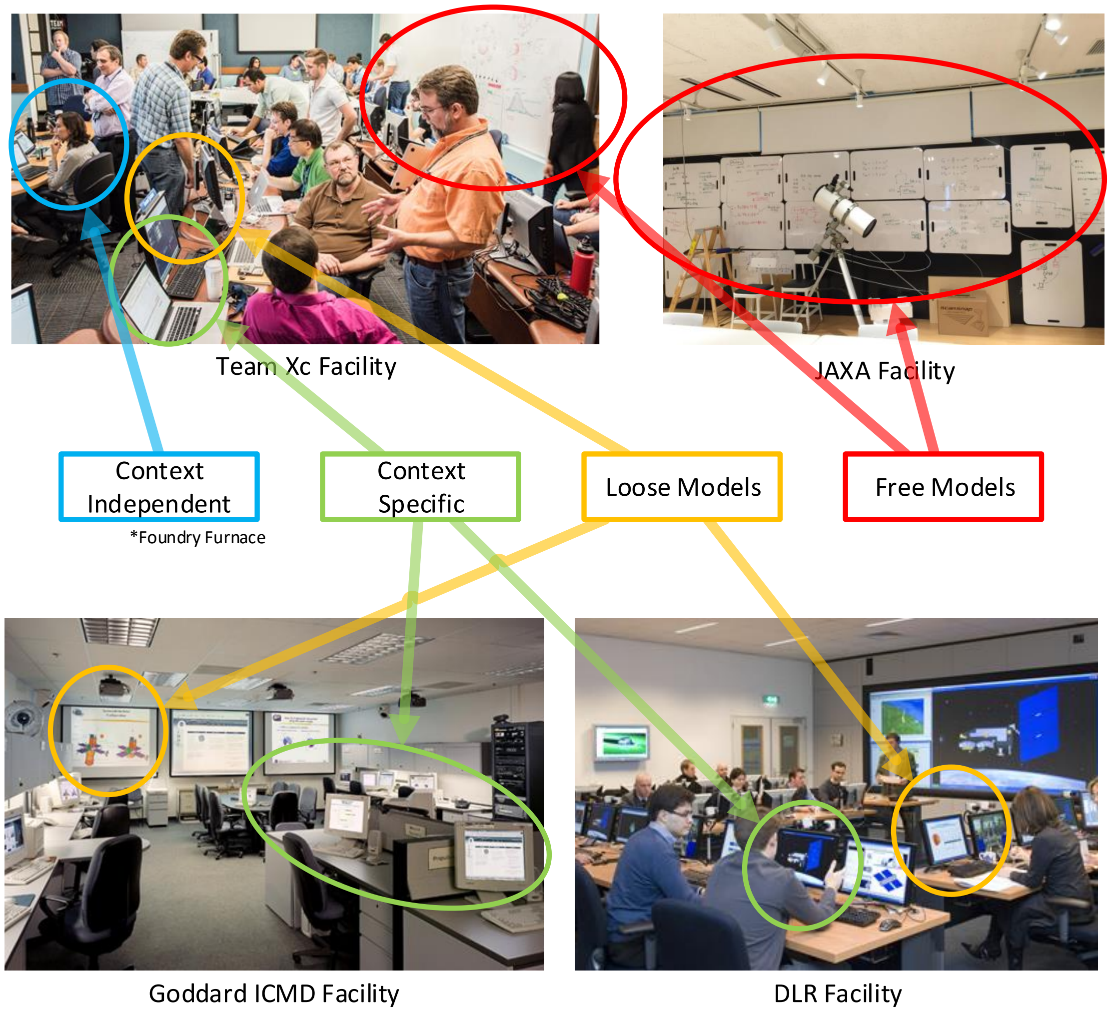
- **Loose Models** are models using general purpose computational tools, as office tools or diagrammatic tools that are only for drawing, or with few modelling capabilities. Loose Models uses minimal syllabus formalism, which funnels the specialist use, requiring learning the minimal set of specific jargon words. This syllabus allows an initial computational interpretation. Moving from scribes to a tool that allows loose models, as Office Productivity Tools, starts to difficult collaboration given the media layer. Storage-wise, as documents, it is easy to save and retrieve data files into a file server, however it requires strategies to extract pieces of data instead of the all files.

- **Context Specific Models** are models using specific tools as: satellite simulators, CAD, electrical, programmatic, requirements, electromagnetic field, thermal analysis, system modelling, software modelling, etc. Context Specific Models have a rigid formalism to describe a specific domain, and the model use requires knowledge of tool details. Collaboration over the same set of data require semaphores strategies, that with big models delays the development given the recurrent entrance in critical parts. This requires computational storage methods to extract pieces to share within the collaboration specialists.

- **Context Independent Models**, are models using generic multipurpose modelling tools, with model transformation capabilities, usually connected to a generic purpose database structure. Context Independent Models have a rigid meta-formalism that describes an abstract domain that can be further specialized, and the model use requires systemic knowledge of tool details. Collaborations over the same set of data requires semaphore strategies, as Context Specific Models, requiring, as well, computational storage methods to extract pieces to share within the specialist.

To exemplify these four types, we did a snapshot analysis of where the collaboration with models occur, in the main design room of the nowadays existing CE Facilities. (Figure 4.2).

Figure 4.2 - Model types in different Facilities.



SOURCE: from the author.

The **Team Xc Facility**, as presented by Murphy et al. (2016), uses the three types of models (loose, context specific and context independent) connected through the Foundry Furnace's Phoenix Model Center. In the Facility illustration we also identify the free modelling collaboration using whiteboards.

The **JAXA Facility**, as presented by Nakajima et al. (2016), uses mainly free models through movable whiteboards. They use the BYOD (Bring Your Own Device) approach regard the use computational tools.

The **Goddard Facility**, as presented by Karpati et al. (2013), uses loose models with specific context models.

The **ESA Facility** uses loose models with some specific context models. This is better presented in the ESA's CDF web-page[1]. It shows all CE disciplines tools, some are illustrated in Figure 4.3 (The U references the discipline's positions).

Figure 4.3 - Models in the ESA.

SOURCE: from the author.

It is important to point out that all the facilities use all types together within

[1]Available at: http://www.esa.int/Our_Activities/Space_Engineering_Technology/CDF/Design_Stations_1_2

different levels of importance and in different moments of the collaboration.

4.1.2 Facility Formality

Regarding the facility formality that impacts the collaboration, we researched the facilities with the eyes in the Germani's Collaborative Environment Heuristics (described in Section 3.5): Teamwork, Communication, Human Involvement and Cognitive Reaction. We intended to establish the formal and informal means of communications, in which sets of information are exchanged, similar attempt was done by Avnet (2009). Germani's heuristics are based on numeric metrics done through user interviews' evaluations. We did a qualitative evaluation of the same heuristic in the Facilities (elicited in Section 2.5). Table 4.1 contains the evaluation of the two diametrical opposite facility styles, regarding only the collaboration during CE Sessions: on one side the most formal facility is the DLR's Facility, and on the other side the most informal facility is the JAXA's Facility.

Table 4.1 - Collaboration evaluation of a Formal and Informal Collaboration facility set-up from the point of view of Collaboration Heuristics.

Collaboration Heuristic	**Formal**	**Informal**
Teamwork	Majority through presentation, describing technical features through representational tools	Majority through discussion, describing the technical functionalities through scribbles.
Communication	Communication Majority use poorly gesture-marked communication, with a referential language towards referring to the model.	Majority use highly gesture-marked communication, with graphical-marked (sketching), using a descriptive language with referring to the model, and physically "manipulating" the models.
Human Involvement	The engagement is temporally assigned, as one speaks each time, mostly for reflecting, and reinforcing an idea, extracting features from models and talk about them.	The engagement is spatially assigned, with group discussions, mostly to help seeking/help giving, and to extract features and to image new concepts and solutions.

(Continue)

Table 4.1 - Continuation

Collaboration Heuristic	Formal	Informal
Cognitive Reaction	The actions happen after model presentations, leading to relations and model elements, to application into a baseline solution.	The actions happen during model presentations, leading to attention in elements, relations and model locations, to application into a baseline solution.

A middle ground is the Team Xc which mixes both approaches in CE Sessions Collaborations. Figure 4.4 shows the two extremes and the mixed approach in a formality continuum.

Figure 4.4 - Formality Continuum.

SOURCE: from the author.

This study indicates the Collaboration Protocol among specialists during CE Sessions. From a formal and centrally orchestrated collaboration, to an informal clustered scribble panel changing collaboration.

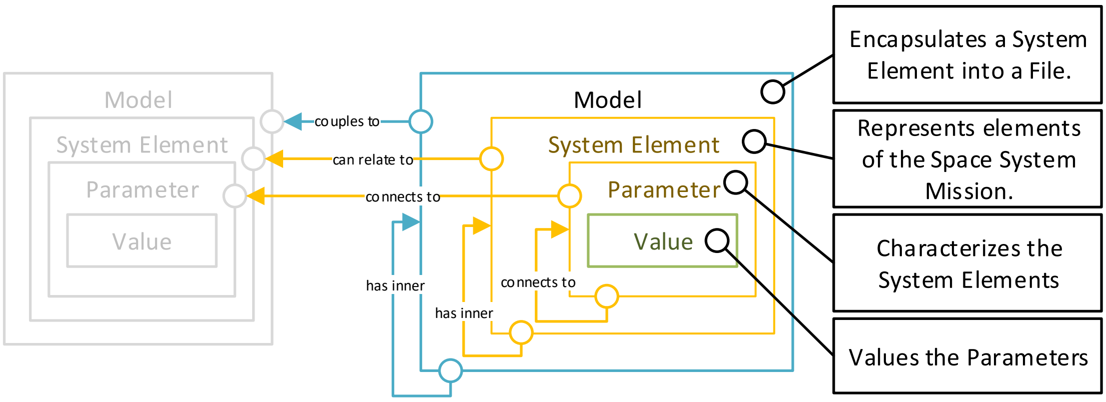
4.2 The Entities

This section describes the information used in CE Sessions - the entities, and its mapping in OPM. This section also describes the OPM mapping in graphs to show how the entities have to be stored to be able to be manipulated by artefacts.

All information, in both DCT and MCT, are stored in container elements, respectively: worksheet files and project files (described in Section 2.4). Both file types to ECSS-E-TM-10-25 - System Engineering - Engineering Design Model Data Exchange (CDF) (ECSS, 2010) are the **Models**, which are integrated through the IDM (Integrated Design Model). The ECSS-E-TM-10-25 also describes the content of the models: the **System Elements** and its **Parameters** (this is described at Section 2.3)

The entities relate to each other (Figure 4.5) as follows: A model can be coupled to other models or have inner models that better describe its contents. A model contains "one" single, or a "set of" inner Models. Into this work the model roots (with its inner models) are atomic entities and describes "one" thing. This thing can be "one" System Element or a "set of" inner System Elements that are not detachable. The System Element can relate to other System Element and have Inner System Elements (again not detachable). The System Element exhibits Parameters. Parameters can be connected to other Parameters, from its System Elements or from external System Elements. And to finalise, Parameters have Values. Values are not a fourth entity type as they are an inseparable part of the Parameter.

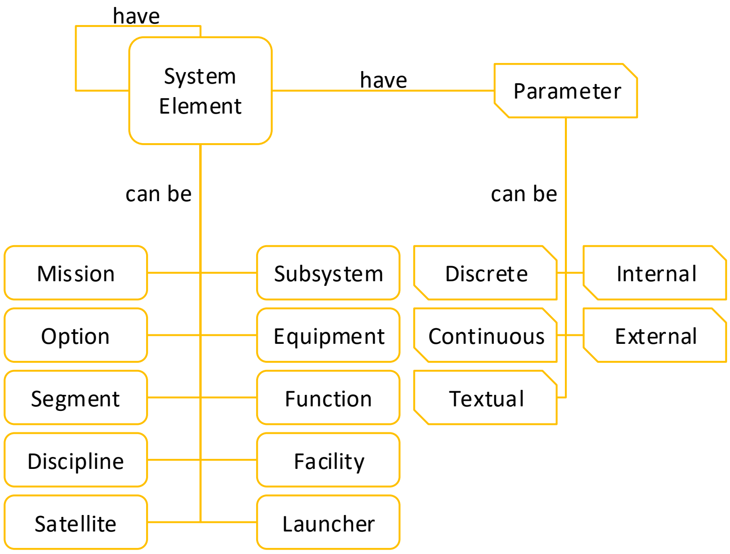
Figure 4.5 - Relations among the Entities.



SOURCE: from the author.

Taking into account the information point of view (Figure 4.6), the information structure of a Model have a System Element, which can have other inner System Elements. The System Element can then be specialized into other types (Mission, Option, etc.). The System Element have Parameters that can be Discrete, Continuous, or Textual, which also may be designed as Internal or External.

Figure 4.6 - Concurrent Engineering Possible Stereotypes.



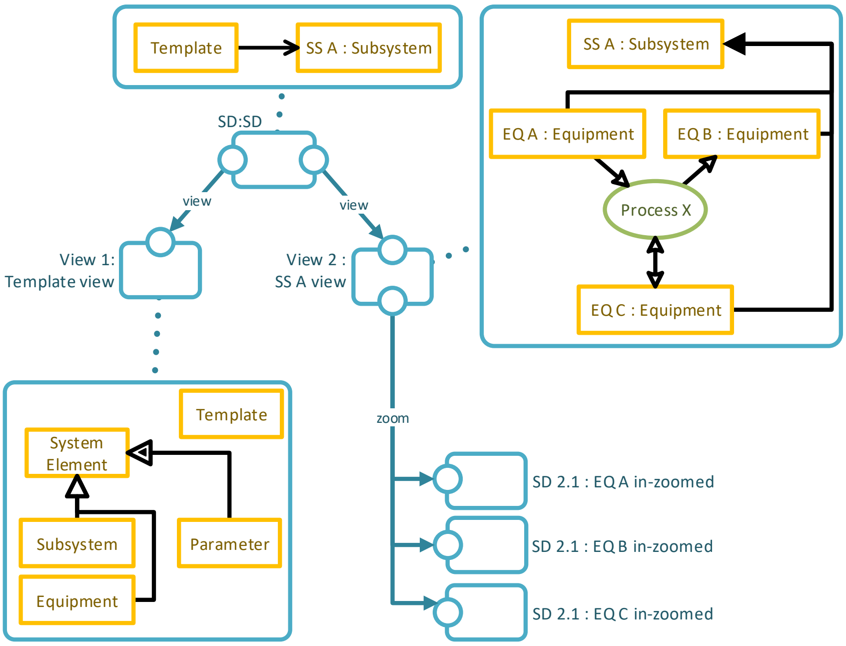
SOURCE: from the author.

These entities are what the specialists use to construct their discipline's domain information. Of course, each modelling approach uses its manner of design.

In the thesis we used OPM as our meta meta-model to describe system solutions through a MBSE methodology. Despite the OPM structure and behaviour into the same repertoire of symbols and the top-down discovery approach, it also has a one-to-one correlation in Graphs. More OPM details are in Section 2.4.4.

The OPM models (called SD - System Designs), exemplified in Figure 4.7, can be connected inside a project file through "views" or "zooms" (blue lines). The OPM vocabulary of the System Designs consists in things and links. **Things** are instances that exist (**stateful objects** - yellow rectangles) or provoke changes (**processes** - green ellipses), and **links** are what interconnect and specifies the relation among things (black lines). OPM can address several styles of modelling, to easy the matching to the tangible interaction, we defined a structure in which the model must be created: (i) The Root System Design has the main two things: a Template thing, and a major system element thing - Subsystem SS A. (ii) A unidirectional relation connects both things. (iii) The Template thing can then be refined in a view, where we add the stereotypes. (iv) The SS A can then be refined in another view, where we add the other things to describe the System Element. (v) Eventually, each other thing can be zoomed and better described.

Figure 4.7 - Example of a System Design (SD) Represented in OPM.



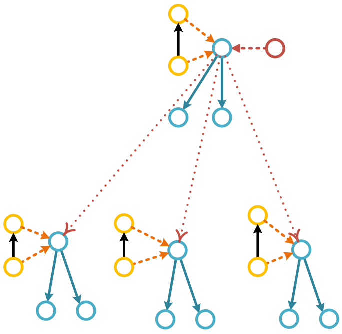
SOURCE: from the author.

Once created inside a model, a thing in any part of the OPM Project File must have exactly the same name to be the same thing. This is important because OPM has a fold-out strategy that collects all related things to create a tree view of the model's elements.

CE uses template to each domain to speed-up by reuse. The templates in DCT (Document-Centric Tools) fix the spreadsheets names and set the cell content positioning. This approach guarantees the data placement in the worksheet so the connection algorithms, the internal calculation sheet algorithms, and other support algorithms, know where to look and find the information. The same approach is achievable with OPM including a Template Thing with a view containing the Stereotypes.

The only available OPM tool is the OPCat. It does not allow to couple OPM models, the only possibility is to import the model, which mixes the designs. This approach couples but turn the uncouple unfeasible. To work around this limitation, we created a specific type of model relation: **the abstract view link**. This link relation does not exist in OPM, but it is the way we used to interconnect models as “atomic” structures. The abstract view links are exemplified at Figure 4.8 by a red dotted line, with an angled arrow head.

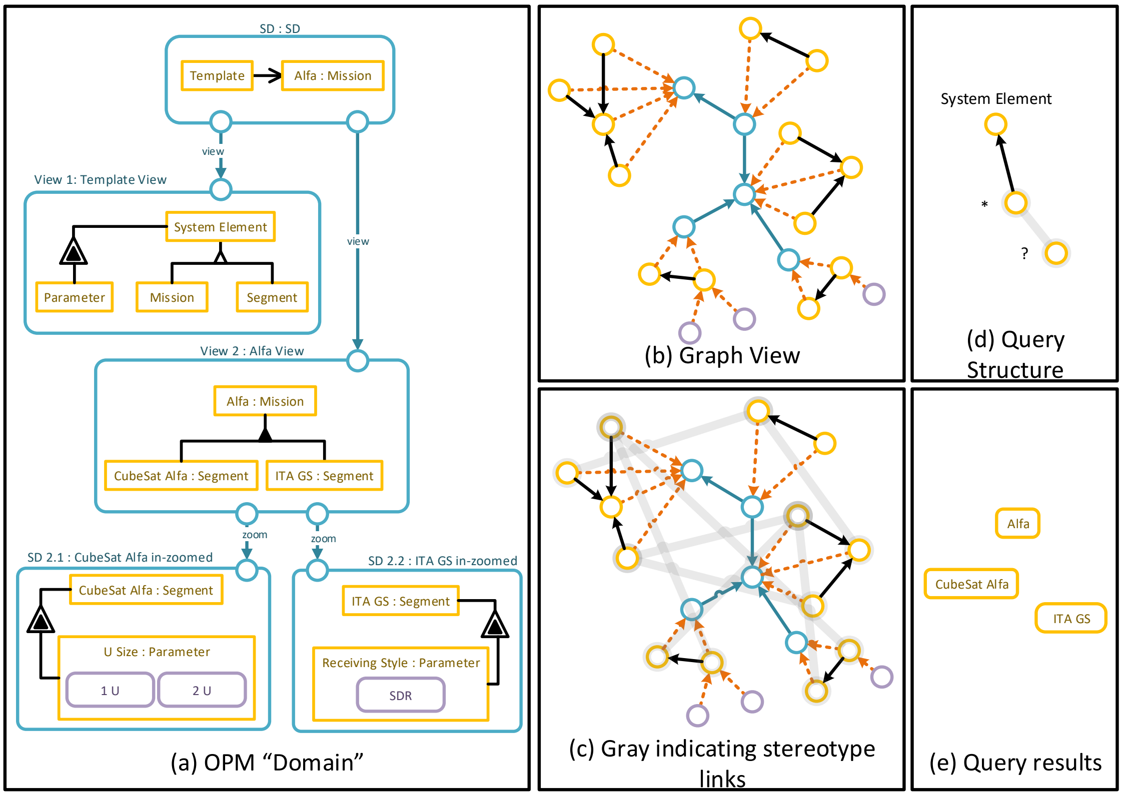
Figure 4.8 - Example of the abstract view link to couple OPM models.



SOURCE: from the author.

In OPM, all data belonging to a model, as well the model extensions are representable as nodes/edges of a digraph (WILSON, 1986). To find information in models we used a template matching to scan for known structures. Figure 4.9(a) illustrates OPM symbols, the models, its data and their relationship. Figure 4.9(b) shows the Graph underneath describing the OPM. Figure 4.9(c) indicates in grey lines the things' stereotypes extensions. Figure 4.9(d) indicates a template query to request all things that have a stereotype thing that has a relation (generalization-specialization link) with a System Element. Figure 4.9(e) shows the query result within three answers.

Figure 4.9 - Relation from OPM model to its Graphs and the stereotypes.



SOURCE: from the author.

4.3 The Use Scenarios of the Entities

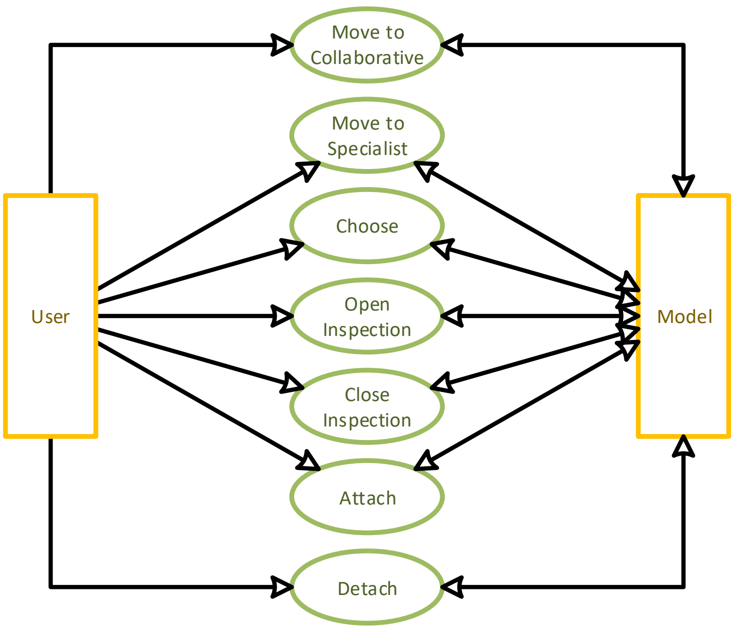
This section describes the use scenarios and each collaboration state of the entities. The use scenarios are input to define the tangible interaction vocabulary verbs and the state to refine the vocabulary adding adjectives to the nouns. The collaboration interactions are listed in Section 2.6.

Model Entity

The Model Entity is considered as the project container that keeps the System Elements and its parts. We consider that the models in collaborations were previously designed into a specific tooling from the Specialist Workspace (notebook, desktop, mobile, tablet, so on), and they can be moved to the Collaborative Workspace to collaboration. If something needs to be changed the model can be moved back to the Specialist Workspace.

In the Collaborative Workspace the specialist can choose a model, and open/close for inspection (showing the inner System Element). The specialist can also attach/detach, to other model, to create a coupled decision. Figure 4.10 illustrates (in OPM) the uses possibilities, where the processes consume the user, and affect the model, as: "*Move to Collaborative consumes the User. Move to Collaborative affects Model*".

Figure 4.10 - Model Entity uses possibilities.

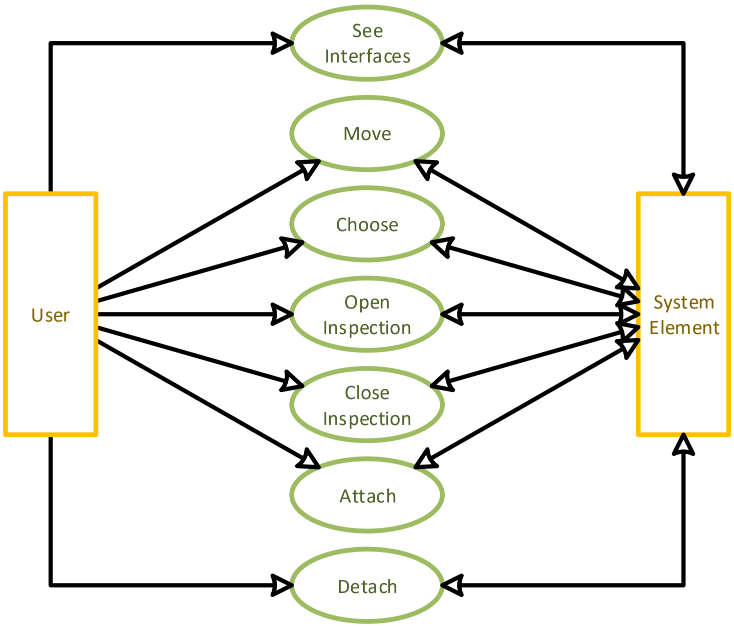


SOURCE: from the author.

System Element Entity

The System Element Entity can be moved through the Collaborative Workspace. The interfaces to other elements can be inspected. Into the Collaborative Workspace the specialist can choose a system element to inspect, and open/close an inspection (showing the inner System Element parameters). The specialist can also attach/detach to other system elements to create coupled decision. Figure 4.11 illustrates (in OPM) the uses possibilities, where the processes consume the user, and affect the system elements, as: "*See Interfaces consumes the User. See Interfaces affects System Element*".

Figure 4.11 - System Element Entity uses possibilities.

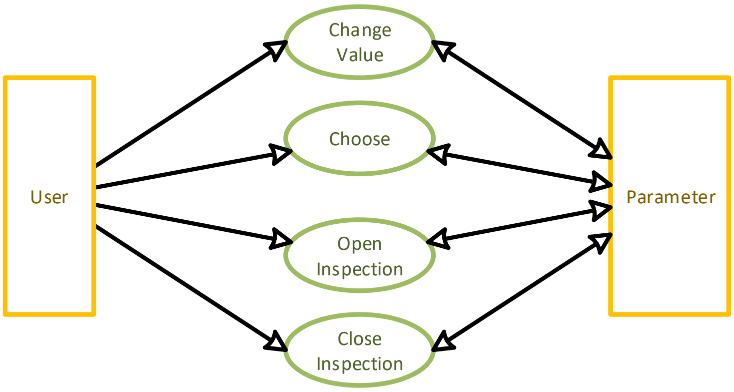


SOURCE: from the author.

Parameter Entity

The Parameters are fixed inside the System Element. The possibilities are: choose (select), open to inspection, and change the values. Figure 4.12 illustrates (in OPM) the uses possibilities, where the processes consume the user, and affect the Parameter, as: "*Change Value consumes the User. Change Value affects Parameter*".

Figure 4.12 - Parameter Entity uses possibilities.



SOURCE: from the author.

A model, within its system elements and parameters, have multiple states. The Model entity, as a macro entity from the use possibilities have three states: single, navigable (to inspect related models), and grouped (attached). The System Element entity has similar possibilities within three states also: closed, navigable (to inspect related system elements) and open (to inspect parameters). The Parameter entity has only two states: closed and opened (to inspection).

4.4 TUI Design

The User Experience Design (UX Design) is the process of creating the products to match the expected relevant user experiences, "encompassing all aspects of the end-user's interaction with the company, its services, and its products" (NORMAN; NIELSEN, 2018). The process of UX Design has three steps: **user research** - with internal iteration to validate ideas, **design** - with internal iteration to design around constraints and **build** (Interaction Design Foundation, 2018).

The Design phase inputs are the context expected user experiences (activities and proprieties), then within the technology constraints, it is possible designed the interaction concept which relates the context with the technology.

We identified five major collaboration groups: (see Section 2.6 and Section 4.3)

- **Move model in/out workplace**: within this collaboration the specialist manipulates the bank of models, picking which one will be mirrored into the Collaborative Workspace.

- **Share System Elements**: within this collaboration the specialist manipulates the model's System Element, navigating in case of a set of System Elements, or coupled models, to show to the team the system elements structure parts.

- **Couple System Elements**: with this collaboration the specialist can couple and uncouple models (which contains the System Elements) to group collaborative decisions.

- **Inspect System Element's Parameters**: within this collaboration the specialist exposes to the team, and inspect, the relevant parameter of a System Element.

- **Control Parameters**: with this collaboration the specialist modifies a parameter value (in this thesis work only discrete and the continuous were considered)

Regarding a tangible collaboration set of properties to a clear user interface, we defined the following properties based on interaction attention (see Section 3.4) and on OPM "scribing" expectations (simple yet expressive & intuitive yet formal (DORI, 2015)):

- **Versatility**: being versatile to represent the entities and its actions adapted to the context of the data.

- **Transientness**: having a dynamic behaviour to change the states, shapes and appearances of the representations.

- **Clarity**: having a clear meaning to avoid ambiguities of interpretation in representation and actions.

- **Expressiveness**: denoting a semantic meaning through a symbolism of an attitude of mind.

- **Simplicity**: being naturally understood and simple to interact.

- **Intuitiveness**: allowing expected behaviours to need to be directly perceived.

- **Formality**: adhering to a established set of rules which allows to correctly manipulate the data.

We listed the collaborative behaviour (Section 4.1), to identify the models types and the formality, where: (i) from the model types, we identified that with TUIs we can balance the models into a “scribble-like more-formal modelling”. TUIs physical orientations and placements, are like free models, it does not have a formal, or correct, place to stay. TUIs intangible representations can describe data hierarchy and its parameters, being MCT or DCT; and (ii) from the formality, we identified that TUI can also balance, as we move artefacts, as informal panel changing, which improves the information appropriation and the sense of broad understanding, without losing the formal aspect of a prior defined set of models that are only being referred to and coupling into a baseline solution.

With regard to the technological choices, other aspects were considered: (i) specific or general tangible artefact (described in Subsection 3.3.2), which implicates into a narrow or broader spectrum of versatileness; (ii) pure tangible or tangible or intangible hybrid approach, which implicates in the level of transientness to create dynamic actions, using intangible visualization through AR; (iii) distributed or centralized intelligence and awareness, which implicates in giving directly control to the artefact to manipulate the models, or to use an environment manager to track the artefacts and make the interactions, the former requires concurrency management, while the latter requires artefact tracking capabilities; and (iv) direct or indirect metaphor, which implicates in artefacts that are visually related with the manipulated domains, or use an indirect semantic vocabulary of verbs and/or nouns to add a relation layer to manipulate the domain.

We adopted a TUI design based in **general**, **hybrid**, **centralized** and **indirect** to collaborate models, where: (i) the **general tangible artefact** we developed with a box-like puck with four buttons and wells, following a generic approach to allow the noun vocabulary versatility; (ii), the **hybrid approach** keeps the clarity of the information, all participants can look at the artefacts and understand its meaning, we adopted Spatial Augmented Reality (BIMBER; RASKAR, 2005), to create the intangible representations - which we called **auras**, (iii) **the centralized control** with a projected collaborative surface tracking allows to control all artefacts within a single source of control, removing from the artefact intelligence of model manipulation and visualization, and (iv) **indirectness of the metaphor** - given the use of a general artefact empowered with an aura.

We opted for a building block visual metaphor, because most of the diagrams used in CDF are interconnected blocks, according to the history of diagrammatic representations found in the SECESA papers (in Subsection 4.1.1).

To handle the five collaborations, we designed a TUI artefact with five states. Given the state it enables a set of possible collaborations as well as a visual aesthetics representation (auras), to show and guide the behaviours (the entities states are in Section 4.3). Where:

- to Move model in/out workplace, the artefact is handling a Model entity (in single or navigable state), called **Totem Aura**;
- to Couple System Elements, the artefact is handling a Model Entity (in group state), called **Big Picture Aura**.
- to Share System Elements, the artefact is handling a System Element entity (in closed or navigable state), called **Share Aura**;
- to Inspect System Element's Parameters, the artefact is handling a System Element entity (in open state), called **Knowledge Aura**;
- to Control Parameters, the artefact is handling a Parameter entity (in closed or opened), called **Control Aura**;

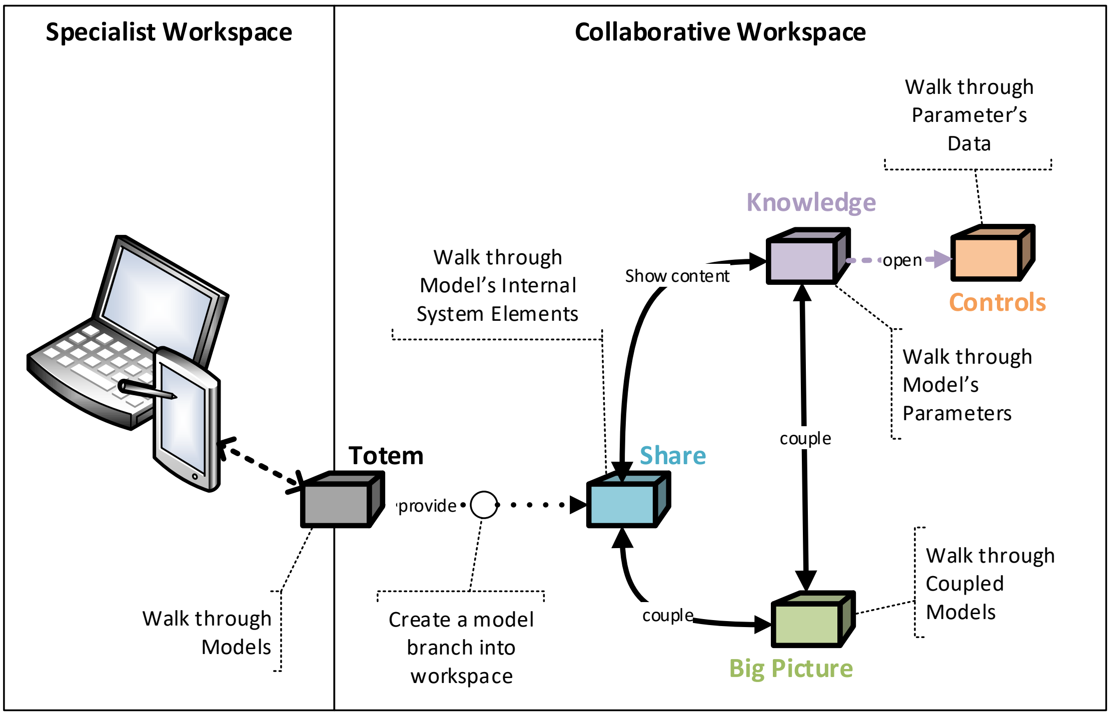
Figure 4.13 summarizes the five auras and the transition among them.

The collaboration starts with the specialist sharing a model into the Collaborative Workspace. To do so, we defined that specialist must use an artefact in the Totem Aura, which allows to navigate through the models' branches, as a collection of possible models. The Totem Aura always stays in the workspace, indicating the continuity space between Specialist's GUI and the Collaborative Workspace. To manipulate the model, the specialist must clone the current Totem Aura creating a Share Aura. This operation also creates a new branch into the collaborative graph workspace underneath. The Share Aura allows to navigate through the system elements that were described inside the model. The Share Aura can be manipulated further with the: Knowledge Aura, to inspect internal parameters, and using the Control Aura to manipulate the parameters, or use the Big Picture Aura, to navigate and show the connected model branches.

4.5 Computer Aided Facility

As a Proof of Concept (PoC), we implemented a simpler Computer Aided Facility (CAF) arrangement to show the possible TUI artefacts collaborations possi-

Figure 4.13 - Relation among the Artefact Auras and what the Aura allows to manipulate.



SOURCE: from the author.

bilities. The facility hosts all equipment that provide design/collaboration to the specialists. As a workplace, the facility must be physically able to accommodate the software/hardware infrastructure to enables: (i) **ways to handle activities**: the human-to-human interaction, (ii) **ways to use the data**: human-to-data interaction, and (iii) **ways to house the tools**: the human-to-facility interaction.

4.5.1 Human-to-Human - Perceptions

The Human-to-Human (H2H) interactions are: speaking, eye sights, and gestures that humans make to each other during conversations. All those symbols that already exist in our repertoire, and as they are perceived by behavioural mental models they are understood and receive meaning. Although this thesis does not cover psychological behaviour, regarding H2H, the specialists' behaviour capabilities during the session must be considered as they reflect into the conduct of the team, thus the collaboration.

H2H perceptions are an important issue with stand-up sessions, which are faster and usually more objective than seated, where all the participants are looking to each-other or to the model being presented in the centre. Standing allows better movements of the specialists and enables to move the physical artefacts through the surface (described in Section 3.6).

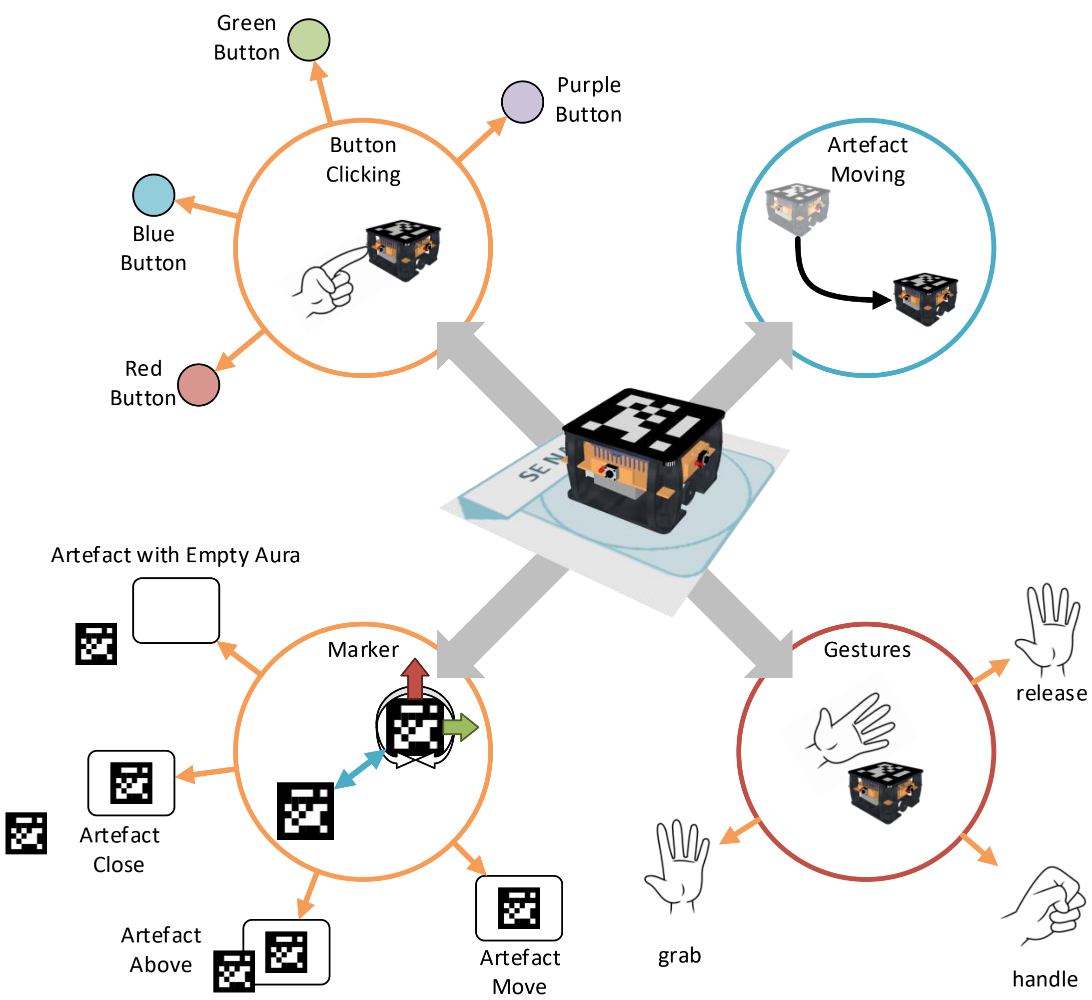
Each H2H interaction modality induces a perspective to manipulate the TUI artefacts, considering that the specialists are looking and manipulating concurrently, with peripheral and central attentions (described in Section 3.4).

Some of H2H explored are:

- **Touching**: the basic interaction that allows users to experience the object though their hands.
- **Holding and positioning**: the physical artefacts positioning are the core of constructive tangible interactions.
- **Gestures**: interactions above the artefact/table surfaces adds a level of possible grammar to interaction, complementing the physical possibilities.
- **Artefacts repositioning**: where users physically experience their appropriated data changing and collaborating with other data parts.

The H2H creates the input interaction vocabulary verbs: button, gestures, and artefact positions (Figure 4.14). Refining, we used four buttons, one each side; considered two broad gestures “grab” and “release”; and four artefact-aura possibilities - artefact with empty aura, artefact close to an artefact-aura, artefact above of an artefact-aura, and moving an artefact-aura; and the artefact moving by the facility commands.

Figure 4.14 - Interactions to create the TUI artefact verbs.



SOURCE: from the author.

Each one of the possibilities of the Figure 4.14 are a starter and/or a finisher interaction. As any interaction is made of the three phases (selection, manipulation, release - see Subsection 3.3.1). The buttons were not implemented as combo interactions, each button click-release is an interaction triggers that initiates one event, that ends by itself. Each marker maker-aura collision is also event triggers. The gestures do the same. Future versions could mix the interactions to make more complex interactions, but to this work we decided to keep it simple.

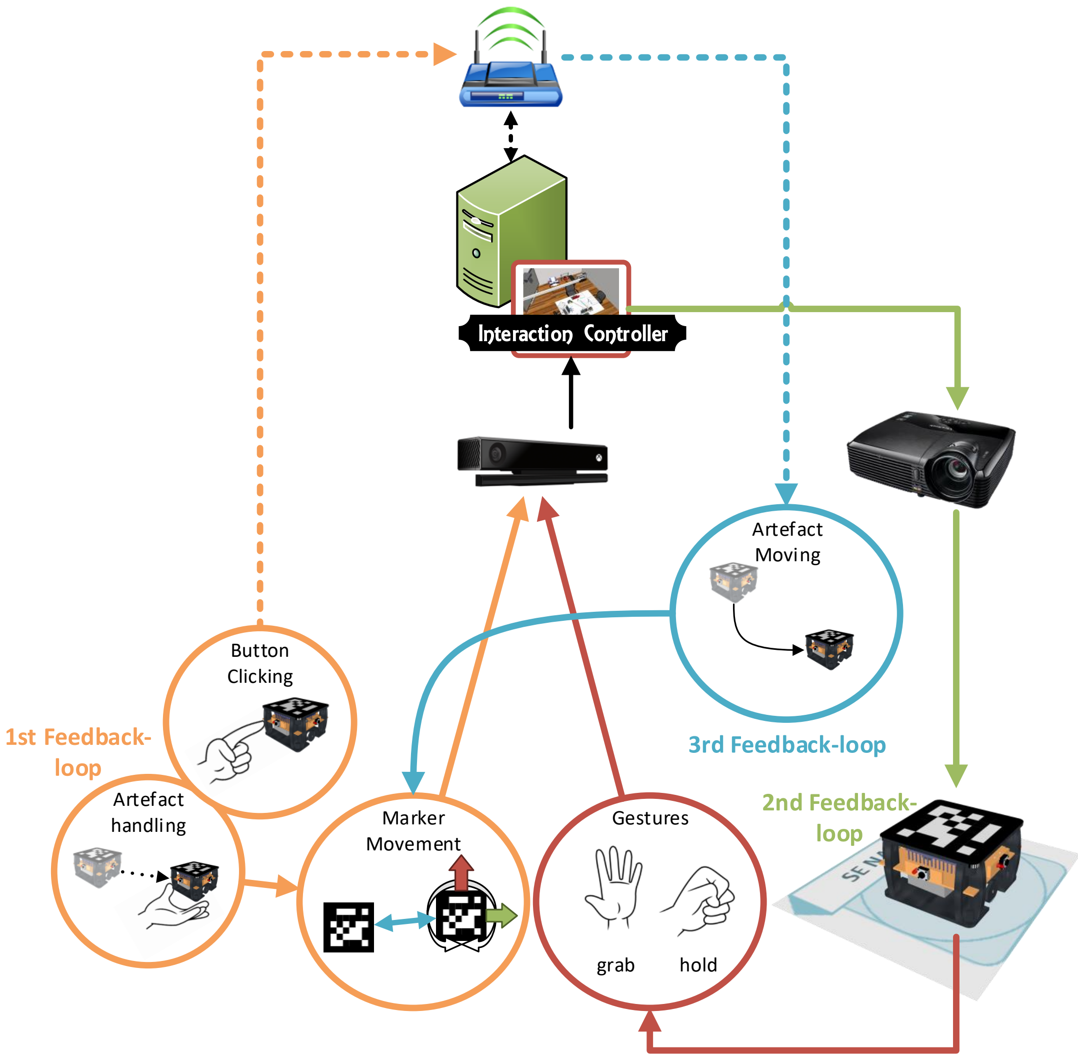
4.5.2 Human-to-Data - Interfaces

Regarding Human-to-Data (H2D) interactions, the facility must provide the physical interface of interaction with the data, which really manipulates the date with the tangible sense, and to this it must deal with the physical requirements and constraints of the interaction equipment, as throw distance, ergonomics, and field of vision. The positioning of the equipment must considerer its constructions, as:

- **The intangible aura projector**: The throw distance is related to the projected image area, and as far is the projector it decreases the projected resolution as the pixels will be bigger;
- **The tracking sensor**: The throw distance is related to the capacity of distinguish surface changes of the depth camera, used to air gestures the sensor has a focal point of +/- 3m, distances inferior of 1.5m are not adequate to depth tracking. The throw distance is also related with the VGA camera, used to marker tracking - as the algorithm is computer vision based, as bigger and clear the trackable are, the better the information are collected.
- **The communication network device**: the equipment must be allocated inside the room to avoid delays and connection losses. Closer access points, will reduce the amount of energy used by the artefacts to sustains the connection.

Figure 4.15 shows the feedback-loops flows of data in coloured lines, where: (i) in orange the 1st Feedback-loop originated by the physical handling of the tangible representation (the artefact) being captured by a communication network device and by the tracking sensor (Microsoft Kinect), (ii) in green the 2nd Feedback-loop creating the projected intangible representation (the aura) though a common projector, and (iii) in blue the 3rd Feedback-loop of a modification of the artefact position by the interaction controller. In red, the depth camera allows to interact with the intangible representation by recognizable hand gestures.

Figure 4.15 - Feedback Loops.



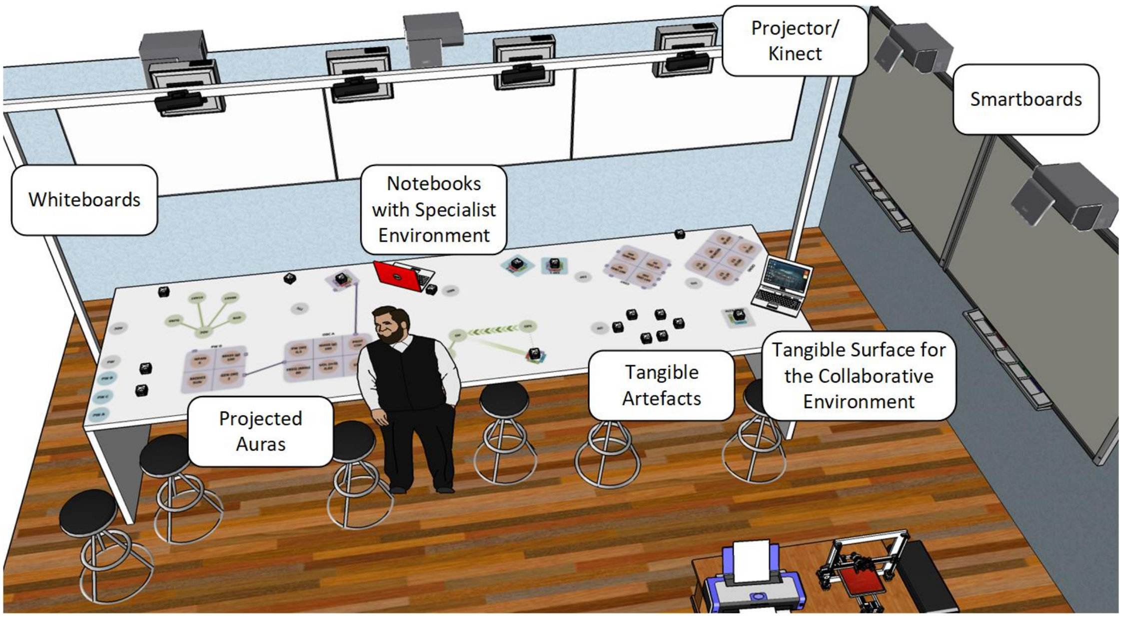
SOURCE: from the author.

4.5.3 Human-to-Facility - Environment

The Human-to-Facility (H2F) interaction consider the ergonomics to achieve the data on the projections, this interaction regards the physical artefacts, or smart tools, used by the specialists. Being physical elements, they can leave the virtual constraint area and remotely manipulate data, if a second interaction area is available and trackable, the virtual intangible representation that were in the first area (if programmed to do so) would move to the second area. Such interactions were not implemented in the PoC, but they indicate the possibility to create multiple interactive areas which are connected through the software infrastructure.

The Facility to support TUI artefacts must have a continuous known surface, so the tangible artefacts can rest on. The sitting-standing position allows comfortable resting as well as agile movements, to reach and interact with the artefacts. With the mean arm reach of about 650mm, and a "safe space" of 700mm, the ideal table width must double to place the specialist areas face fronting. Figure 4.16 sketch exemplifies the sitting-standing ideal desk to collaborate with this thesis's tangible artefacts.

Figure 4.16 - Ideal Desk to collaboration with artefacts.



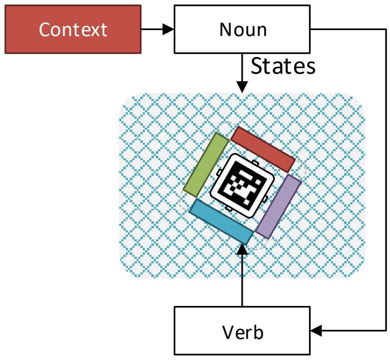
SOURCE: from the author.

Figure 4.16 also shows possible whiteboards, Smartboards, Notebooks to use Specialist's Tools, and the Tangible Surface to Collaboration with the tangible artefacts and its projected auras.

4.6 Tangible Interaction Vocabulary

To Build the interaction vocabulary we defined the sentences rules and the elements. The Nouns comes from the Entities, and are specialized by each Entity State. The Verbs comes from the possible interactions with the Entities (described in Susbsection 4.5.1). The Verbs are the actions that implies into changes: in representations, states, model arrangements, so on. The illustration in Figure 4.17 shows the relation between the Context, which includes the Collaborations and Entities, and the vocabulary parts, which includes the stateful nouns and verbs.

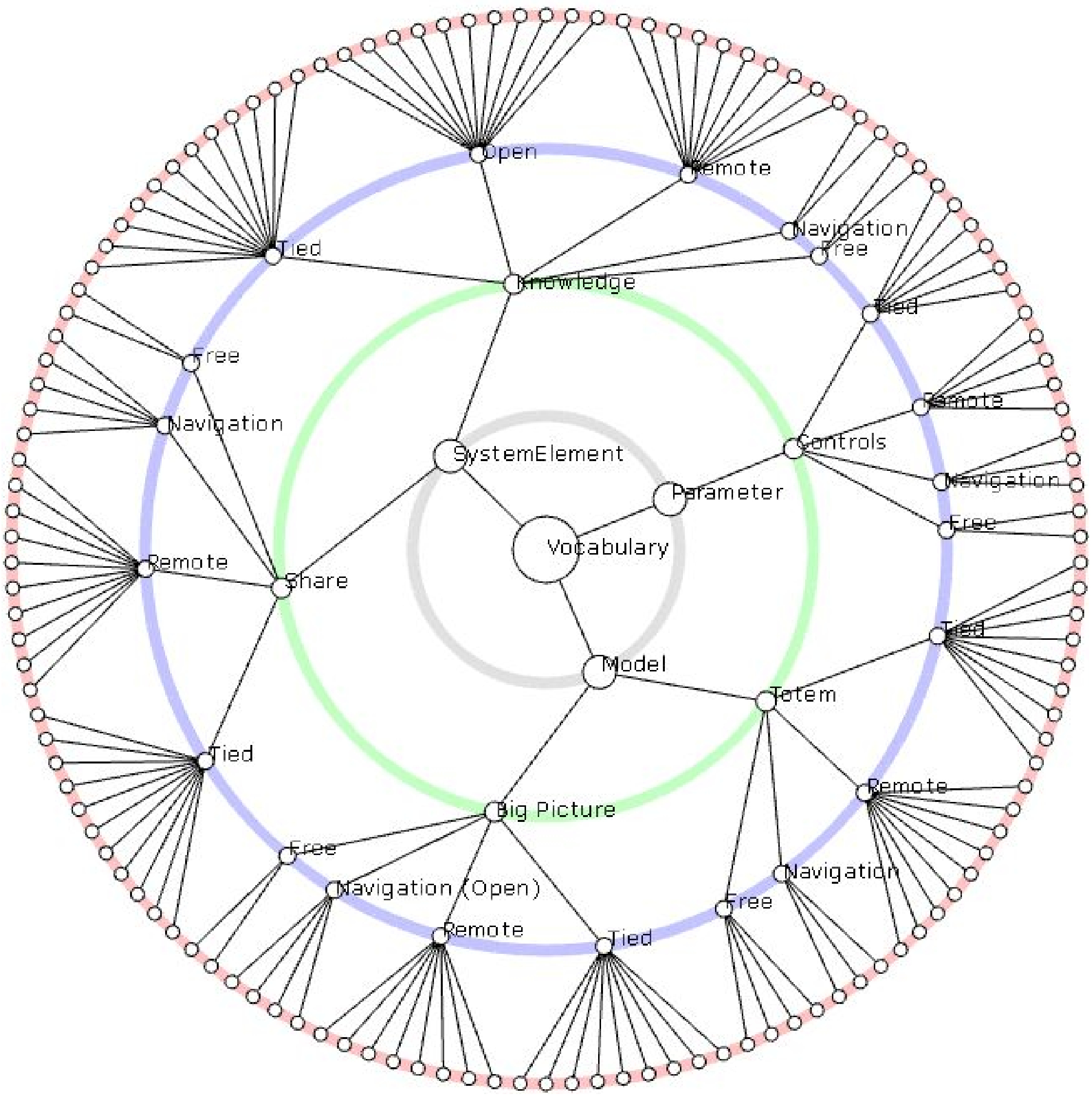
Figure 4.17 - Relation of the Vocabulary Elements.



SOURCE: from the author.

Figure 4.18 illustrates all vocabulary, starting from the node root to the Entities (Model, System Element, and Parameter), following by the Nouns (Totem, Big Picture, Share, Knowledge, and Control), the nouns adjectives (entity states), and at the border the verbs. Total of 252 combinations or 252 interactions in the TUI vocabulary.

Figure 4.18 - Radial Tree of all TUI Vocabulary.



SOURCE: from the author.

As an example, the Big Picture Aura is described in the following subsection.

4.6.1 Big Picture Aura Example

Big pictures are wide representations containing only the main data, as maps that hides the details to allows more covered area. This metaphor is used here, to create an aura meaning that represents the availability of an aura/artefact to create macro representations and couple the solutions.

Association to CE sessions:

As the specialists converge to the solutions and a baseline, each proposed piece must be coupled together. The big picture of a solution shows to all specialists that their solutions occupies (physically) a place into the final solution, increasing the sense of appropriation, as the specialists watch physically its solution into the baseline. The Big Picture Aura can be a local cluster, to discuss the relations, or the final baseline, to the next iteration.

Artefact Interactions:

From the Model Use Scenarios, we refined the Big Picture metaphor to deal with the coupling models, attaching mode, in four states: Tied, Remote, Host and Free. In Tied, the artefact controls the noun aura with overlay, the aura only shows the. In Remote, the artefact controls the noun on distance, into a "nearby embodiment" - the aura locks on the surface and is remote controlled. In Host, the Big Picture aura allows to host a coupling branch, allowing to control de connected auras. In Free, the aura does not have an artefact associated. Figure 4.19 shows the interaction/transition mapping, with the relational events (action verbs) that makes transitions.

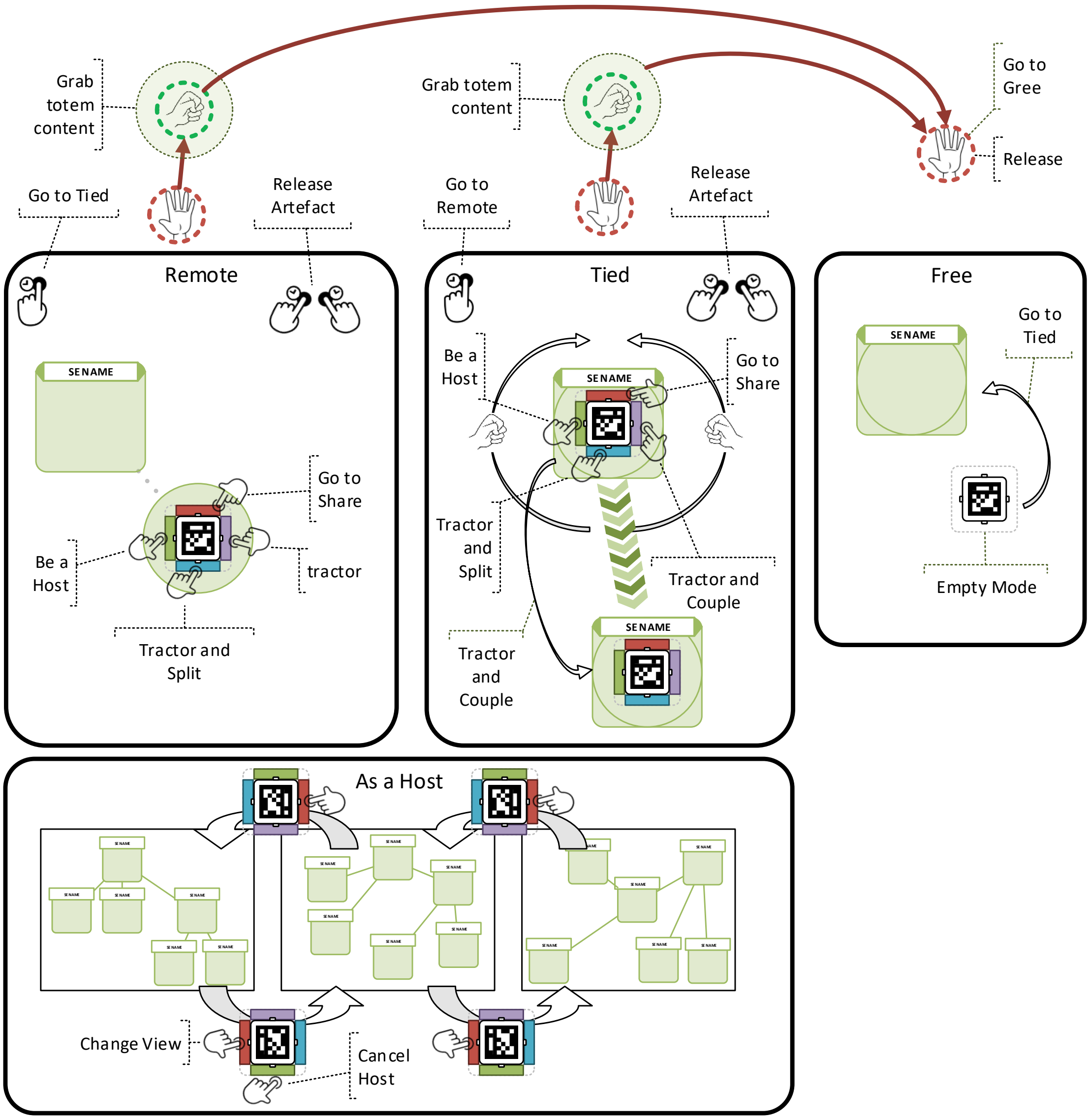
Figure 4.19 - Big Picture Verbs.

Interactions		Big Picture Noun States			
		Tied	Remote	Host	Free
Big Picture Verbs	Button_Red	Go to Share	Go to Share	Change View	
	Button_Blue	Tractor and split	Tractor and split		
	Button_Green	Be a Host	Be a Host	Cancel Host	
	Button_Purple	Tractor and Couple	Aura tractor		
	Button_Hold	Go to Remote	Go to Tied		
	Button_DoubleHold	Release artefact	Release artefact		
	Gesture_Grab	Hold Aura	Hold Aura		
	Gesture_Release				
	Artf_EmptyProx				Go to Tied
	Arft_AuraProx	Tractor and Couple			
	Artf_PlaceAbove				Go to Tied
	Artf_Move	Follow (move together)			

SOURCE: from the author.

Figure 4.20 illustrate all verbs, and the noun. As this thesis copies the building blocks metaphor, the System Elements are represented as blocks.

Figure 4.20 - Big Picture Example of all Verbs.

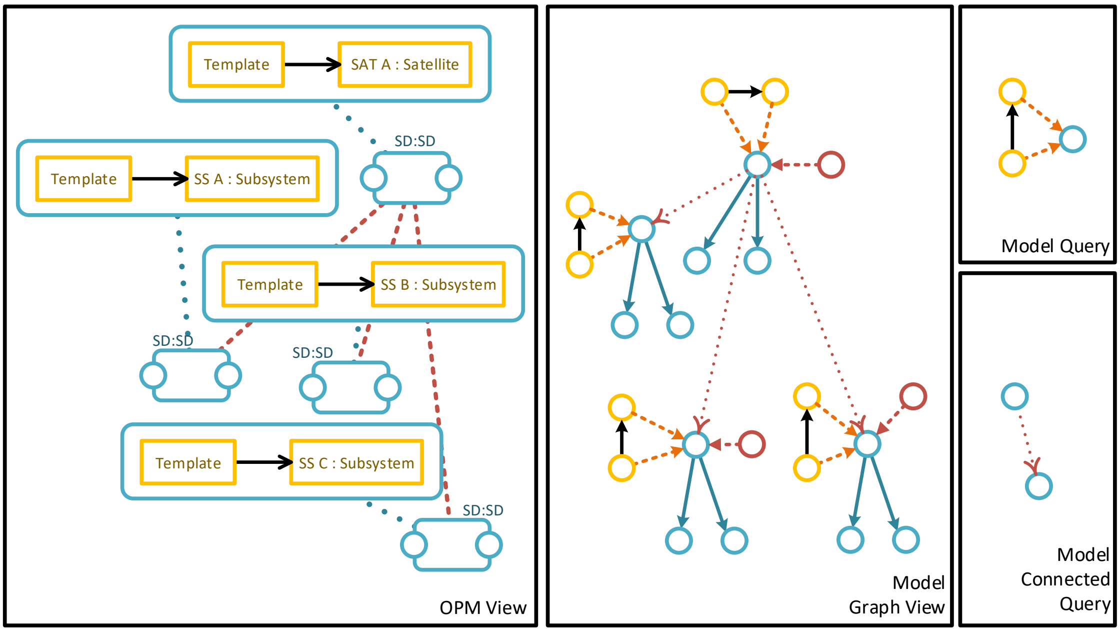


SOURCE: from the author.

Queries to manipulate data:

Figure 4.21 illustrates the Graph query of the Big Picture Aura. The left panel shows the Specialist OPM View of a model example, it shows a series of coupled models (dashed red line). The middle panel contains the graph showing the graph connections into between each pair of model nodes. The Right Panel, shows the queries, the first queries models, the second queries the model couple link.

Figure 4.21 - Big Picture Query.



SOURCE: from the author.

Appendix A describes the other 4 auras: Totem, Share, Knowledge and Controls.

5 IMPLEMENTATION

This Chapter presents the tangible artefact implementation. It is divided into three sections:

- **Artefact Design**: describes the artefact parts and construction;
- **Interaction Controller**: describes the engine that matches the artefact interactions with the model to create the aura projections;
- **Viability Proof**: describes the viability experiment to proof the main driving question.

5.1 Artefact Design

This section describes the three design subjects regarding the artefact: electronic, mechanical and logic.

5.1.1 Artefact Electronics

The artefact electronics complied with: (i) touch - sensing buttons, (ii) movement actuator wheels, and (iii) communication - to control and acquire buttons.

The design was done using the Fritzing[1], which has a model library made of designers' contributions. This library has a myriad of components available to help the electronic design. Following the IoT (Internet of Things) trend, closer to the Cross-Reality definition, it was adopted a Wi-Fi SoC (System on Chip) integrated solution based on the Expressif's ESP8266 chip[2]. The ESP8266 has several module board distributions and development kits. To the artefact main board, in this thesis, was adopted the NodeMCU[3] development Kit, which is based on the ESP-12E module.

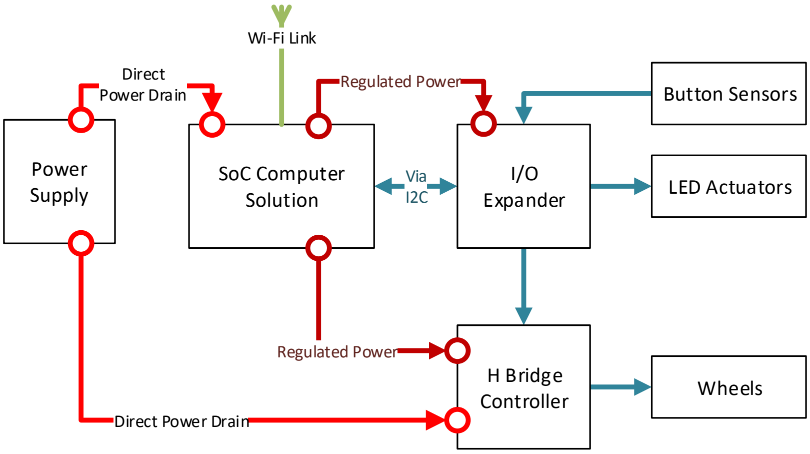
To interface the touch commands, we used four buttons, one on each artefact lateral panel. A capacitive grid to touch sensing was not used as it would misinterpret grasping instead of actively choosing an option. One common usability issue is feedbacking action, so the user know that the command is being processed. To implement the acceptance of the command, a paired LED was implemented in each button. The movement of TUI artefacts are commonly implemented using wheels connected into

[1]http://fritzing.org/home/
[2]https://en.wikipedia.org/wiki/ESP8266
[3]https://en.wikipedia.org/wiki/NodeMCU

a DC brushless motor. Due to NodeMCU electrical current limitations, the motors can't be powered directly by the board. So, to control the spin direction, and drive current to torque, we built a H-Bridge circuit through an I/O expander.

The diagram block in Figure 5.1 summarizes the interconnections of the main elements. The power supply (batteries) are connected directly to the SoC Board and to the H-Bridge, which drives current to the wheels. The SoC Board regulates the tension to a lower level, enough to power the TTL circuits of the I/O expander and the H-Bridge logics. The data control is transmitted/received to/from the I/O Expander by the two-line connection I2C.

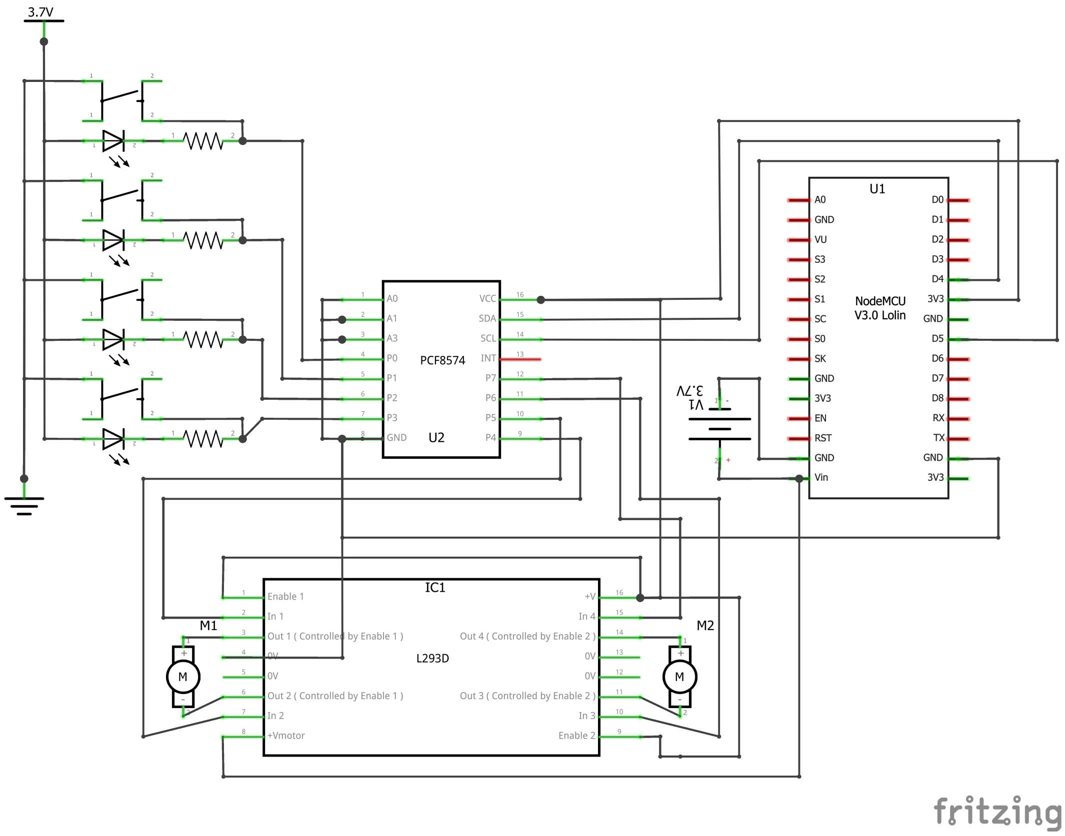
Figure 5.1 - Artefact's Block Diagram.



SOURCE: from the author.

Figure 5.2 shows the electronic schematic:

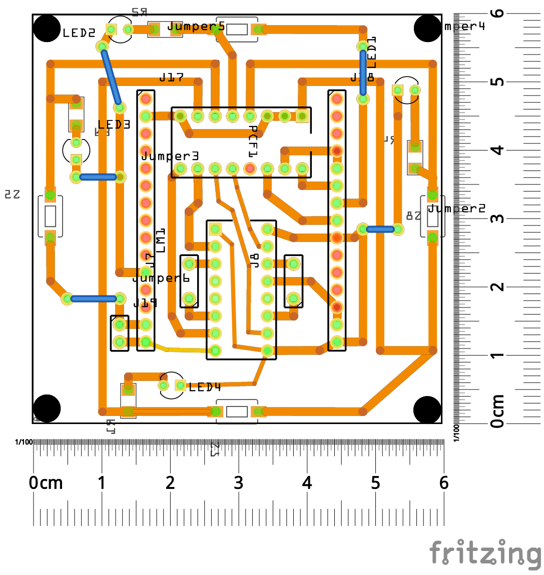
Figure 5.2 - Artefact's Circuit Diagram.



SOURCE: from the author.

Figure 5.3 shows the board layout.

Figure 5.3 - Artefact's Circuit PCB.



SOURCE: from the author.

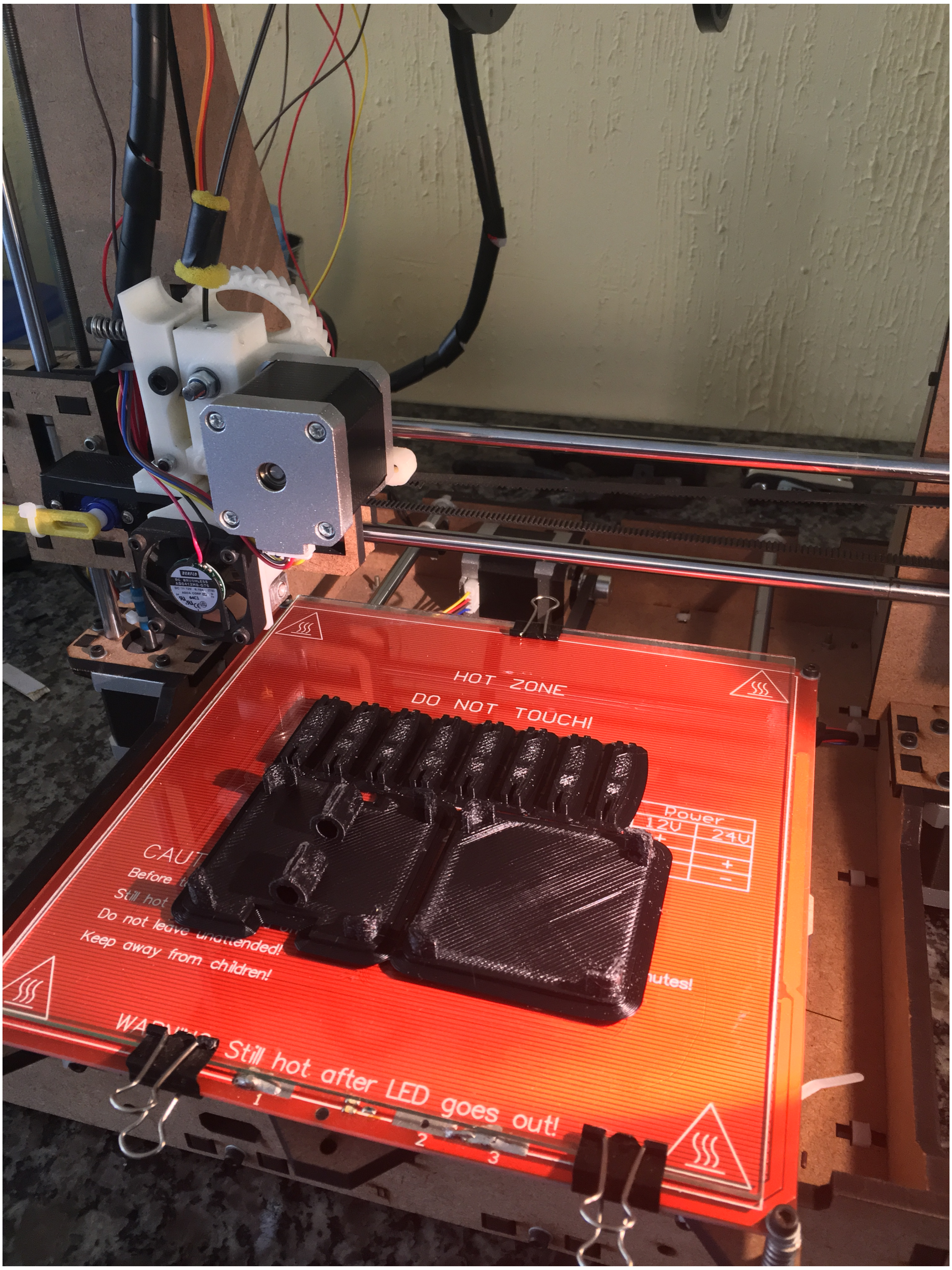
5.1.2 Artefact Mechanics

The structural format of the artefact complied with the: (i) designed interaction style - Tangible User Interface, (ii) approach - generic meaning artefact, (iii) hand size - easily graspable to fits in the hand, (iv) tracking infrastructure - visible pattern size, and (v) electronic size - to hold and organize the electronics.

The mechanical design was done using the SketchUp[4]. The SketchUp is very intuitive, and it has an extensive 3D model library made of designers' contributions[5]. All the electronics components 3D models were available to download, helping to design the positioning of inside the artefact envelope. SketchUp also allows to export into STL to 3D printing (Figure 5.4).

[4]https://www.sketchup.com
[5]https://3dwarehouse.sketchup.com/

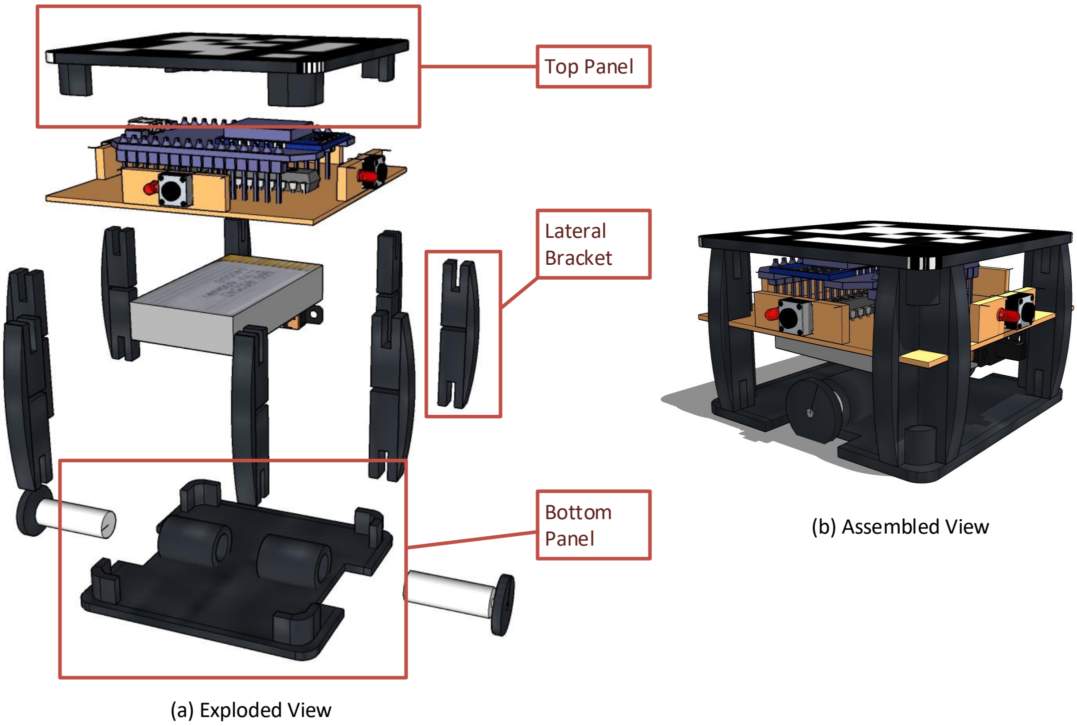
Figure 5.4 - 3D Printing the artefact.



SOURCE: from the author.

Figure 5.5(a) illustrates an explosion view, highlighting: the table bottom panel with the wheels socket, the eight lateral brackets, and the top marker panel. Figure 5.5(b) illustrates the artefact assembled.

Figure 5.5 - Artefact Views.



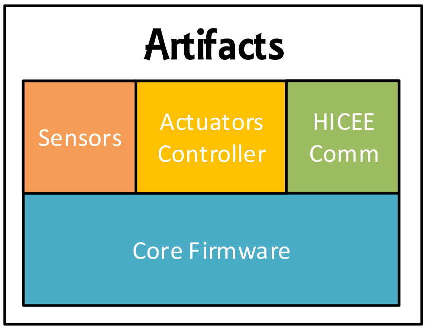
(a) Exploded and (b) Assembled.
SOURCE: from the author.

5.1.3 Artefact Embedded Software

The artefact embedded software is responsible to control and collect all hardware data and communicate the changes (as pulled) to the host. Figure 5.6 illustrates the main blocks of the software, with: (i) the Sensors - responsible for collecting sensor status, (ii) the Actuators Controllers - responsible for controlling the wheels and the LEDs, (iii) the HICEE[6] comm - responsible for answering the Interaction Engine data requests and movement/acknowledge commands, and (iv) the Core Firmware responsible for the integration of the upper layer, executing the artefact's algorithm.

[6] HICEE is the name given to the Interaction Controller Software

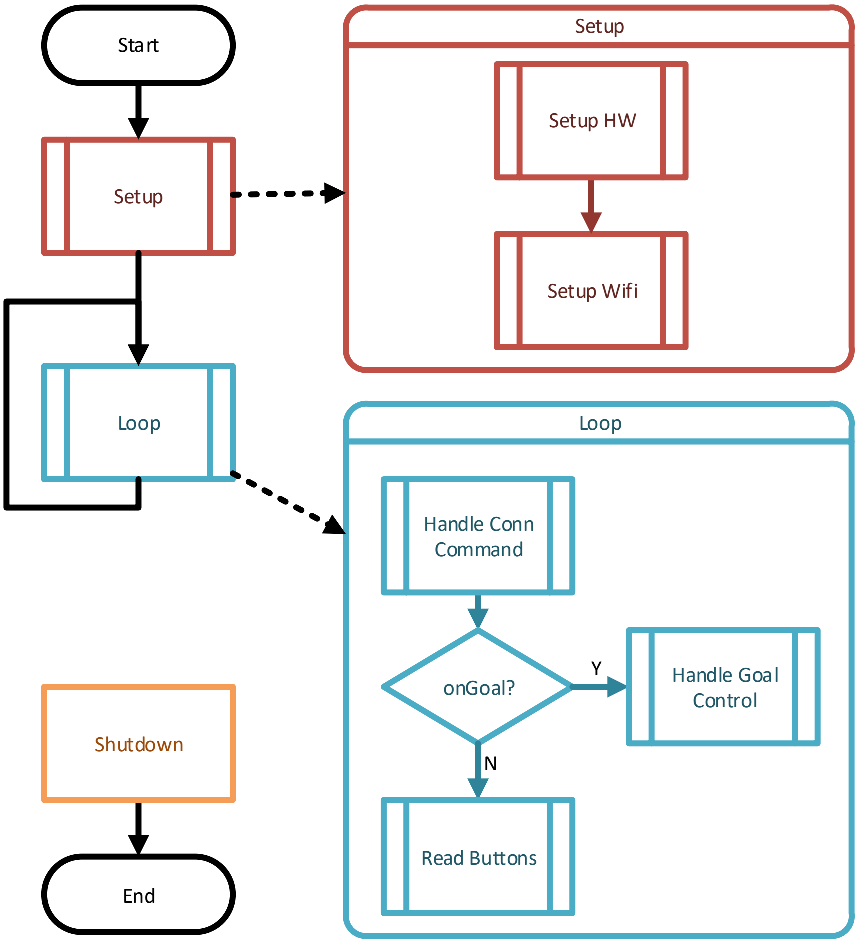
Figure 5.6 - Artefact Embedded Software Architecture.



SOURCE: from the author.

The ESP-12E can be programmed as an Arduino[7], following the same two main functions structure: (i) **setup** - initial, one-time execution, to instantiate the coupled hardware classes and login into the network; and (ii) **loop** - to repeatedly execute on-loop algorithms to check incoming requests, and if executing a movement controls the wheels, otherwise read the input buttons. (Figure 5.7)

Figure 5.7 - Artefact Embedded Software Flowchart.

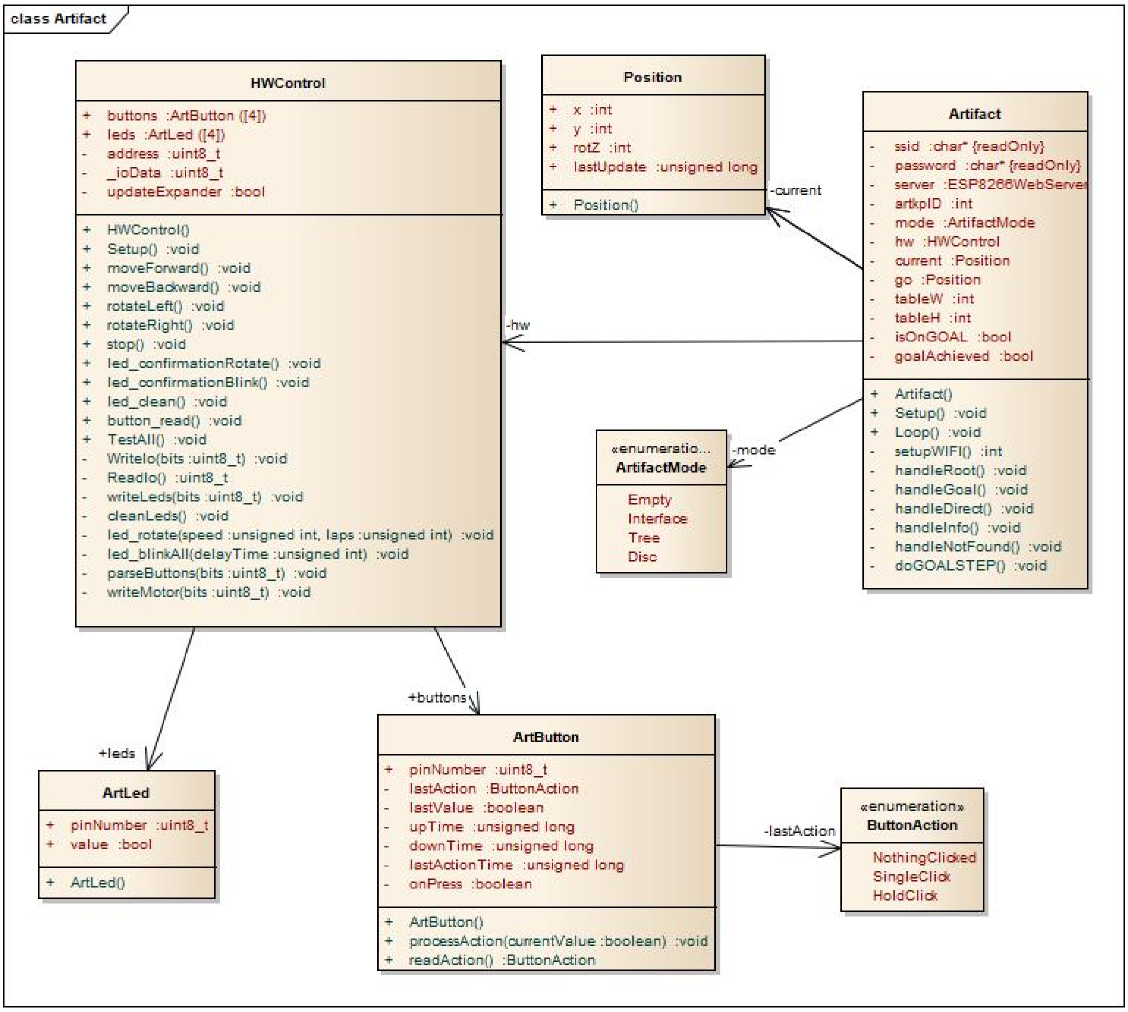


SOURCE: from the author.

[7]https://www.arduino.cc/

The advantage to use Arduino style on ESP-12E is to use C++ to design the code, allowing to organize the elements in classes, as illustrated in Figure 5.8.

Figure 5.8 - Artefact Embedded Software Class Diagram.



SOURCE: from the author.

The main class is the **Artefact class**, which instantiates the all TUI artefact attributes and methods, as the Wi-Fi library WebServer and the hardware controller. The **Hardware Controller** (HWControl) encapsulates the code to change and read the hardware. **ArtLed** and **ArtButton** assist to control and store the hardware statuses as well as, in the case of the Button, to store debouncing methods. The Wi-Fi library tries to parse the HTML query parameters and organize the host incoming request in callback functions, which handle specific matters.

5.2 Interaction Controller

This section describes the Interaction Controlle that handles the models and track interactions to create the auras. There are only two data natures being handled: artefact aura and model data.

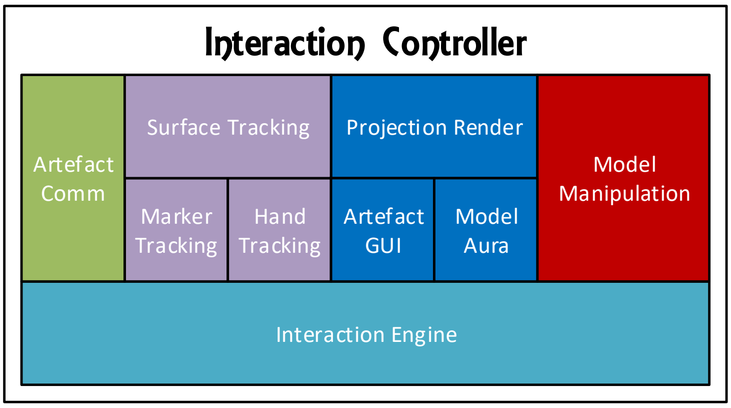
- The artefact aura are all the inputs elements, that are processed relatively to the artefacts and auras locations and modes and outputted through movement or projection.
- The model data are all storage models, that are manipulated by the interaction input, and feedbacks to be outputted.

The TUI is one of the possible user-interfaces paradigms that can interact with the model data, reasoning the motives to this separation. To this example case, was developed an HICEE[8] application, built over the C++ openFrameworks[9] development library, common in this type of environment, as it is faster to render big assets, calculate image processing, and easier to communicate with hardware; and the model data stored and handled using any given storage method, due to the graph similarity, a graph-based database seem more appropriated.

Figure 5.9 illustrates the HICEE Controller architecture, where the interaction data is basically from 3 sources: (i) the Artefact Comm: which contains the artefact query commands, and the processing of the artefact answers; (ii) the Surface Tracking: which contains the computer vision algorithms of both VGA marker tracker and depth sensing hand tracker; (iii) the Projection Render contains the creation of the data to be projected, rendering the artefacts' controls, and the models' aura; and (iv) the Model Manipulation contains the algorithms to track model through model templates to match with the model sections which the user interface is handling. The Interaction Controller contains the algorithm that iterates through the inputs and data, to create the projection and control the artefacts.

[8]HICEE is the name given to the Interaction Controller Software
[9]http://www.openframeworks.cc/

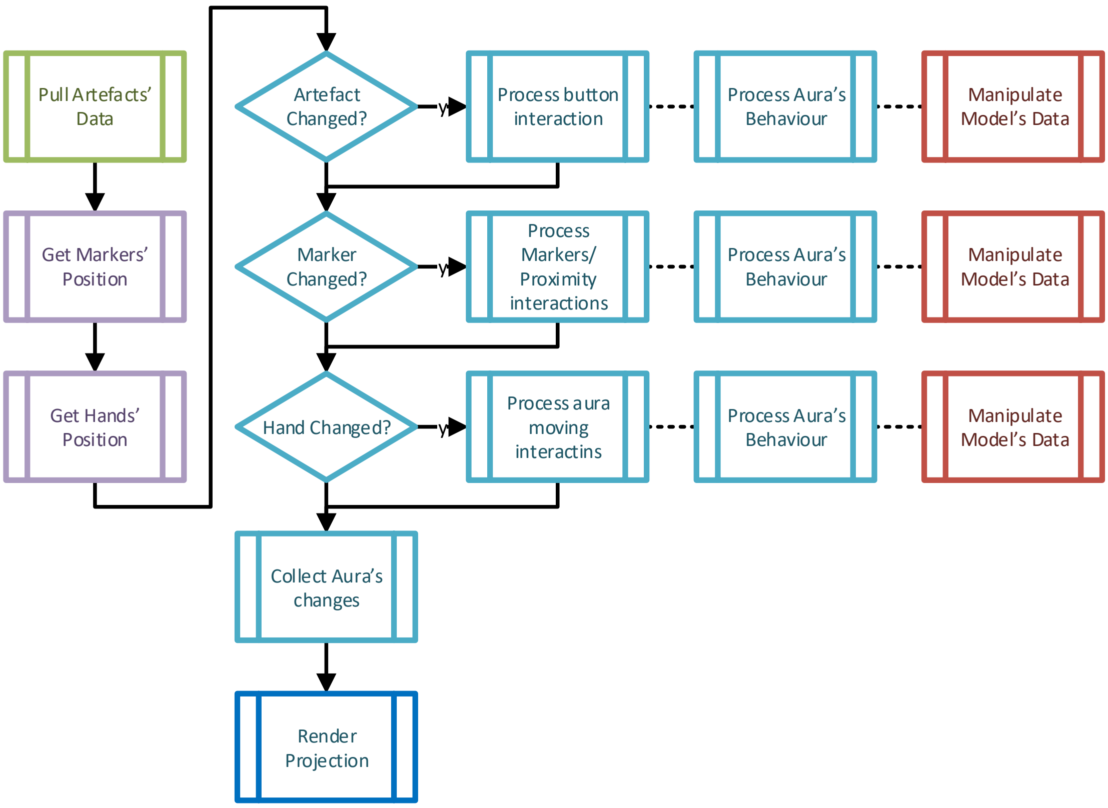
Figure 5.9 - Interaction Controller Software Architecture.



SOURCE: from the author.

Logically, the Interaction algorithm must pool all sources of input, to check if anything has changed. With all data in place, the precedence order is Artefact change, Marker Change and Hand Change. Each one of those checking leads to the processing of its interactions, which further requires the processing of the auras involved and the model associated. (Figure 5.10)

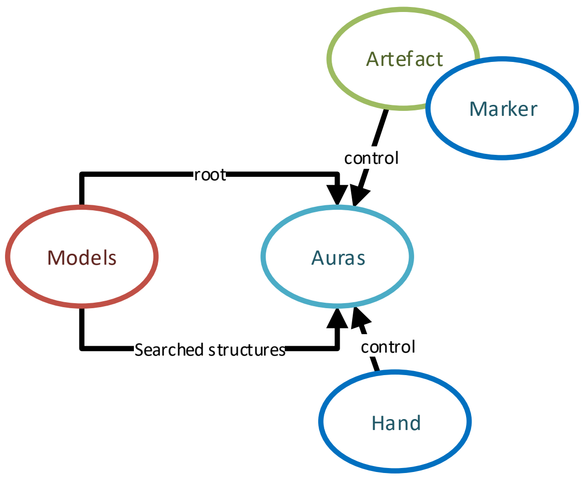
Figure 5.10 - Controller Interaction Loop.



SOURCE: from the author.

Regarding the internal software, this solution has four main structures: (i) the auras, (ii) the artefacts, (iii) the hands, and (iv) the models (Figure 5.11). The center of the structures are the auras, which are the intangible representations that are created in consequence of interaction and model data. The auras have two types of links regarding the models: (i) the root - which contains the head link towards the beginning of the model description, in this case it points to the node's System Design element; and the (ii) searched structures - which contains all the structures found (and the relations) that are manipulated by the aura. The artefacts are the tangible control to the aura's behaviour, and they have their own inputs, as well as the market tracking input, which also can trigger aura's behaviours. At last, the hand air gestures are a second away to control the auras around the collaborative workspace, by grabbing and releasing gestures.

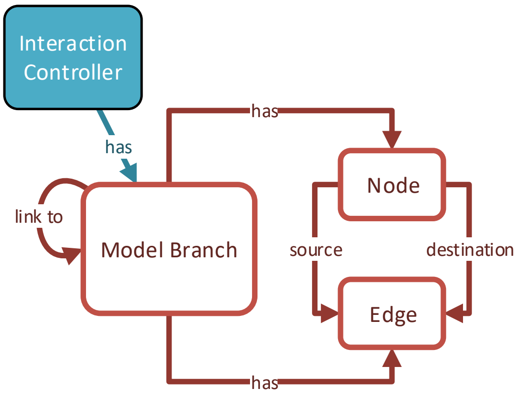
Figure 5.11 - Controller Main Elements.



SOURCE: from the author.

The models are a list of models' branches, instead of an all model accessible space, which is implemented in graph-based databases, doing this we simplified the Interaction Engine to handle only the nodes and edges, with the appropriated OPM representation meaning. (Figure 5.12)

Figure 5.12 - Graph Model Structure.



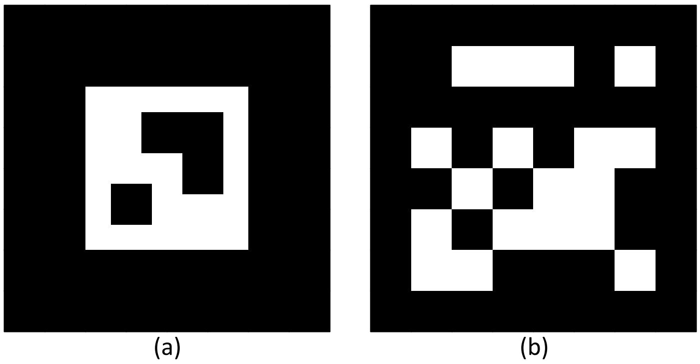
SOURCE: from the author.

This thesis TUI is using three feedback-loop inputs: (i)touch, (ii) movement and (iii) air gestures, and one output: Physical Feedback.

- Touch interactions are tracked through the artefact button physical interfaces, the data is sent directly through a Wi-Fi http request.
- The movement and air gesture are tracked using camera sensors. The video feed is processed by Computer Vision (CV) algorithms.

AR based environments main technology is the Pattern Matching artificial fiducial marker called ARToolKit (KATO; BILLINGHURST, 1999). As ARToolKit, other frameworks provide the tracking data to blend the realities searching for a known visual code. A different approach from ARToolKit is the ARToolKitPlus (WAGNER; SCHMALSTIEG, 2007). ARToolKitPlus differ from ARToolKit into the marker identification, as it uses a 36 bits ID instead of a pattern matching algorithm. This difference in one hand allows a better CV processing rate and in other hand, as the marker is a visual code, it does not provide a visual hint to the users of the marker functionality. Fig 5.13 shows the two (a) ARToolKit and (b) ARToolKitPlus Markers.

Figure 5.13 - Fiduncial Markers.



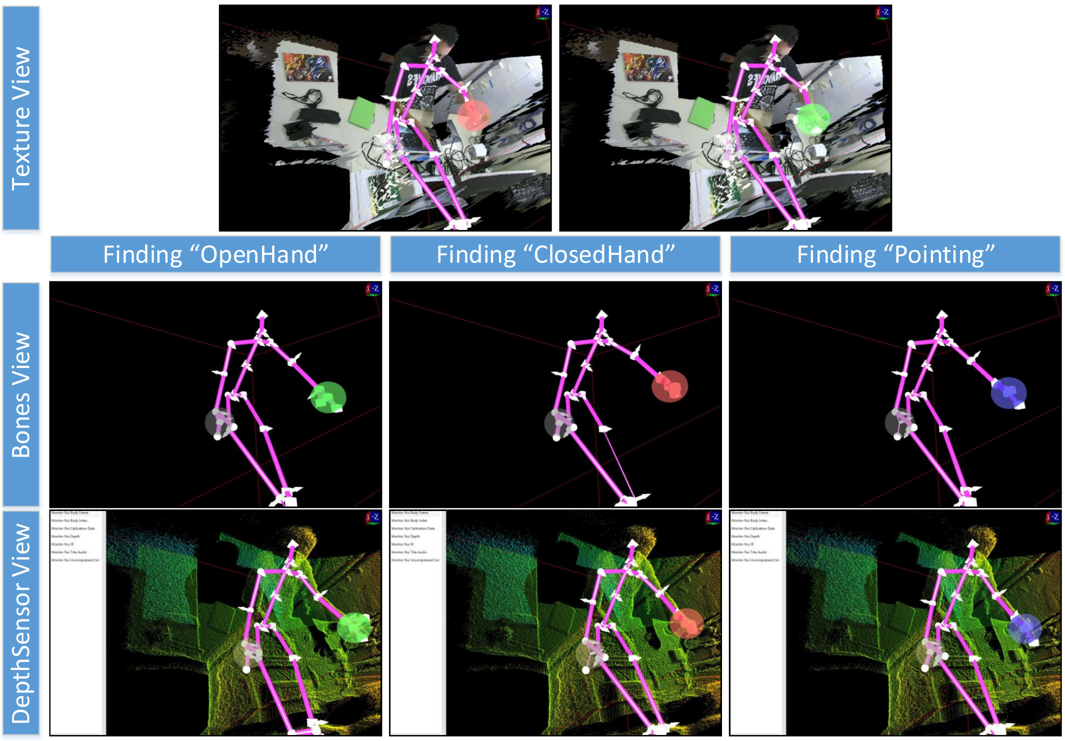
SOURCE: from the author.

The facility must track all the TUI artefacts positions to apply the behaviour to the: (i) movement, (ii) positioning, and (iii) artefact proximity. The marker on the artefact's top panel must be always visible to the camera to be tracked.

Air gestures are also tracked by CV algorithms that search hand-like patterns on the video feed. The hands are tracked, and their fingering combinations can be associated to a contextual command. Using depth cameras, as the Kinect.

The Kinect projects a cloud of regular spaced IR points, shown in the third row of Figure 5.14. The IR camera than process the visible points, scoring the points to their neighbour's spacing. Closer points mean that a surface is closer to the camera, far points means that a surface is far to the camera. Finding the skeleton structure, it then finds the hand and assign the gesture, as the second row of Figure 5.14. So, tracking those distances blobs, instead of picture CV processing, looking for hand-like patterns provide the capability to track a 3D hand air-gesture through known hand facing formats.

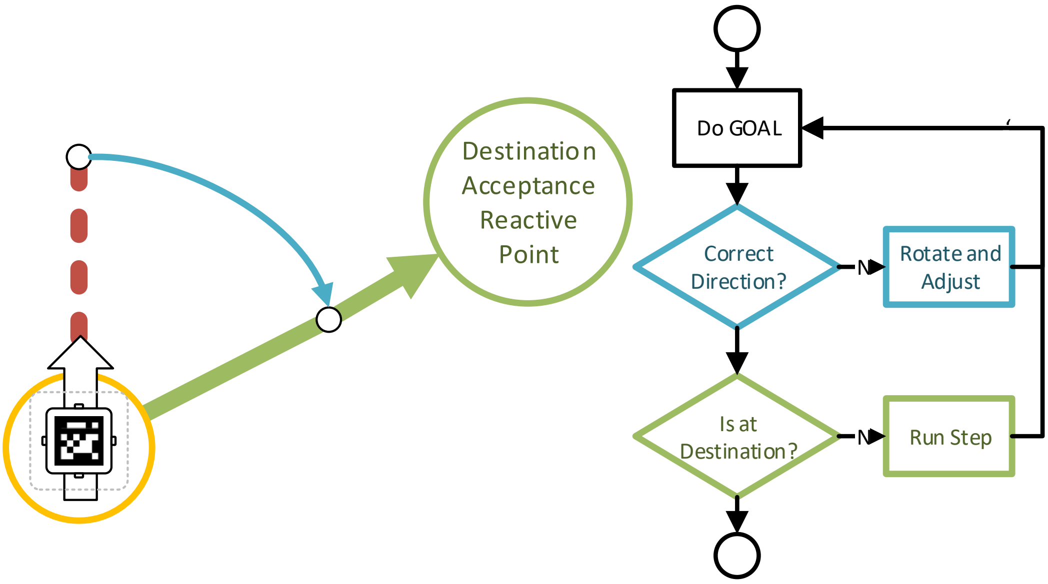
Figure 5.14 - Kinects output example.



SOURCE: from the author.

The last tangible representation, is due the third feedback-loop which is the facility making physical changes into the artefacts, which is represented by moving the artefacts. This by itself is a closed-loop control case, to manipulate and move the artefacts using the embedded wheels and the fiducial tracking. We did not implement a control law, instead we used a GOAL approach (GOC et al., 2016), illustrated in Figure 5.15.

Figure 5.15 - Artefact GOAL to control position.



SOURCE: from the author.

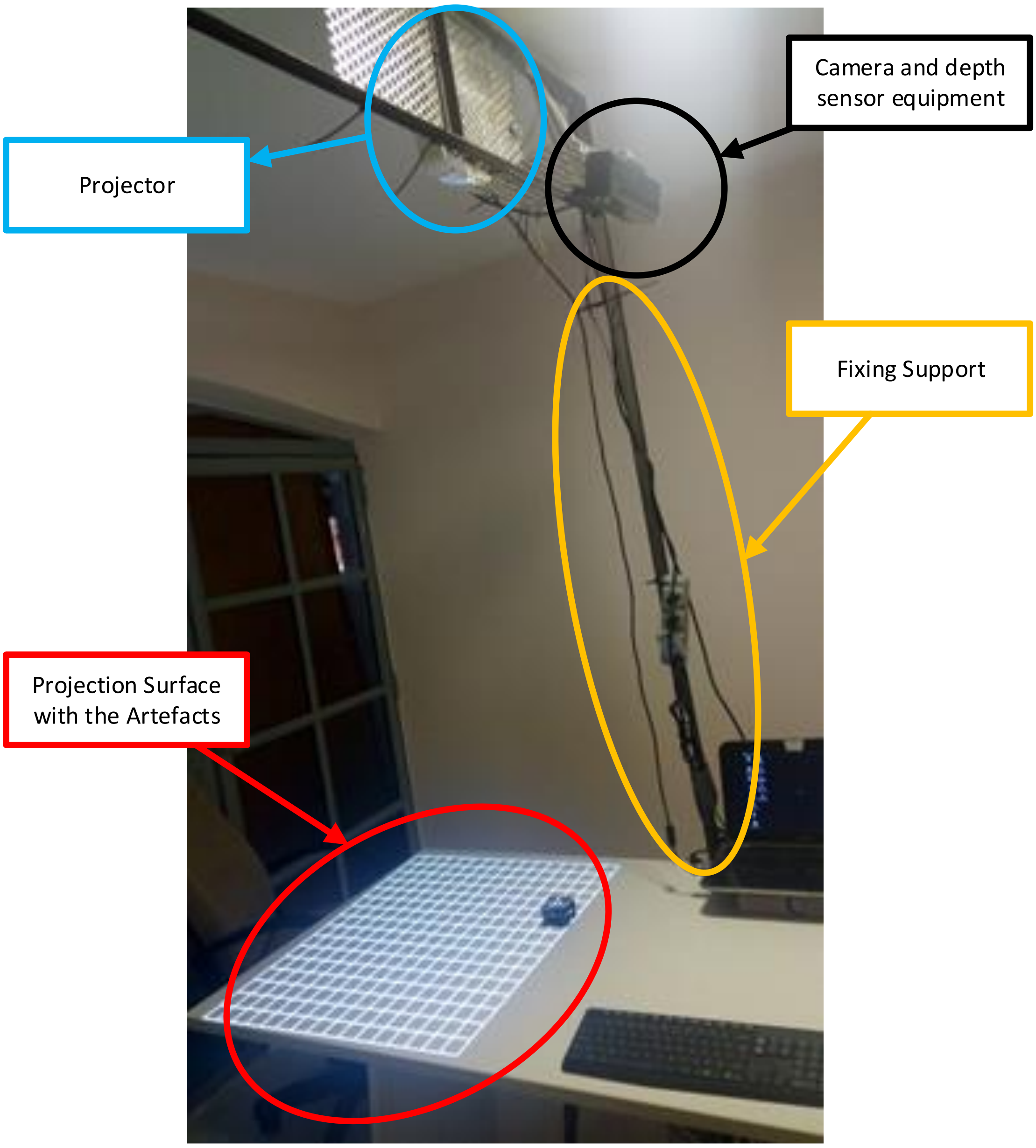
This Interaction Controller was implemented because of the chosen centralized intelligence and awareness CAF.

5.3 Proof of Viability

Regarding the viability proof to answer the driving question "Can **Tangible User Interfaces** be integrated to handle **models** in **CE Sessions**?", was designed a demonstration scenario to illustrate one of the described branches of the vocabulary.

To create the proof scenario, we placed the equipment as illustrated in Figure 5.16, pointing: (i) the camera and depth sensor equipment, (ii) the projector, (iii) the fixing support, and (iv) the projection surface with the artefacts.

Figure 5.16 - Proof of Concept Installation.



SOURCE: from the author.

The scenario chosen was the Big Picture Aura, as it is the consequence of all other uses of artefacts, where all models are coupled into a single final model branch - the baseline.

This demonstration only covered the vocabulary described to the Big Picture Aura, and not contains the other Auras, or mechanism to prevent/recover from failures. In this scenario we tested the way:

a) to explain a model,

b) to present and discuss a model,

c) to couple models, and

d) to show connected models.

Futhermore, it was conducted a usability questionnaire adapted from Kirner and Kirner (2013) and Martins et al. (2013) to meet the four heuristics defined by Germani et al. (2010).

The following subsections present the proof of concept demonstration and the questionnaire questions/answers.

5.3.1 Proof of Concept Demonstration

The scenario demonstration of the Big Picture aura was conducted with the aid of the setup described in the earlier subsections.

The way to explain a model:

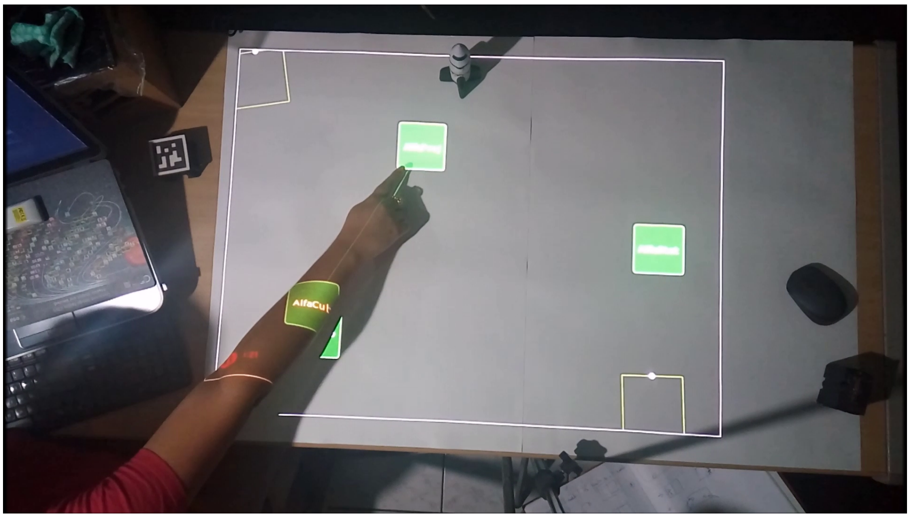
At session, the specialists to collaborate their models by presentations, where they show their system element model. Figure 5.17 exemplify a model presentation behaviour during CE Sessions. Document-centric and model-centric have the same approach to present into sessions: someone seated, or in upright position, explains his/her modelling environment to the other specialists.

Figure 5.17 - Explaining models during CE Sessions example.

SOURCE: from the author.

Using TUI the media is the same to all, the system elements in collaboration are represented by building blocks and controlled by the physical artefacts. The specialist points out into the surface the system element node that wants to collaborate and explains to the other specialists. Figure 5.18 exemplify the way to collaborate the model using TUI.

Figure 5.18 - TUI explanation example.



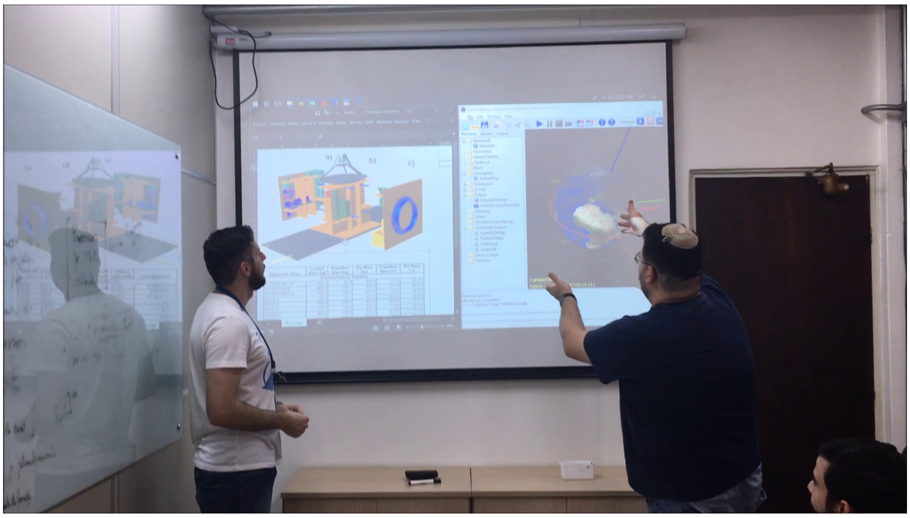
SOURCE: from the author.

Some users complained the lack of details to explain the model, as it is represented only by a projected box, however this scenario only covered the Big Picture Aura that is used to couple the models. The Big Picture Aura vocabulary does not expose of internal parameters.

The way to present and discuss a model:

During a CE Session, either specialists may: present their models seated, converge coupled disciplines, or exhibit both disciplines and discuss the interfaces and their decisions. Figure 5.19 exemplify this discussion.

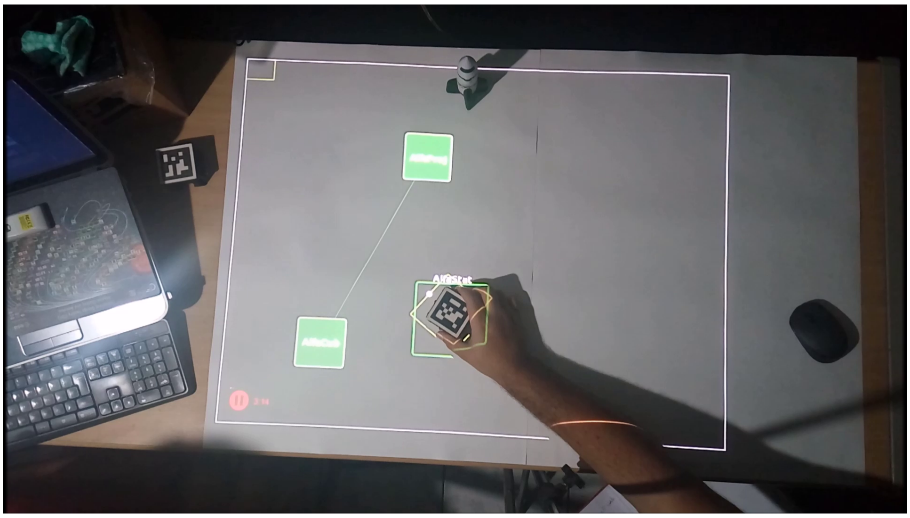
Figure 5.19 - Discussing models during CE Sessions example.



SOURCE: from the author.

Using TUI, specialists may move their models around the surface, to approximate their designs for discussions. All disciplines can be exhibited. Figure 5.20 exemplifies the possibility to move the model around the collaborative environment, according to the Big Picture Aura state the aura follows the artefact.

Figure 5.20 - Moving the model through the collaborative space to discuss.



SOURCE: from the author.

Some users complained the lack of details to explain, due the same problem of the earlier scenario tested.

The way to couple models:

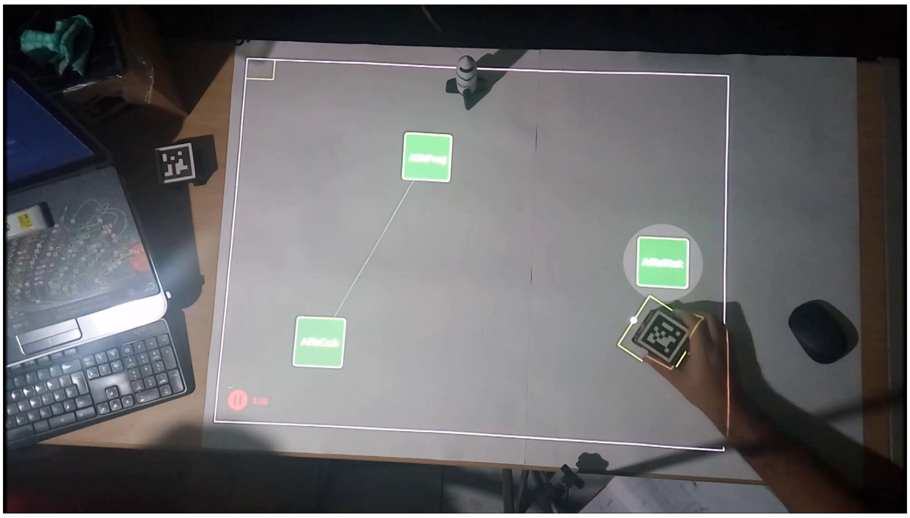
To couple models in CE sessions, the links must be previously done, connecting the worksheets or models interfaces. There is no coupling/uncoupling during the sessions. In this scenario, the only possibility is the specialists observe their interfaces into their specialist workspaces, as exemplified in Figure 5.21.

Figure 5.21 - Checking coupling interfaces into specialist workspaces.

SOURCE: from the author.

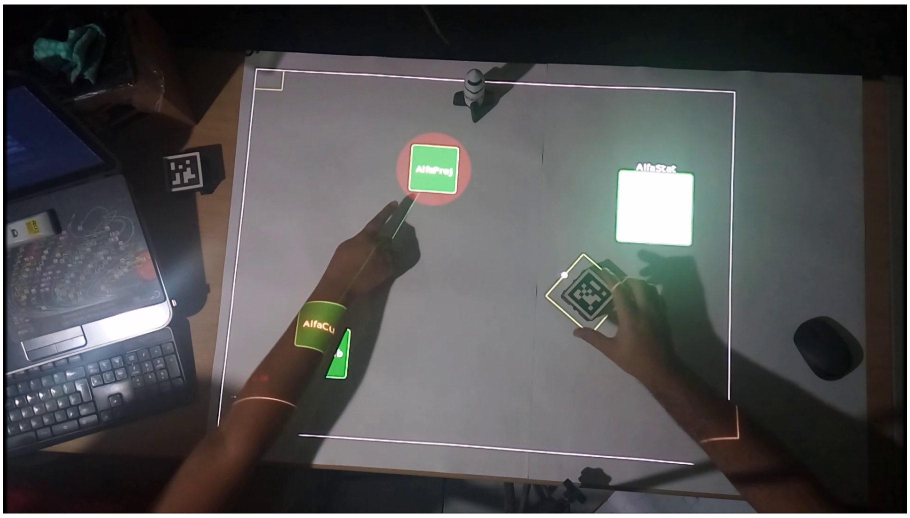
Using TUIs, and the model structure proposed by the **abstract view link**, the user can during sessions couple/uncouple the models to create the baseline model branch. Figure 5.22 exemplifies the user picking a model - a white circle indicates that the artefact is close to the model and able to pick, Figure 5.23 the user selecting the model to couple - a red circle indicates that the artefact is pointing towards its direction helping to visualize the model that will be coupled, and Figure 5.24 the models connected - a new line shows the new connection between the nodes.

Figure 5.22 - User picking a model.



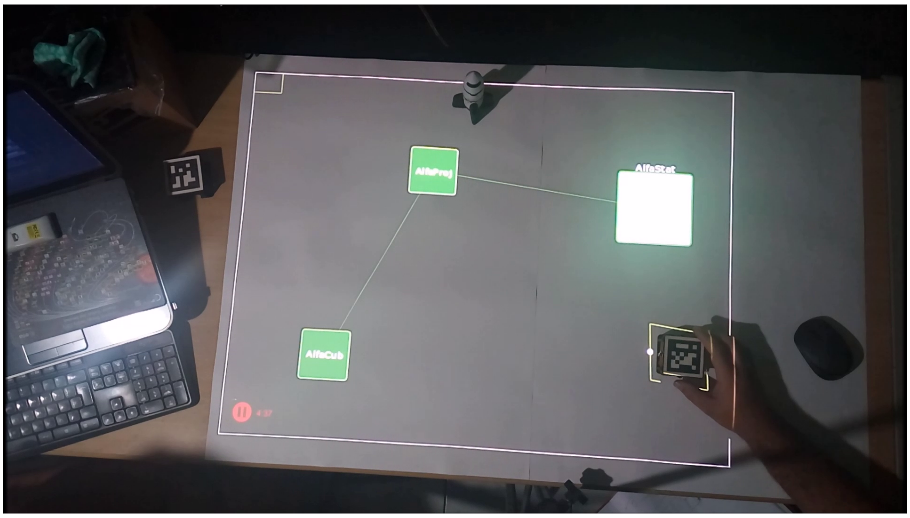
SOURCE: from the author.

Figure 5.23 - User selecting a model to couple.



SOURCE: from the author.

Figure 5.24 - Coupled models.



SOURCE: from the author.

The users described the easiness to couple/uncouple models with single steps. The users could reposition any model that the structure of the branch was redrawn.

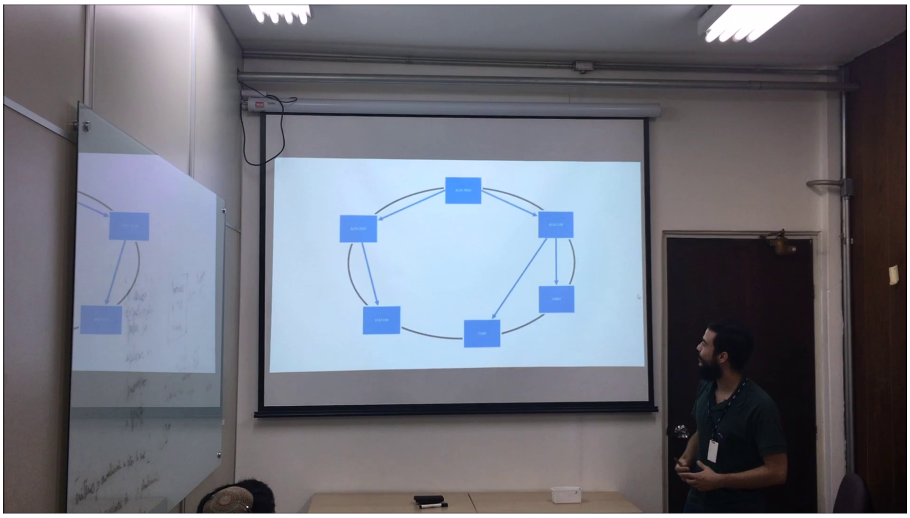
The way to show connected models:

The last scenario was the presentation of the connected models. In CE Sessions, the diagrammatic representation of the coupled models is done using scripts or 3rd party softwares. OPM allows to unfold into a tree view, but others did not have a specific re-drawer of the coupled models into specific arrangements. If a connection diagram is required, it must be done into the specialist workspace (Figure 5.25) in order to be explained into the collaborative workspace (Figure 5.26).

Figure 5.25 - Creating coupled diagrams.

SOURCE: from the author.

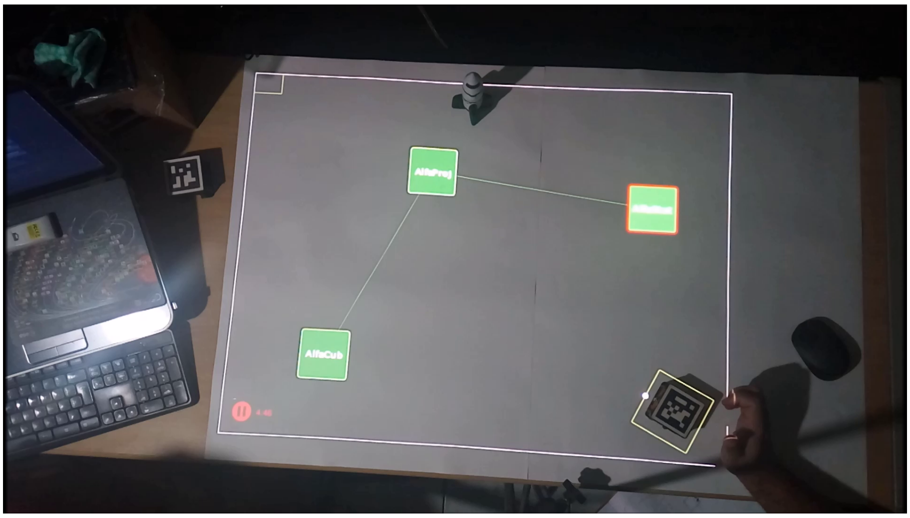
Figure 5.26 - Showing coupled diagrams.



SOURCE: from the author.

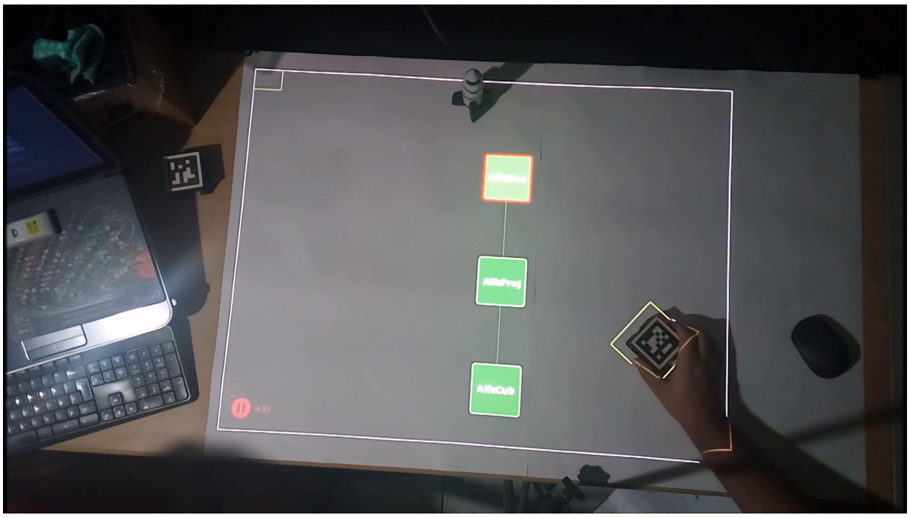
In this thesis, through the artefact that points to a model that hosts a Big Picture - with the red square around the aura, the user can re-arrange the auras displacement. Figure 5.27 exemplifies a free arrangement, Figure 5.28 a tree arrangement and Figure 5.29 a disc arrangement. The tree and disc are calculated in real time with the information of the abstract view link queries.

Figure 5.27 - Big Picture free aura arrangement.



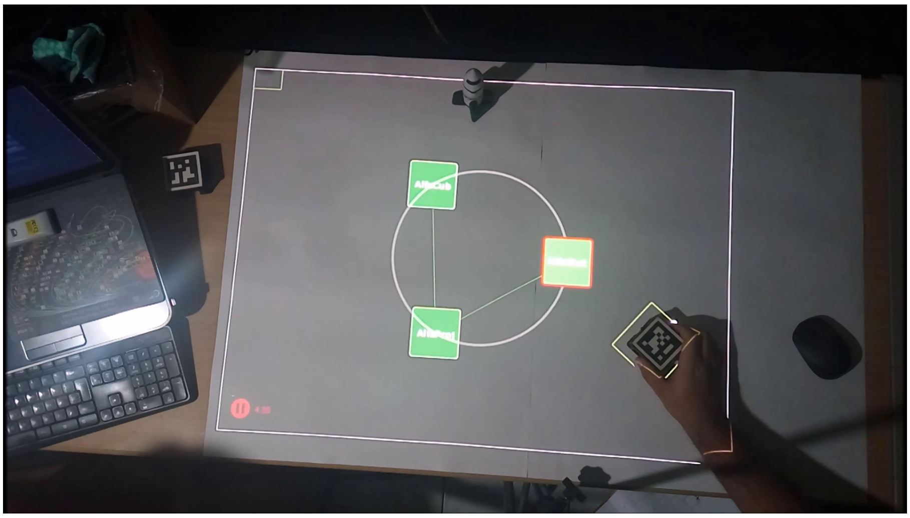
SOURCE: from the author.

Figure 5.28 - Big Picture tree aura arrangement.



SOURCE: from the author.

Figure 5.29 - Big Picture disc aura arrangement.



SOURCE: from the author.

The users described the interest of easily re-arrange the models to better visualize the interaction between models.

5.3.2 Usability Questionnaire

This subsection contains the questionnaire applied to user group formed by the alumni of the INPE's doctoring program, and a summary of the answers.

We asked one question related to each Germani et al. (2010) heuristics:

- **1. Teamwork**:
  - **1-1. Decision Making Process Stage**: How appropriated the user-interface represents the model?
  - **1-2. Design Content**: How the vocabulary represented the desired manipulations?
  - **1-3. Actor Skills**: How easy was to manipulate the model over the collaborative area?
- **2. Communication**:
  - **2-1. Interaction Style**: How does physical manipulation helped to point out information?
  - **2-2. Verbal Communication Style**: How does the vocabulary references the block-diagram metaphor used by tools?

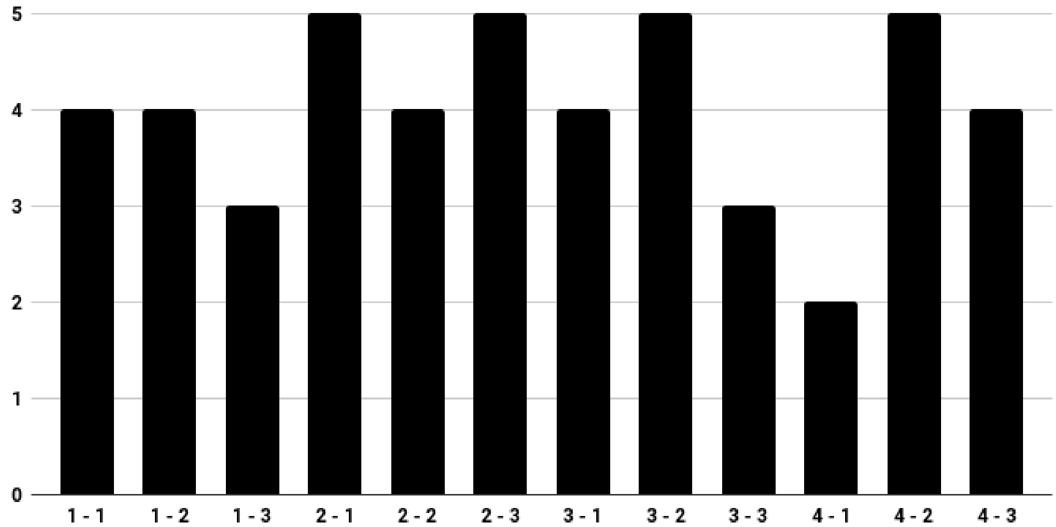
- **2-3. Nonverbal Communication Style**: How clear the positioning of the artefact reflects the meaning of the situation?

- **3. Human Involvement**:
  - **3-1. Mutual Engagement**: How clear was that the artefacts could couple the users' models?
  - **3-2. Collective Creativity**: How intuitive was to giving the global understanding of the scenario?
  - **3-3. Stimulate Integration**: How does the intangible representation allows to imagine and forecast the behaviour?

- **4. Cognitive Reaction**:
  - **4-1. Cognitive Reaction to Model**: How clear was the relocation of artefacts meanings?
  - **4-2. Cognitive Perception of Model**: How the use of physical artefacts improve the attention into the model relations?
  - **4-3. Cognitive Decision Making**: How does the use of physical artefacts enables to understanding a new solution?

The alumni group was formed by 13 students of the INPE's ETE course. All of the same age group (around 30s), both genres, with prior knowledge of System Engineering and Augmented Reality. The mean results are shown in the chart of Figure 5.30.

Figure 5.30 - Usability questionnaire mean answers chart.



SOURCE: from the author.

Note that question 4-1 score was low given the described lack of a better intangible representation aid to support the meaning of each type of relocation allowed and the fact that the scenario proposed only considered the Big Picture Aura that does not allow to exhibit the internal details; question 1-3 score was due the restricted area allowed by the test setup, and question 3-3 score was due the lack of more visual aids that could indicate the resulting behaviour of an interaction before it was finished.

6 EVALUATIONS AND FURTHER DISCUSSIONS ABOUT THE FUTURE WORKS OPPORTUNITIES

This Chapter presents the evaluation of the Tangible Collaboration applied into Space System Concurrent Engineering Concept Studies.

The evaluation was done via similarity analysis of the described TUI collaboration against the nowadays collaborations found on Concurrent Engineering literature, and via an argumentation towards this the raised questions presented in Chapter 1 towards the relevance of the presented approach. This Chapter also presents further discussions about the future work scenario within some opportunities to include other technologies to create a Hyper Reality workplace to Concurrent Engineering.

- **Section 6.1 - Evaluations**: contains the proposed evaluation intended to demonstrate the design relevance through two Design Science Evaluation methods;
- **Section 6.2 - Further Discussions about Future Works**: contains the future works opportunities found during this thesis elaboration towards the context of the Space 4.0 and creation of an Hyper Reality Concurrent Engineering Facility;

6.1 Evaluations

This section shows the quantitative evaluation description related to the Evaluation Criteria Propositions (in Section 1.4), which were the: **Analytical Architecture Analysis** and the **Descriptive Informed Argument**.

6.1.1 Analytical Architecture Analysis

The utility is demonstrated through a comparison with the CE Sessions collaboration interaction in both Document Centric Toolset (DCT) and Model Centric Toolset (MCT). These collaborations are described in Section 2.6.

To compare, Table 6.1 lists the same technical propositions regarding collaboration of the entities (Model, System Element and Parameter) and the macro interactions of the Collaborative Workspace, with the Tangible Collaboration Description

Table 6.1 - Tangible Collaborations fitted in the Collaborations of the Researched Environments.

Topic	Category	Tangible Collaboration
Collaborative Workspaces	**Style**	Collaboration in TUI, with a projection/artefact configuration.
	Big Picture	Through the Big Picture aura, that shows a tree or ellipsoidal structure.
	Detail Level	The detail is controlled through the number of opened Auras on the surface.
	Design Exploration	Only done by external 3rd party application.
	Design Selection	An option is a model branch with a set of coupled models. The decision implicates the coupling into a final model branch
	Sharing Conduct	Through the Share aura.
	Remote Design	The remote collaboration can be done, through a remote mirror of the workspace or using virtual reality goggles to create telepresence.
Model	**Send/Retrieve to Collaborative Workspace**	Use an artefact with Totem Aura, as a mirror of a select model into the specialist workspace.
	Manipulation **Visual Appearance**	Each artefact is a representation of a model entity. Coloured square projections.
	Navigation	The hierarchy is achievable by navigation through tree or ellipsoidal structures.
	Inspection	The model is inspected by showing on tree or ellipsoidal structure its inner System Elements.
	Coupling - Attaching / Detaching	Both must be at Big Picture Mode. The user must position the tractor into the direction of the desired point to insert.
	Explicit handle System Elements	The Share and Knowledge Modes, directly handle System Elements.
System Element	**Manipulation**	Tangible manipulated by the artefacts movements.

(Continue)

Table 6.1 - Continuation

Topic	Category	Tangible Collaboration
	Interface Inspection	In Knowledge mode, the aura shows the interface of the system elements.
	Explicit Structure	Seen in tree or ellipsoidal structure.
	Behaviour	The behaviours are described into the models, and only seen into the specialist workspace.
	Explicit handle Parameters	The Knowledge Aura explicitly shows the Parameters and allows to be picked by an artefact.
Parameter	**Visual Appearance**	Coloured square projections.
	Navigation	If attached to the Knowledge Aura, the parameters are navigated by positioning the artefact over the aura. If not attached it needs to be attached through an ellipsoidal structure.

Fitting the Tangible Collaborations, we aimed show that the technical prepositions to promote collaboration can be done within physical artefacts. This analysis shows the relevance as it can represent the same activities within a novel user interface.

6.1.2 Descriptive Informed Argument

To argue the relevance we use as a convincing argument the fulfilment of the thesis's driving questions. To answer the questions we used the theories from knowledge base and the Build & Design of this thesis.

In orde to evaluate the fitness of proposal of the TUI in CE Sessions, the following subsection addresses the questions 1 to 3 and finishes with the main question.

Question 1 - How does the team of a CE Session manipulate models?

Through a research regarding how the information is exchanged during CE Sessions, the collaborations, and the modelling approach, we found a set of common characteristics regarding the collaboration formalism, the specialized language of the exchanged model, how the model is interpreted by a computational infrastructure, how occur the collaboration and how the models are stored. Based on these characteristics we were able to propose four broad types of models which are handled differently:

- **The Free Models**: are free representations into whiteboards, mock-ups, so on.
- **The Loose Models**: are representation in formulas, or filtered database forms. (as Excel)
- **The Context Specific Models**: are representations in Domain Specific Tools. (as AutoCAD)
- **The Context Independent Models**: are representations in Abstract Modelling Tools. (as Visual Paradigm)

With this CE Models in Collaboration Taxonomy, as far as we known, can describe all models used in CE Sessions Collaborations. We can also fit the proposed Tangible Collaboration, within a balanced approach. The artefacts have the free aesthetics and behaviours as the drawings in boards, within a model (loose, context specific or context independent) being tracked. In Section 4.5.1 we presented the natural interactions that impact in the models. Extending to Domain Specific Vocabularies, would also allow the TUIs to represent Context Specific models. In space applications we could move artefacts to change simulation parameters that could reflect, as instance, in a projected orbit simulation.

Question 2 - How adapted are the current tools to collaborate during a CE Session?

The current practice in model formalization to collaborates in CE are based in document-centric tools, like the Office Productivity Tools as the Microsoft Office (Excel and Power Point applications). Despite the MBSE *"differentiationism"* attempts, such tools follows a model-based approach, as any Engineering activities does. The point is that the model meanings (what the model describes to the CE Sessions) are loosely tied into the documents - as the documents does not use ontology strategies or create atomic building blocks that encapsulate data and meanings. Regarding the coupling of the information among models, they are through the information exchanges (see Section 2.4, but what ties the big picture of the concept solution during the collaborations are the specialists mental models.

These Document Centric Tools, as the main tooling, have been adapted with third party functionalities, to create integrated tools. After several iterations of accumulated use practice, the CE teams created their discipline's sheet templates and integrated tools through the IDM (Integrated Design Model). Even without automations of Model Centric Tools, they are still resourceful.

As a second wave, CE teams started to research MBSE initiatives to use explicit modelling provided by model-based methodologies (which has a process, a method and a tool). Two methodologies to Phase 0/A are gaining momentum: (i) the Arcadia Methodology - to architecture design and (ii) the Object-Process Methodology - to concept design, which turned into an ISO standard [1]. Both can be adjusted to CE. However, they miss the collaborative aspects that the document-centric already evolved, on both the products and the use processes.

Despite the encouraging benefits to use MBSE, it is arguable if it is justifiable the effort to create localized solutions that create models to a given context not interconnecting them in the entire life-cycle, without the expectation to be incrementally used and coupled through the life cycle. (CARROLL; MALINS, 2016)

This question research showed that DCTs are better prepared to collaboration than MCTs. However, it is easier to implement TUI with a MCT, as the information is modelled with a certain rigor of the model formality. Using OPM to guide the MBSE approach is shown even more appropriated, as it has a directly graph relation, allowing to create algorithms to match template structures that are manipulated in the TUIs.

Question 3 - How does the collaboration among the members occur during a CE Session?

This questions refers to the human actions among the team. In Section 2.6 we reviews all collaborations regarding the entities that are exchanged into the Facilities.

CE dimensions are all integrated and the collaboration is the reflex mainly of the team, as stated by (BRAUKHANE; BIELER, 2014). The other dimensions also influences the collaborations as: the facility layout, which drives a more centralized or paralleled cooperation; the modelling approach, which drives the collaboration vocabulary of the symbols that will be used and the medium of the information exchange, which defines where the information has to be placed to computationally tie the all model.

[1] https://www.iso.org/standard/62274.html

The facilities research showed the two extremes related to the ways the collaboration happens, where at one side the collaborations are very formal through an orchestration and at the other side the collaborations are informal through clustered discussions (described in Section 4.1.2. This formality classification was done using the Germani et al. (2010) collaboration heuristics, which includes: teamwork, communication, human involvement and cognitive reactions.

Using the same heuristics, we evaluated qualitatively what the artefacts comply with the metrics described by Germani et al. (2010). Table 6.2 contains the Collaborative Heuristic analysis of the collaboration through artefacts.

Table 6.2 - Collaborative Heuristics to the Tangible Collaboration.

Collaboration Heuristic	**Through artefacts**
Teamwork	Majority through solving the artefact positioning, describing technical features adopting the same metaphor od the domain (building blocks).
Communication	Communication by physically interacting with the model, with a referential language (talking at, pointing, touching) towards highly gesture-marked communication.
Human Involvement	The engagement is spatial assigned (shared objects), mostly for reflecting and reinforcing an idea, extracting features from models and talk about them.
Cognitive Reaction	The actions happen during model elements, with the attention to model, its relations and their locations, to elaboration of a solution arrangement.

The formality classification research showed the collaboration formats the specialists use. With TUI we tired to balance informal whiteboard drawing discussions with the formal orchestrated computer assisted parameter changing. Move the artefacts and the projection is cognitively similar to a drawing, when the aura moving is like erasing the ink and drawing somewhere else. This still keeps the formality of the parameter tracking.

Can Tangible User Interfaces be integrated to handle models in CE Sessions?

The answer to the main question was discussed in Chapter 4, which described a

Computer Aided Facility with Tangible Artefacts. Through the Chapter was conceptualized a general purposed cognitive artefact enhanced with an augmented reality layer (the Aura), with bidirectional communication through the virtual and physical worlds implemented through artefact's sensors and actuators. As a Proof of Concept, it was showed that it is possible and feasible to integrate TUI into CE Sessions.

Physical artefacts are intrinsically collaborative and improve the appropriation of ownership and responsibility when compared to any virtual representation on a GUI, or other purely virtual user interfaces. With artefacts we can touch a thing, not a bit (at least not yet) - which may change one day as presented by the Radical Atoms Concept (ISHII et al., 2012).

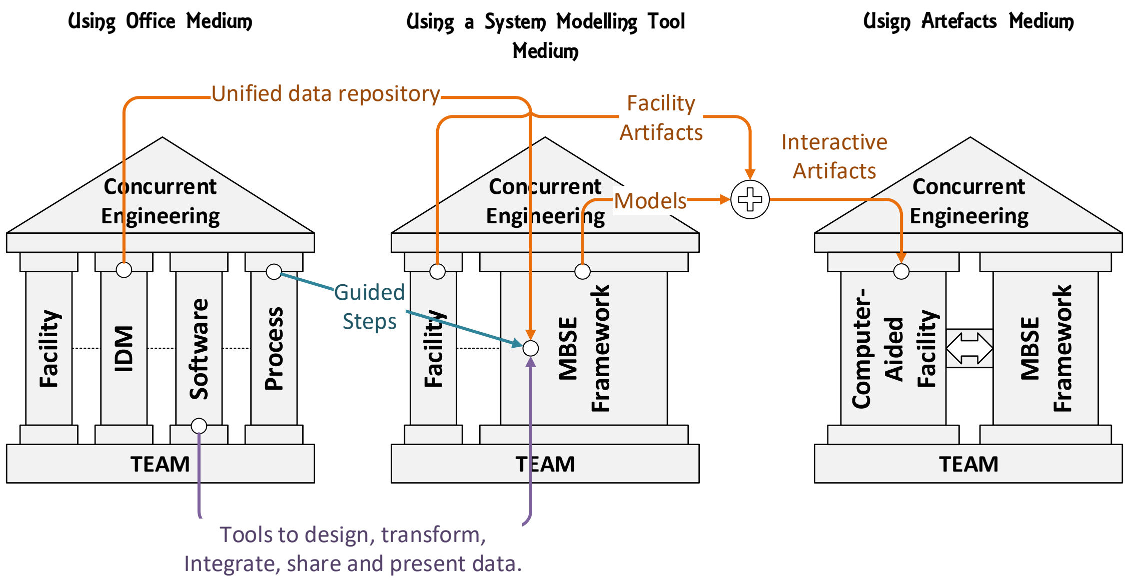
Nevertheless, it is important to attempt to the myriad of elements that can compose a TUI artefact. To this issue we proposed a taxonomy of TUI elements, which support the Rigor Cycle Feedback of the Design Science Research. The taxonomy is in Appendix D.

Despite of the multidisciplinary technological difficulties (metaphor design, vocabulary creating, data-base, pattern recognition algorithms, computer vision, embedded software, mechanical design, interaction handing) in creating a TUI collaboration, physical artefacts can balance the model manipulations, placing a compromise approach from context independent to free, from DCT to MCT, and from formal to informal.

Concerning the integration of technologies itself, this thesis showed that it is possible to integrate TUI into CE sessions, but it is not the only driver to an implementation use. The use of TUI artefacts requires a well-established MBSE approach in the phase before the TUI artefacts can be implemented. As the artefact handle information that are computer interpretable and researchable.

So, we observed that the original Concurrent Engineering which uses the Office Tools as a medium to collaborate (Figure 6.1(a)), are changing to a System Modelling Tool medium. The MBSE methodologies, as OPM (with the OPCat Tool) or Arcadia (with the Capella tool), are two possible approaches to implement this medium. MBSE methodologies integrates into the MBSE Framework: (i) the way to integrate the models and tools (rather than through the IDM), (ii) the modelling software tools and (iii) the embedded process of the methodology. Figure 6.1(b) shows the CE using a System Modelling Tool medium, and we can note the unbalanced pillars,

Figure 6.1 - Gradual steps to use Artefact Medium to collaboration.



SOURCE: from the author.

with a bigger MBSE Framework and a smaller Facility. This thesis aimed to show the feasibility of reintroducing connected physical artefacts into the CE Sessions, to manipulate the models during collaboration, balancing the pillars with the use of a Computer-Aided Facility (rather than a purely virtual Computer-Aided Design tool), as illustrated in Figure 6.1(c).

6.2 Further Discussions about Future Works

This section describes the opportunities discovered through this thesis development with further details. These opportunities are Industry 4.0 related issues that can be used in Concurrent Engineering Facilities to create a connected user-experience tooling.

This section describes and points out the intersection of technologies for the future works, giving further details about the following topics:

- **TUI Authoring Tool**: this subsection describes the need of a TUI authoring tool that has all dimensions to create the artefacts;
- **Artificial Intelligence**: this subsection describes the uses of artificial intelligence to aid solution making and design space explorations that could help the CE Sessions as well as the artefact creation;
- **Modelling and Simulation**: this subsection describes the use of artefacts

through the life cycle tied with the use of modelling and simulation;

- **Multiple Levels and Personalized Views**: this subsection describes a collaborative approach that adds personalized data layer to the team using Augmented Reality Glasses;

- **Horizontal and Vertical Integration through MBSE**: this subsection describes how MBSE can integrate the life cycle horizontally (through phases) and vertically (though domains);

- **Industry 4.0 and Space 4.0**: this subsection describes the scenario of the integration of prior subsection concepts into Industry and the Space Field;

- **Hyper Reality in Space Systems Concurrent Engineering Concept Studies**: this subsection describes a futuristic view of the possible impacts of this thesis and prior sections in the Concurrent Engineering activities.

6.2.1 TUI Authoring Tool

This thesis described an ad-hoc process from collecting the data to creation of the TUI vocabulary, as an authoring tool to the Space Systems Concept Studies domain context. But, how to change the TUI context, even though using the same artefacts/facility? We would have to re-write all software: control, tangible representation feedback, model, and intangible representation feedback. And, how to update the artefact with one more modality? We would have to recreate the artefact physically, and all software.

TUIs need an authoring tool to its own, to deal with all dimensions of design required to create the artefacts and its interactions, as the ones used in this thesis:

- User Tracking: track hands, head and other body parts that can interact with gestures and proximities.

- Structure and Mechanisms: artefact parts, fitting and moving parts.

- Feedbacks: tangible and intangible user feedbacks

- Actions: Input stimulus to the control layer of the user interface

- Interaction with the Data Model: different data searches and manipulations of the data sources
- Electronics: The active computational elements to interconnect artefacts, facilities, so on.
- Embedded Software: the different software functionalities that need to be considered
- Facility Communication: in case of using active facilities, the facility need to communicate and track artefacts / users, to create interactions
- Artefact Tracking: the artefacts position and orientation
- Other Connected/Unconnected Tracking: tracking the other elements of the environment that can interact with the use.

There is no tool nowadays available that consider all those dimensions together. A possible direction is to use Model Driven Engineering, Multidisciplinary Optimizations and Design Languages to aid the development of TUIs.

The tooling must provide a meta language that needs to be specialized into the desired domains, including all needed aspects of authoring the design language itself. A vocabulary will allow engineers to author their products from a framework of pre-designed possibilities, describing the data to the level that it requires, and using model automations, what will allow to pass from a global / systemic design, to a local / specialized design.

6.2.2 Artificial Intelligence

Artificial Intelligence (AI) started in 1950 as a Research Theory, and since them engineering has been using it, as with: Perceptron, Clustering Algorithms, Decision Trees, or Rule Based Systems (Expert Systems). In the 80's the Machine Learning started to be used for prediction, analytics, and data mining, using: Backpropagation algorithms, Neural Networks, and later Deep Learning. (WHITBY, 2008)

The Narrative Science Report (NATIONAL BUSINESS RESEARCH INSTITUTE, 2017) catalogued the main research trends in Artificial Intelligence, highlighting: Deep Learning, Evidence Based, Machine Learning, Prescriptive Analytics, Natural Languages, Text Mining, Predictive Analytics, and Recommendations. The report states four market trends:

- AI adoption is eminent, despite marketplace confusion.
- Predictive analytics is dominating the Enterprise
- The shortage of data science talent continues to affect organizations
- Companies that generate the most value from their technology investments make innovation priority

Space Systems Concept Studies strongly benefits of AI techniques, as data mining and evidence research, to design recommendations (CUCO et al., 2011). With the Knowledge Base constructed through the CE Facilities Studies, "intelligent assistants" are a field of research which can help to optimize and recommend suggestion from a text/graph mined set of requirements. Including TUIs also in the all Concept Study, as TUIs are abstract handling tools, it requires more intelligent data handling that automatically do the repetitive data manipulation and suggestions work.

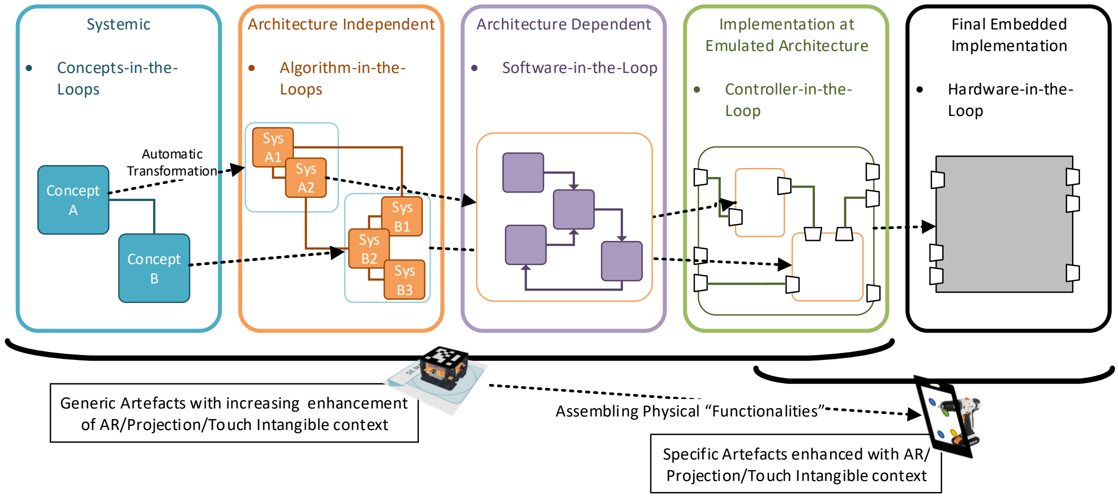
6.2.3 Modelling and Simulation

The rapid development of complex systems requires manipulation of multidisciplinary pre-existing data obtained from a Knowledge Base. All necessary engineering data must be computation understandable and correctly tagged with ontologies.

The global or systemic representations in a more abstract engineering, as Systems Engineering, will substantially be benefited with TUIs as physical artefacts are more abstracts allowing to use a generic group of symbols that encapsulates the broad behaviours that will be specialized in later automatic transformation processes. This approach is subject of Model Driven Engineering studies and related domains.

The systemic modelling deals in a level higher than an architecture independent approach, with broad (and able to be refined and specialized) components. The systemic vocabulary does not specify the final engineering symbol of the disciplines or context, allowing more multi-purpose generic TUI artefacts. So, the TUI can manipulate the systemic data model, which can be successively transformed. In space engineering field, the transformation of the systemic data model usually go into: (i) architecture independent model where high-level functions will be specialized into a specialized domain vocabulary, (ii) architecture dependent model where functions will be implemented to address the specificities of the architecture with visual programming languages to design and test behaviours, (iii) emulated architecture where the implementation is tested into an emulated environment that mimics all real behaviours, and finally (iv) the final embedded implementation where both hardware and software are, respectively, constructed and deployed into the final solution (EICKHOFF; ROESER, 2009). This process is exemplified in Figure 6.2, which also illustrates the software and hardware implementation into the process, taking into account the types of simulations (Concept in the Loop, Algorithm in the Loop, Software in the Loop, Controller in the Loop, or Hardware in the Loop) and the main design entities that can be handled.

Figure 6.2 - Artefacts and what it handles regarding model and simulation through the life-cycle under V&V.



SOURCE: from the author.

It is worth noting that with purely virtual artefacts, where the specialist manipulate only virtual elements can also manipulate the engineering data. Using TUI the interaction tends to be more constructive and abstract, and the intangible representations (projections and through AR Glasses) layers add the explicit meaning of the interactions.

Nevertheless, such abstract approaches are converging into a common language in the System Engineering research field, more specifically, in Model Based System Engineering (MBSE). Systemic modelling methodologies can become a common core to a global engineering, and create a common data model and a common message exchanging through its interfaces are topics under research in the MBSE context. A common language and methodology for systems representation could lead to standards that could be used into TUIs as well.

The local or specialized simulation level requires specific tools, with specific meaning building blocks associated with the context language. Different contents create difficulties to represent the model parts in artefacts using TUIs. It requires research of the use domain to find the nature of the information that can be handled.

6.2.4 Multiple Levels and Personalized Views

A collaborative environment provides a shared view of the data where every person interacts over the same artefact and the intangible representations (auras). Though the information can be expanded, specialists could desire to see specific additional data from the exposed artefact auras. An approach to implement this is adding Augmented Reality Glasses to personify a layer of data. So, beyond the intangible/tangible representation level, the environment could add other levels that are specific to a discipline, as: cost, programmatic, thermic, power consumption (to power balance), weight (to structure), so on.

Into the Enterprise Sector, pushed by Industry 4.0, AR Glasses are providing help into the factory plants, some examples currently available are: Artheer[2], Google Glass[3], Lenovo[4], Microsoft Hololens[5], Meta 2[6], and Magic Leap[7]. (Figure 6.3)

Figure 6.3 - Examples of AR Headsets.

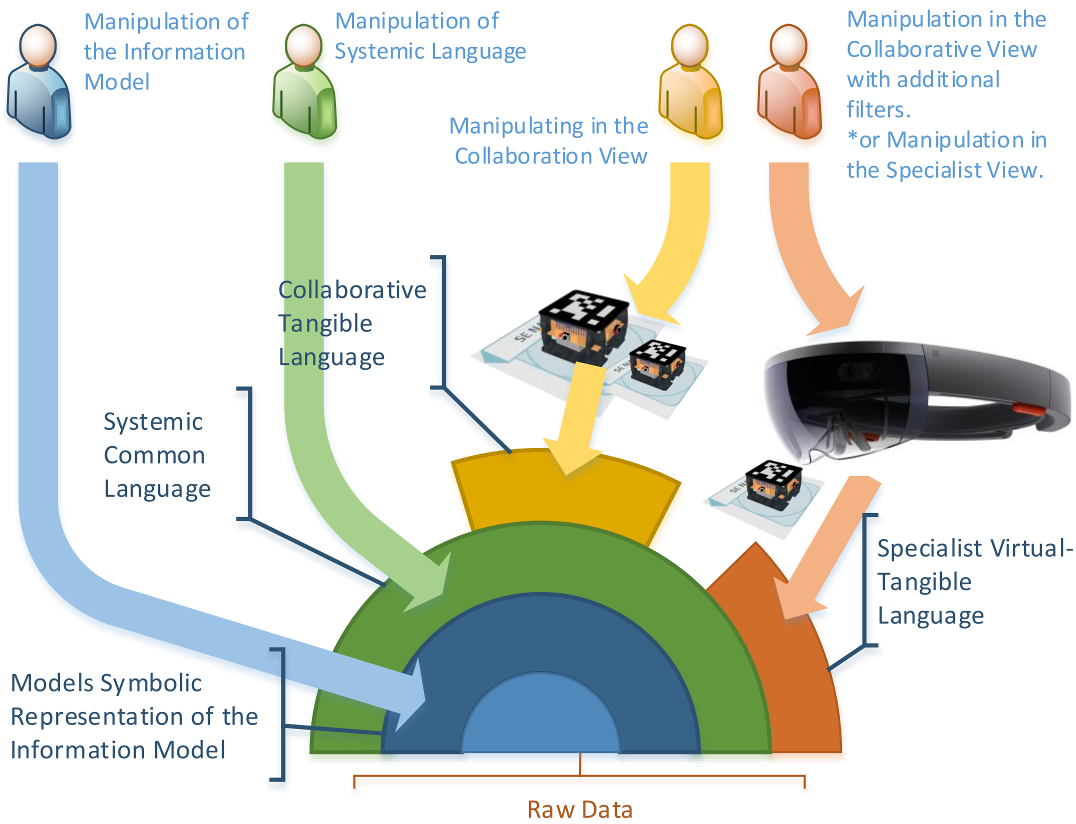
SOURCE: from the author.

The personal glasses add specialized content filters, adapted to the interest of the

[2]http://atheerair.com/air-experience/
[3]https://www.x.company/glass/
[4]http://www.lenovo-ar.com/ces/html/index.html
[5]https://www.microsoft.com/en-us/hololens
[6]http://www.metavision.com/
[7] https://www.magicleap.com/

discipline, showing only the specific information to the specialist. Figure 6.4 exemplifies where we can manipulate directly the raw data into the Information Model representation, through a Systemic Common language, through the Collaborative Tangible Language or via the Intangible Holograms through a virtual-tangible language.

Figure 6.4 - Example of possible languages to manipulate Concurrent Engineering data, with the inclusion of the AR Glass.

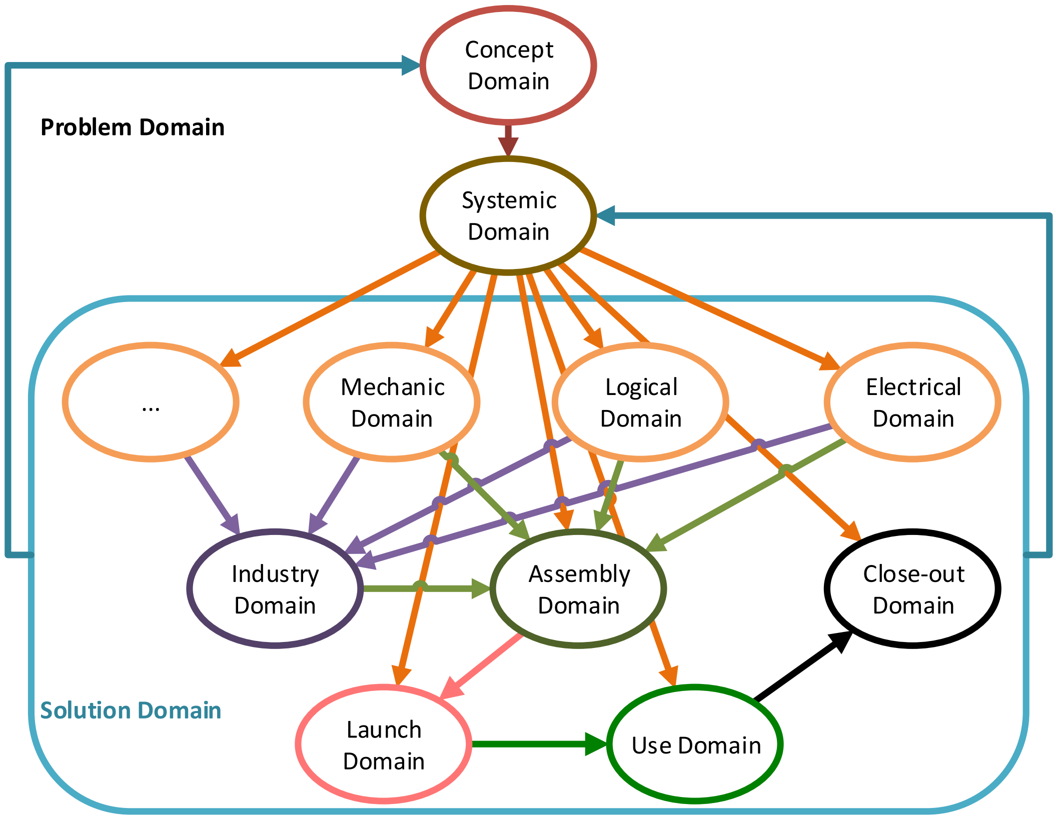


SOURCE: from the author.

6.2.5 Horizontal and Vertical Integration through MBSE

Concerning the challenges in MBSE issues, in our research we concluded that the institute / company / industry interested in MBSE must apply modelling through all domains and activities of the life cycle, integrating the Systems through the Chain of Design, Production, Integration and Operation (CARROLL; MALINS, 2016). Starting from the Concept Domain to the Close-Out Domain, every information should be connected and tracked through Model Driven Engineering. In this approach, the integration of models defines a computational baseline structure across the full life-cycle, across all domains (disciplines), across all the tools, and all the personnel involved. This integration improves the reuse, so the body of knowledge accumulated of the decomposition phases (Mechanic, Logical, Electrical, ...) and the realization phases (Industry, Assembly, Lauch, Use, Close-Out) feedbacks into new decisions in future works, as well as, re-evaluations, verifications and validations during a project life-cycle, as illustrated in Figure 6.5.

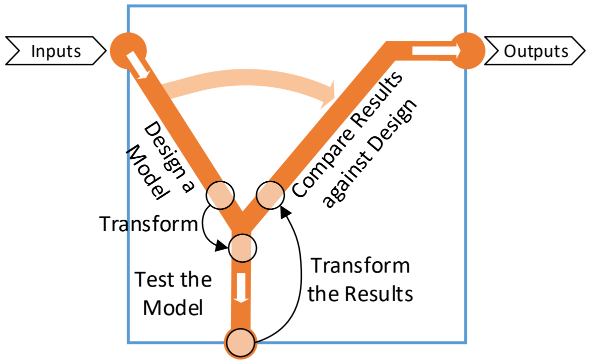
Figure 6.5 - Interconnected Life-Cycle Domains.



SOURCE: from the author.

It is valid to point that each domain repeats a a set of common activities, including: (i) receiving data, (ii) designing a solution model - assisted by a CAD tool, (iii) transform to a given test environment, (iv) perform the testing, (v) transform the results to the evaluation environment/visualization, (vi) perform the comparison of the results against the solution design, and (vii) retrieving data into to next domains. In essence is similar to what Norman (2013) proposes in his interaction cycle. (Figure 6.6)

Figure 6.6 - Common activities.



SOURCE: from the author.

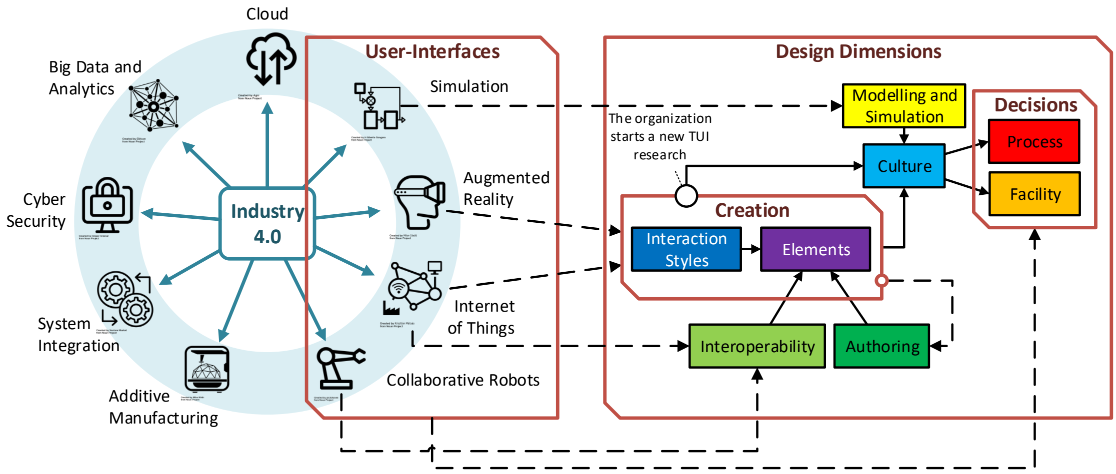
6.2.6 Industry 4.0 and Space 4.0

The foreseen Industry 4.0 is driving a transformation in Industry and Engineering, considering an intensive use of Information Technologies to provide a more connected bus of services which collaborates to provide better understanding and control of plant and design processes. The Space Segment Industry is also on the way to prepare itself to Industry 4.0 in a program called Space 4.0.

Industry 4.0 is organized into the following building blocks (GILCHRIST, 2016): (i) Cloud, (ii) Big Data and Analytics, (iii) Cyber Security, (iv) System Integration, (v) Additive Manufacturing, (vi) Collaborative Robots, (vii) Internet of Things (IoT), (viii) Augmented Reality (AR) and (ix) Simulation. (shown on the left side of Figure 6.7)

Collaborative Robots, IoT, AR and Simulation are the Industry 4.0 building blocks that impact on designing user interfaces (Highlighted into Figure 6.7). The others are more related to back-end infrastructures to provide the data and integrations.

Figure 6.7 - Industry 4.0 Building Blocks and TUI Design Dimension Issues.



SOURCE: from the author.

Industry 4.0 elicited Augmented Reality and IoT as interaction elements, the former to interact with the digital layers while the latter to handle intangible representation found on the tools or in the machinery. Both, as well as other alternatives, define the **interaction style** of the user interfaces. The understanding of the styles is important to design a TUI, to check if TUI is appropriate to the business domain, and later to identify and filter the **interface elements** that compound the user interface concerning its maturity and availability.

Despite the final inspection and the routine operation in the Industry plant, which constraints the tools to a given set of possible actions, a key element of a user-interface success is its capacity to create and handle content. This capacity is named **Authoring**, which allows engineers to create engineered solutions. TUIs deal with both virtual and physical representations, demanding studies of the business and the representativeness of the models into natural direct meanings. Dealing with TUI in Industry 4.0, requires distribution of intelligence through the things, collaborative robots (Cobots), and IT infrastructure. All must **interoperate** via a common language. Only through a connected bus those elements will provide information to big data analytics that will drive via Artificial Intelligence the performance improvements.

The implementation of TUI in the organization's tools depends on the **cultural aspects** involved and refers to a well-established **modelling and simulation** toolset. The toolset contains metaphor and strategies that already had settled the data into models and allows breaking down data into components, to manipulate through the

TUI artefacts (things). It should also be considered what and how the organization is prepared to change from an established engineering life-cycle **process** and make affordable **facility changes** to host a different user interface to the engineering tools, before taking a decision on adopting TUIs.

All the words in bold of the previous paragraphs indicate the design issue dimensions, which are illustrated in right-sided boxes of Figure 6.7. In this Figure, the black arrows indicate the dependency relationship among the dimensions and the dashed arrows map the building blocks elements from Industry 4.0 for the user interfaces design dimensions. We used keywords characterizing the dimensions to organize the groups of design issues.

6.2.7 Hyper Reality in Space Systems Concurrent Engineering Concept Studies

Integrating the artefacts facilities, with a easy tool to create their contexts, empowering them with connection capabilities and some level of intelligence, to manipulate the CE team modelling necessities with novel user interfaces leads to open researches for virtual - real artefacts and virtual avatars - specialists collaboration. This scenario leads to a Hyper Reality style of user interfaces (described in Section 3.1).

Foreseeing the next steps in facility-software integration, the future works on CE environments considering mode interactions possibilities, where the specialists interact with intelligent artefacts of the design facility, communicating with the models, virtual artefacts representing support applications, and other virtual collaboration avatars, which will automatize searches, optimize answers, and automatically transform data.

In this thesis we explored only the artefacts building aspect of this roadmap. Virtual artefacts and virtual avatars to support tasks are becoming reality as the increasing use of virtual assistants, as: the Google Assistant[8], Apple Siri[9], Microsoft Cortana[10] and the Amazon Alexa[11] . In this context, CE being fully equipped with interconnected model centric tools (both real and virtual) allows the specialist team and a virtual team of avatars to collaborate. Figure 1.3 indicates the transformations of the collaboration environments from the Office medium, to the System Modelling medium that uses the own Modelling tools to collaborate and to the externaliza-

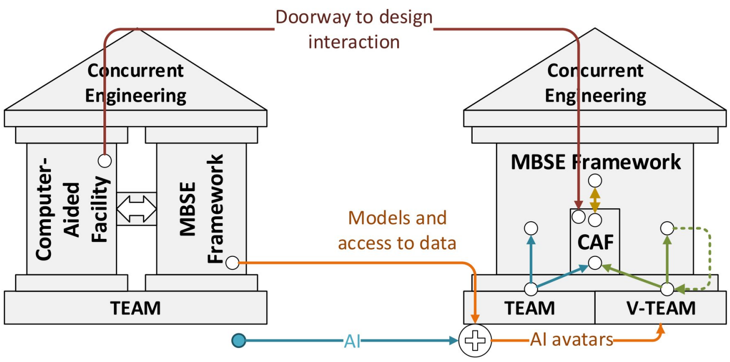
[8]https://assistant.google.com/
[9]https://www.apple.com/ios/siri/
[10]https://www.microsoft.com/en-us/windows/cortana
[11]https://developer.amazon.com/alexa

tion of the models to the facility through Tangible User Interfaces. Incorporating IA enabled assistants to share and collaborate in the same medium (the Computer Aided Facility - CAF), directly manipulating the knowledge base into the MBSE Framework outlines our vision to a Concurrent Engineering Facility based in Hyper Reality. Hyper Reality is defined as:

> "*a technological capability that makes possible the seamless integration of physical reality and virtual reality, human intelligence and artificial intelligence: HR = the seamless integration of (PR, VR, HI, AI) where PR = Physical Reality, VR = Virtual Reality, HI = Human Intelligence and AI = Artificial Intelligence*" (TIFFIN; TERASHIMA, 2001)

This facility, as illustrated in the Figure 6.8, would have two teams in parallel: the real specialists and the virtual assistants (V-Team). Both could interact with the models of the MBSE Framework and manipulates the facilities artefacts that represents the entities of the MBSE. In this arrange the real specialists would perceive and interpret the changes through the human senses and the virtual assistants through tracked artefact and model changes. The Hyper-Reality environment allows design via virtual and physical artefacts and virtual and physical collaborations with real specialists and virtual specialists, so this thesis is the physical artefacts increment towards this foreseen environment.

Figure 6.8 - CE with the Artificial Intelligence Increment.



SOURCE: from the author.

The elements of such environment will likely be:

a) A Enhanced MBSE Framework based in:

- Tools interconnection based on Model-to-Model transformations (BÉZIVIN, 2005) to provide a common model and its transformation through the domains;
- Automatic model selection based on a stored model repertoire and Optimization Techniques (MARTINS; LAMBE, 2013), to automatically pre-filter the better model combinations;
- Automatic architecture modelling based on Design Language Paradigms (GROSS; RUDOLPH, 2012) to incrementally couple/uncouple models to create family of solutions;
- Development of a EMF based OPM to use the Eclipse Modelling Ecosystem of model transformation as Arcadia (Capella) does;
- Integration of the OPM to Concept and Arcadia to Architecture into one Systemic Modelling tool.

b) A multi-modal Computer Aided Facility containing:

- Artefact Assistant based on Personal Assistants (LALWANI, 2016) to receive voice commands;
- Active Facility based on interconnected and intelligent artefacts to manipulate model user-interfaces (design and collaboration);
- Touch tables based on touch screens to manipulate model details;
- Hologram Glasses based in See-Through AR Glasses (MICROSOFT, 2018) to visualize and manipulate data in 3D;
- Additive Manufactured Artefacts based on Additive Manufacture (EIRIKSSON et al., 2017) to create physical domain representations on-demand of the activities.

c) A Virtual Team that has:

- Autonomous agents based in Machine Learning (MITCHELL, 1997) to continuously refactor design based into interactions;
- Search agents based in Big Data (CHEN et al., 2014) to refine specialist's decisions looking through model options;

A Hyper Reality Concurrent Engineering idea and above considerations give a futuristic direction towards the collaboration among humans and robots indicated by the 4th Industrial Revolution.

7 RELATED WORKS

This Chapter contains some related works of the literature, which has parallels between the developments presented in this thesis.

TUI in CE Sessions has the fundamental objective to propose and verify the feasibility to reintroduce physical artefacts to perform collaboration, thus, it relates to the concepts of Tangible User Interfaces, Collaborative Environments and the use of Concurrent Engineering as a methodology to perform Space Systems Concept Studies.

The literature of TUI does not shows multidisciplinary uses of the technology and there are few engineering cases. Most of the cases related to TUI are in Educational Collaborative Environments, where TUIs are source of learning, we can cite:

- the work done by Fjeld et al. (2007) to create a tabletop with artefacts to teach chemistry. This work uses a third person projection based to show the intangible representation instead of a full or nearby embodiment. He used basically two types of artefacts, one to host the content and a second as an actuator, to interact with the content. To exhibit the representation was used a traditional GUI approach, seen using a third person Augmented Reality display in front of the user;
- the Blocks project (BLIKSTEIN et al., 2016), which is intended to teach programming with a tangible only interface, without intangible representations. This work uses specific function tangible parts that has a known behaviour by its appearance. Within building blocks, physically realizing a programming approach similar to Scratch[1];
- Patten and Ishii (2007) developed an application to explore cellphone towers distributions. This work introduced mechanical constraints as computation constraints, as with artefacts not only the own devices interact, but other, non-tracked artefacts can obstruct the behaviour and positioning. Also this example uses a full embodiment within the same tabletop medium.

These three approaches summarizes all TUI based educational approaches, which includes (i) the use of artefacts that provide a control to an environmental screen,

[1]https://scratch.mit.edu/

(ii) the use of attachable artefacts that construct a context, and (iii) the hybrid approach of an artefact and an intangible representation. This thesis follows a blend of the three approaches as: it uses AR to track the artefacts, uses multiple artefacts to create a big picture context as and has a full approach towards both representations.

Related to the Architecture uses of TUIs, Underkoffler and Ishii (1999) develops a Spatial Augmented Reality within building shapes to simulate situations of urban planning, regarding wind, shadows and lighting. Urp uses the full embodiment projection and relates the context with coloured markers tracked by a camera. It uses the only nouns to describe the buildings, and an actuator artefact which also describes only a noun: the sun/wind direction.

The usefulness of the use of TUIs associated with models was presented by (PEDERSEN; HORNBÆK, 2011) where tangible active artefacts, controlled simultaneously, interact with a music loop, where each artefact controls an instrument. An early development using passive artefacts was also used to demonstrate the control of a music loop as well (PATTEN et al., 2001). Both used generic artefacts contextualized by intangible representations.

Instead of empowering the artefacts, it is also possible to augment the facility itself. Blackshaw et al. (2011) describes the Recompose project that created a physical reactive surface with Arduino and pneumatic pistons. The actuated surface can change according to the movement model or through physical interactions pressing the pistons or tracked by a depth camera (Kinect). This approaches could be used sided by active artefacts but the downside is that it requires changes in the facility and big equipment.

The ZeroN project follow the same design of the Recompose project to create active facilities. The ZeroN is a controlled magnetic levitation tangible interface that can move an artefact (in the case a metallic sphere) through a 3D volume. The technology still requires big equipment to install a small collaborative volume. (LEE et al., 2011)

Related to Engineering use of a Tangible, Harris et al. (2011) developed a path planning artefact dedicated to reservoir geosciences and oil engineering. Within a snake-like artefact the engineer can control a pipe model to develop a more organic routing. This work externalized to the passive artefact what is done into 3D GUI interfaces, using 2D input devices. The Snakey used a series of camera tripods to build the artefact within leds and vibros to create the second feedback-loop in the tangible artefact.

Other cases of Collaborative use of TUI are, as instance, on: (i) rehabilitation field: Augstein et al. (2016) use specific artefacts within tabletop screen to Neuro Rehabilitation, the use of specific artefacts in this case is high recommended due the therapeutic uses; (ii) children toys field: Parkes et al. (2008) use a construction kit of attachable artefacts (Lego like) to provide educators the STEM resources to program, build and control artefacts without a computer interface.

Regarding the use of swarms of tangible active artefacts, Goc et al. (2016) demonstrated how to control multiple artefacts collaboratively. This project used a projector to project a high frequency template pattern to the artefacts track their positions. The context requires the use of other physical artefacts (with content information) as the artefacts are generic.

Related to the use of a proper Systemic Language into CE Sessions to describe Models, (PASQUINELLI et al., 2016) point out that using Arcadia to use a SysML-like is helpful not only during design phase, but also during the other phases using domain specific transformation tools. (MURPHY et al., 2016) describes the use of an adapted SysML within the legacy Document-Centric Toolset (DCT) to backward-compatibility access the design history. The only work found related to CE Sessions and OPM was published by the authors (CERQUEIRA et al., 2016), which was an early structuring research.

The team collaboration studies about CDFs have been also presented by Braukhane and Bieler (2014) relating the "good, bad and ugly", as they describe, of Concurrent Engineering. The work narratively describes some of the conflicts and pitfalls of collaborations through the experience in ESA's CDF. The paper lists: costumer expectations, lack of requirements, breaks and basic behaviours, schedule & time issues, missing customers, problems with video conferences, the use of tools (the IDM and the Smartboards), endless discussions, workloads and excuses.

Regarding of how the CE specialists see the future, Biesbroek (2016) conducted a research with the ESA Concurrent Engineering Teams within the intention to improve the human-machine interfaces of the ESA's CDF. The work raises the four typical interaction/exchange information tasks: participate to discussions, discuss assumptions, keep team up to date and interact with other sub-systems. His research also brings a list of "pains" regarding the information exchange and their proposals as "pain relievers". The paper quotes the same situations as Braukhane and Bieler (2014), indicating that the issues persevered. The issues described are: difficulties with the IDM, lack of cooperation and attendance, lack of visibility, expectations not meet, baselines not clear, missing computer infrastructures, missing collaboration tokens, and difficulty to find data of previews studies.

Avnet (2009) describes the approaches to shared knowledge in NASA's CE Teams, classifying in: naturalistic, collective and holistic types. In the work Avnet proposes a balanced shared knowledge model among the types. Nakajima et al. (2016) described a creativity-driven design room, with the BYOD (Bring Your Own Design) concept, which the team had to collaborate using physical movable whiteboards. None of those done a comparative research from a defined set of collaboration metrics to determine and improve the format of the sessions.

Technologically this thesis has similarities with the other shown approaches, the main difference is in the proposition of an integration within an integrated multidisciplinary design facility through a Model Based System Engineering Methodology to Space Systems.

8 CONCLUSIONS

Inspired by the movement towards paradigm change from document centric tools to model-centric tools, and the concepts regarding Space 4.0, which will require researches of the optimal ways to empower physical artefacts into the engineering processes, this thesis took an artefact-oriented perspective on designing the collaborations into the Space System Concept Studies. Tangible User Interface is not new concept in Human Computer Interface, but it remains largely unexplored in Engineering applications, due to its technical challenges to create the environment and the difficulty to scale the physical artefacts through the engineering elements.

The first concern of Concurrent Engineering is team building, and the second is how they collaborate. Collaborations on Concurrent Engineering Sessions (the CE Sessions) are the basis of information exchange and activities convergence of the team. Although the tangible collaboration feasibility and adoption to collaborations in CE Sessions were the main drivers of this thesis.

Concerning how the team manipulate models during CE Sessions, we concluded that there are four collaboration models types (free, loose, context specific, and context independent) that coexist but have different gains regarding a modelling and the toolset required to use the model.

On looking for the understanding on how the human-data collaboration occurs during sessions, we concluded that the already established document-centric tools are settled, but requires the team the extra effort to prepare a presentation script directly from the raw data; changes are very difficult, as changing into sheets can corrupt data; model centric still is not ready to be fluently used into CE, though the models can be directly used into the presentations and discussions; Tangible Collaboration is an alternative research opportunity, however physical artefacts tends to be abstract requiring the research of support tools to deal with the details.

Concerning the collaboration formality of the CE Sessions, we concluded that the main facilities have different degrees of formalities, this thesis identified the two extremes by using a Collaboration Heuristic to evaluate the teamwork, communication, human involvement and cognitive reactions. Each degree of formality is a consequence of the collaboration protocol defined by the culture, the room format, and the technologies used to support the sessions.

Chapter 4 described the design process of how to map the design domain into the

TUI, and the decisions done through this thesis process - uniting the data from the Relevance Cycle (CE and MBSE) and the theories from the Rigor Cycle (TUI).

Regarding the technical arrangement, this thesis presented a construction assembly to enable interactions using TUI and the elements of the CE that it interacts to. Supporting the claim that, in the future, displays can be used as interactive surfaces and into the artefact itself, both as versatile platform for different demands and tasks. Through the search we also catalogued the multiple elements to create TUIs, proposing an TUI Artefact Taxonomy that may help to TUI developers and encourage the TUI authoring tool development.

We consider that this thesis is a step towards a Hyper Reality Concurrent Engineering Facility, that will include: artificial intelligence, explicit modelling and multiple formats of data visualization. This thesis presented the step where the facility become augmented, showing the feasibility of adding artefacts to CE Sessions Collaboration.

8.1 Limitations

This thesis covered only the collaboration situations in which the specialists bring in CE Sessions their prepared assumptions and decisions in models.

We assumed the existence of a Specialist Tool to create the OPM models, as well as some strategies to couple the OPM models. Despite the existing OPCat tool, it does not have connectivity to integrate into a bus of tools so we could connect with this thesis workspace..

We also considered as existing a Data Base where the collaboration artefacts would scan for the specialists (or disciplines) models. To emulate the database we did this model scan into a graph stored inside the application itself to run the algoritms.

The Proof of Concept only implemented a small workspace to demonstrate the feasibility of the technology arrangement. The projector used have a small field of view and the cameras to map large areas scanning for artefacts require high resolutions which slows the Computer Vision algorithms, due the amount of calculations within a big video frame. An ideal setup would require more projectors and cameras, connected into a computing grid. Regarding the artefacts, as a prototype: we neither consider a power budget, nor implemented sleep strategies to save artefact's energy and nor protected the electronics with an carcass piece.

The interaction controller is generic, but only interpret the programmed interactions. Within this implementation it is not possible to program other interactions or combinations of interactions.

We considered interactions only within the building blocks of the Systemic Modelling, while the Domain Specific Models were not implemented.

8.2 Contributions

This thesis practical contributions:

- Description of the CE Sessions Collaborations, the types of models, the formality towards how to collaborate and the collaboration interactions. Later works may compile and extend to build tools to handle CE and the Space context with more dimensional interactions outside the computers but still model-based.
- Development of a base architecture to tangible artefact, using Internet of Things and Spatial Augmented Reality.
- Description of a process to create a Tangible Interactive Vocabulary from the Space Systems Concept Studies entities and the expected collaboration behaviours.
- Exploration of OPM as meta meta-model, as dual cognitive modality and its characteriscs of allowing the model be described in graphs. This characteristic could help to build automatic transformations and optimizations to assist CE activities.
- Classification of the Tangible User Interface elements to define the tangible artefacts.
- Description of a back-end model based in digraphs to represent the CE disciplines' models.
- Graphical chracterization of the six main existing user interface styles.
- Description of a roadmap of technologies related to Industry 4.0, which could be implemented in CDFs.
- Description of the use of Collaborative Environment heuristics to evaluate qualitatively CDFs.

Some contribution, from a more practical approach may be applied to the INPE's activities in the future, as:

- Use of OPM to describe System Concepts and Operational Scenarios, as well as simulate state-driven behaviours;
- Baseline for future works on Model Based Engineering applying the Object-Process Methodology (OPM) as a basis model to overview the big picture of the things and relationships among a space mission concepts and later use Graph model properties, and translations, to automate the modelling, optimization, and solution finding;
- Improve the dynamic interaction among the specialist participants on a CE session, helped with the list of identified interactions, in order to optimize the CE team interaction.

8.3 Publications

This section contains the publications done during this thesis. The publications are divided in: strongly related and weakly related. All first pages of the publications are in the Appendix E.

Strongly Related Publications

- CERQUEIRA, C. S., AMBROSIO, A. M., KIRNER, C., SOUZA, F. L., 2014, Structuring a Cross-Reality Environment to support a Concurrent Engineering Process for Space Mission Concept, 6th International Conference on Systems & Concurrent Engineering for Space Applications - SECESA 2014 - 08-10 October, Vaihingen Campus, University of Stuttgart, Germany
- CERQUEIRA, C. S., KIRNER, C., 2014, Structuring Spatial Cross Reality Applications using openFrameworks and Arduino (Construção de aplicações de Realidade Cruzada Projetiva utilizando openFrameworks e ARDUINO), Tendências e Técnicas em Realidade Virtual e Aumentada, ISSN 2177-6776
- CERQUEIRA, C. S., RODRIGUES, I. P., MOREIRA, C. J. A., CARRARA, V., AMBROSIO, A. M., KIRNER, C., 2015, Using Virtual, Augmented and Cross Reality in INPE's Satellite Simulators (Utilização de

Realidade Virtual, Aumentada e Cruzada em Simuladores de Satélites no INPE), Tendências e Técnicas em Realidade Virtual e Aumentada, ISSN 2177-6776

- CERQUEIRA, C. S., AMBROSIO, A. M., KIRNER, C., 2015, Structuring on-demand Software User Interfaces based in Spatial Augmented Reality to Control Hardware (Arduino) (Construção de interfaces on-demand baseadas em Realidade Aumentada Projetiva para Controle de Hardware (Arduino)), Tendências e Técnicas em Realidade Virtual e Aumentada, ISSN 2177-6776
- CERQUEIRA, C. S., AMBROSIO, A. M., KIRNER, C., 2016, A Model Based Concurrent Engineering Framework using ISO-19450 Standard, 7th International Conference on Systems & Concurrent Engineering for Space Applications - SECESA 2016, Universidad Politécnica de Madrid (UPM), Spain

Weakly Related Publications

- YASSUDA, I. S., OLIVEIRA, M. E. R., LOPES, I M L, MORAIS, M. H. E., GONDO, S. M. H., OLIVEIRA JUNIOR, E. M., CERQUEIRA, C. S, NONO, M. C., 2015, Creating and maintaining a workshop for graduate course in space engineering and technology and its usefulness to the training of future researchers. ITST - International Symposium on Space Technology and Science. Japan
- RODRIGUES, I. P., AMBROSIO, A. M., CERQUEIRA, C. S., 2016, Towards an Automated Hybrid Test and Simulation Framework to Functional Verification of Nano-satellites' Electrical Power Supply Subsystem, Latin American IAA CubeSat Workshop
- RODRIGUES, I. P., AMBROSIO, A. M., CERQUEIRA, C. S., 2016, A Framework for Automated Model Validation Applied to Pico-satellite Electrical Power Subsystem, 7° Workshop em Engenharia e Tecnologia Espaciais, INPE
- CERQUEIRA, C. S., SILVA, P. D., RODRIGUES, I. P., AMBROSIO, A. M.; VILLANI, E., 2016, Two Independent Processes of Verification Applied to a Satellite Simulator, 7° Workshop em Engenharia e Tecnologia Espaciais, INPE

- CERQUEIRA, C. S., AMBROSIO, A. M., KIRNER, C., 2017, Using ISO-19450 to Describe and Simulate a Small Sat Operational Scenario, 8° Workshop em Engenharia e Tecnologia Espaciais, INPE
- CERQUEIRA, C. S., AMBROSIO, A. M., SANTOS, O. F., GEUS, I., BARROS, L., 2017, Describing Model Behaviour using OPM to an Operational Satellite Simulator (Descrição do comportamento de modelos para um Simulador Operacional de Satélites em OPM), 8° Workshop em Engenharia e Tecnologia Espaciais, INPE
- BÜRGUER, E., LOUREIRO, G., MARIÑO, G. G. C., CERQUEIRA, C. S., 2017, Alfa Project Mission Definition (Definição da Missão do Project Alfa), 8° Workshop em Engenharia e Tecnologia Espaciais, INPE
- RODRIGUES, I. P., GÓES, R., CERQUEIRA, C. S., AMROSIO, A. M., 2017, Data Collection Subsystem Modelling and Simulation using Simulink, 8° Workshop em Engenharia e Tecnologia Espaciais, INPE
- JESUS, G. T., CHAGAS JUNIOR, M. F., CERQUEIRA, C. S., LIMA, J. S., DINIZ, G., 2017, Initial Risk Management in Educational and Technological Space Missions (Gerenciamento de riscos na fase inicial de uma missão espacial de iniciativa educacional e tecnológica), 8° Workshop em Engenharia e Tecnologia Espaciais, INPE

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APPENDIX A - AURA DESIGN

This appendix describes the four Auras, with its nouns, states, and verbs. In each Aura containing: the metaphor justification, the relation with the CE Session, the interactions describing the nouns, states, and verbs, the internal queries into de graph to manipulate data, and examples of the projected Auras.

This appendix is divided in the following sections:

- **Section A.1 - Totem**: this section describes the aura that handles the Model entity in single state;
- **Section A.2 - Share**: this section describes the aura that handles the System Element entity in closed state;
- **Section A.3 - Knowledge**: this section describes the aura that handles the System Element entity in opened state;
- **Section A.4 - Controls**: this section describes the aura that handles the Parameter entity.

The Big Picture Aura is described at **Subsection 4.6.1 - Big Picture Aura Example**

A.1 Totem

A Totem is an icon, a representation, a simplification, or into tribal cultures, they mean a guide through the material and spiritual world. This metaphor is used here to create an aura meaning that is the connection between the specialist and collaborative workspaces.

Association to CE sessions:

During sessions, when the specialists want to share their solutions, the Totem Aura is the representation of the specialist workspace: local/remote notebook/desktop, tablet, cell phone, or any other design media that hosts the specialist tooling. The Totem makes the continuity representation between both user-interfaces: GUI and TUI, indicating the boundaries of a specialist to transverse de content.

Artefact Interactions:

From the Model Use Scenarios, we refined the Totem Aura metaphor to deal with the model noun in four states: Tied, Remote, Navigation and Free. In Tied, the artefact controls the noun aura with overlay - the aura follows the artefact. In Remote, the artefact controls the noun on distance, into a “nearby embodiment” - the aura locks on the surface and is remote controlled. In Navigation, the totem aura allows to inspect/navigate the models - the artefact can select from the shown menu. In Free, the aura does not have an artefact associated - the only interactions are gesture move or attaching an artefact.

Figure A.1 shows the interaction/transition mapping, with the relational events (action verbs) that makes transitions.

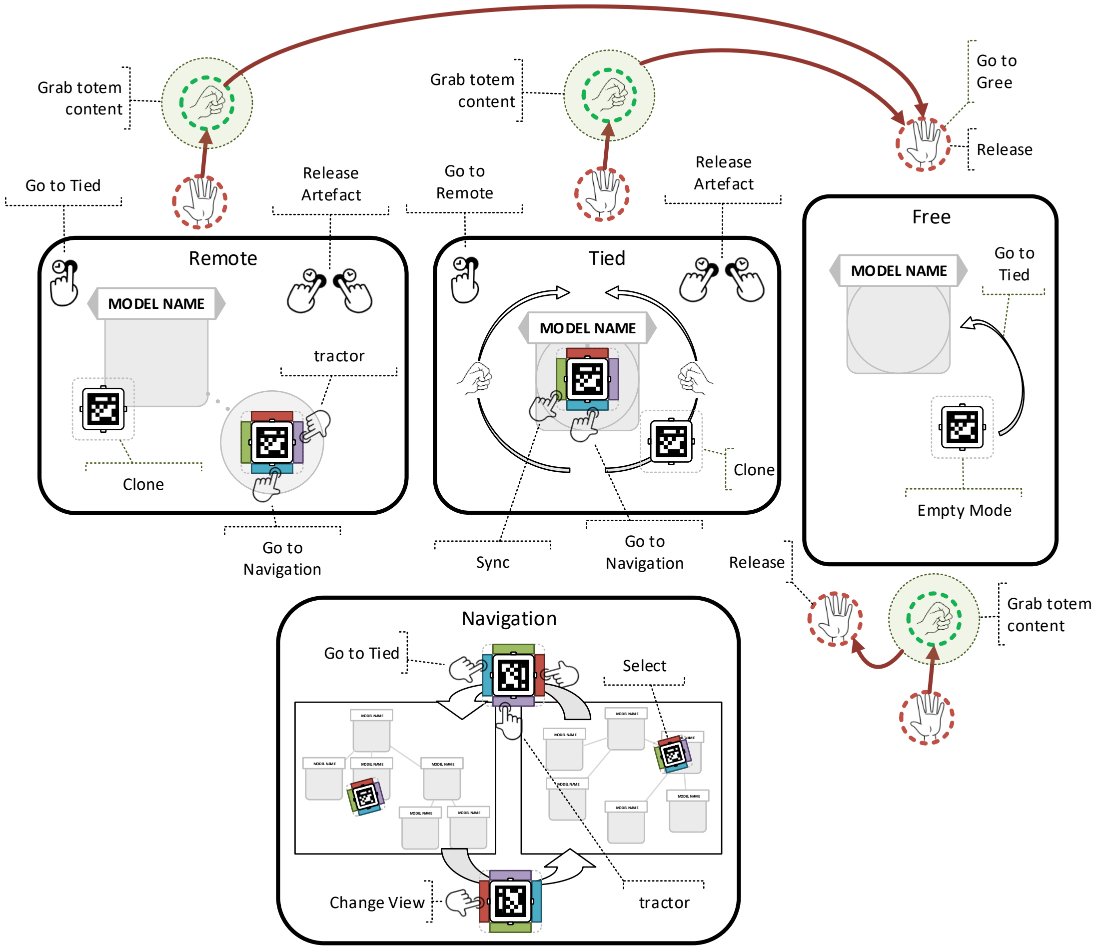
Figure A.1 - Totem Verbs.

	Interactions	Totem Noun States			
		Tied	Remote	Navigation	Free
Totem Verbs	Button_Red			Change View	
	Button_Blue	Go to Navigation	Go to Navigation	Go to Tied	
	Button_Green	Sync	Sync		
	Button_Purple		Aura tractor	Aura tractor	
	Button_Hold	Go to Remote	Go to Tied State		
	Button_DoubleHold	Release artefact	Release artefact		
	Gesture_Grab	Hold Aura	Hold Aura		Hold Aura
	Gesture_Release				Release Aura
	Artf_EmptyProx	Clone	Clone	Select	Go to Tied
	Arft_AuraProx				
	Artf_PlaceAbove	Clone	Clone	Select	Go to Tied
	Artf_Move	Follow			

SOURCE: from the author.

Figure A.2 illustrate all verbs, and the noun. As this thesis copies the building blocks metaphor, the models are represented as blocks.

Figure A.2 - Totem Example of all Verbs.

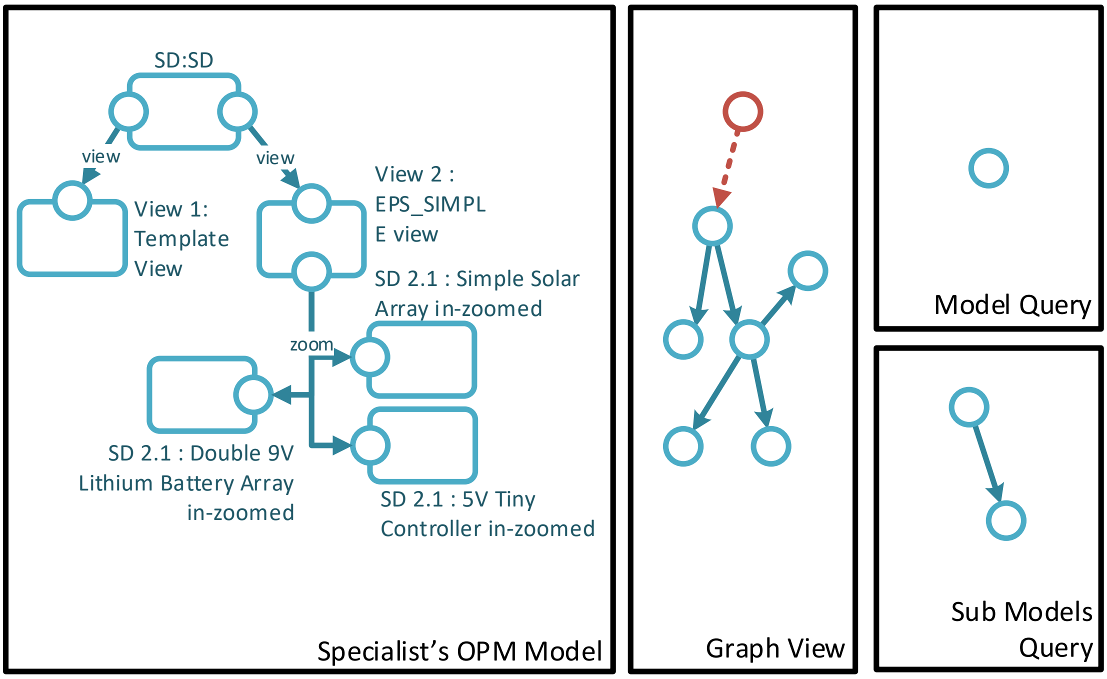


SOURCE: from the author.

Queries to manipulate data:

As soon as the graph branch (Illustrated by the example model on Figure A.3) with the model information is included into the workspace area, a Totem Aura is available to pick. Always a branch has a single user linking to the SD root model, indicating the original ownership of the specialist. In Figure A.3 Graph View, the red circle identifies the ownership node of an aura. The artefact manipulating a Totem Aura can makes two queries into the branch: (i) models, and (ii) sub models. Querying models will return all models bellow where the query starts on the branch and querying sub-models will return only the sub-models, of a given link type, bellow where the query starts.

Figure A.3 - Totem Query.



SOURCE: from the author.

A.2 Share

Peons of a board game possess the information regarding the accumulated game steps and are handled to manipulate and evolve the game. This metaphor is used here, to create an aura meaning that is responsible to host the link among representations and the internal solution's data.

Association to CE sessions:

When specialists want to manipulate the information of a model, the Share Aura represents the common thing that represents a proposed solution. In this, all models derive from template models, which contains the stereotypes of common CE things. The higher stereotype is the System Element entity. The Share Aura possibilities to navigate, and inspect the System Elements, sharing to the other specialists the elements of the solution.

Artefact Interaction: From the System Elements Use Scenarios, we refined the Share metaphor to deal with the system elements noun, until the interface is in hide state, in four states: Tied, Remote, Navigation and Free. In Tied, the artefact controls the noun aura with overlay - the aura follows the artefact. In Remote, the artefact controls the noun on distance, into a nearby embodiment - the aura locks on the surface and is remote controlled. In Navigation, the Share aura allows to inspect/navigate the system elements - the artefact can select from the shown menu. In Free, the aura does not have an artefact associated - the only interactions are gesture move or attaching an artefact.

Figure A.4 shows the interaction/transition mapping, with the relational events (action verbs) that makes transitions.

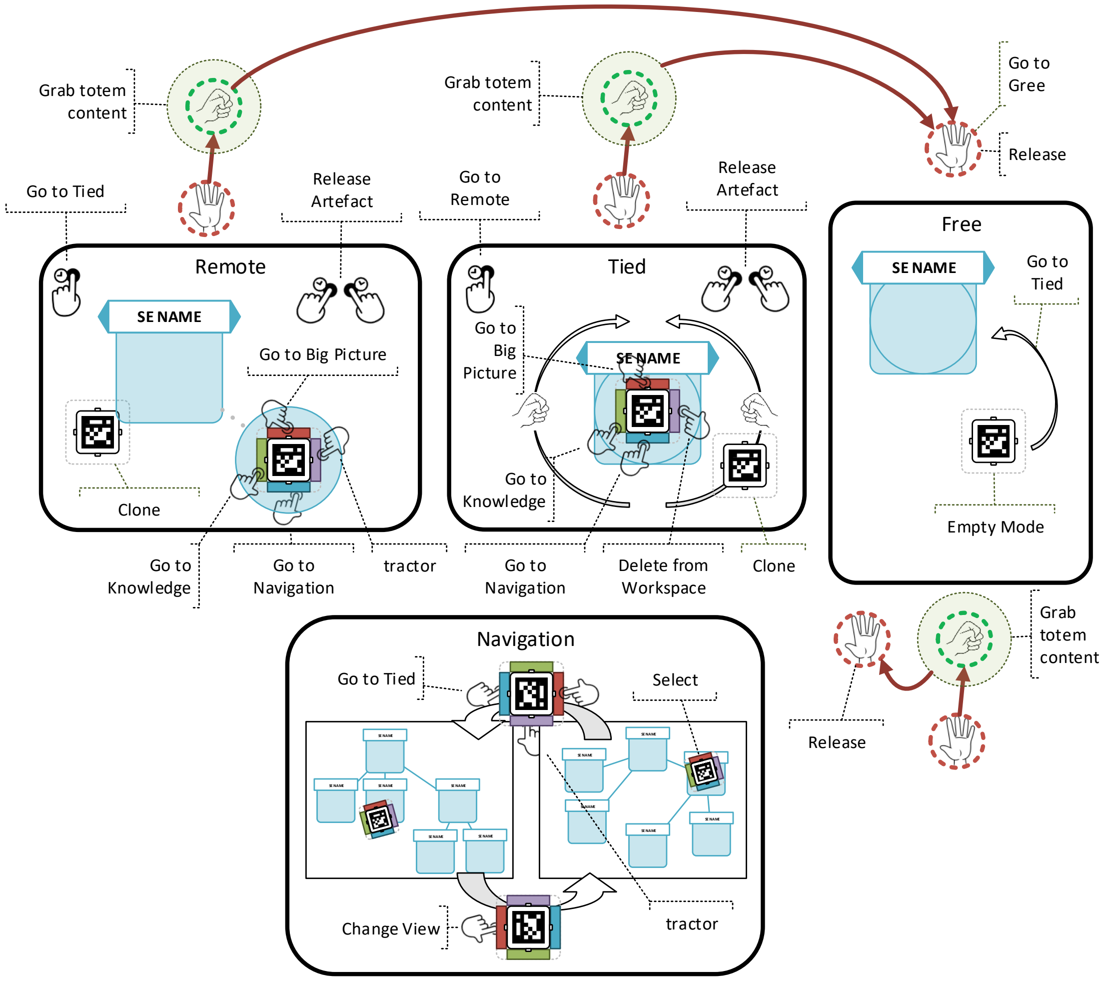
Figure A.4 - Share Verbs.

	Interactions	Share Noun States			
		Tied	Remote	Navigation	Free
Share Verbs	Button_Red	Go to Big Picture	Go to BigPicture	Change View	
	Button_Blue	Go to Navigation	Go to Navigation	Go to Tied	
	Button_Green	Go to Knowledge	Go to Knowledge		
	Button_Purple	Delete from Workspace	Aura tractor	Aura tractor	
	Button_Hold	Go to Remote	Go to Tied		
	Button_DoubleHold	Release artefact	Release artefact		
	Gesture_Grab	Hold Aura	Hold Aura		Hold Aura
	Gesture_Release				Release Aura
	Artf_EmptyProx	Clone	Clone	Select option	Go to Tied
	Arft_AuraProx				
	Artf_PlaceAbove	Clone	Clone	Select option	Go to Tied
	Artf_Move	Follow			

SOURCE: from the author.

Figure A.5 illustrate all verbs, and the noun. As this thesis copies the building blocks metaphor, the System Elements are represented as blocks.

Figure A.5 - Share Example of all Verbs.

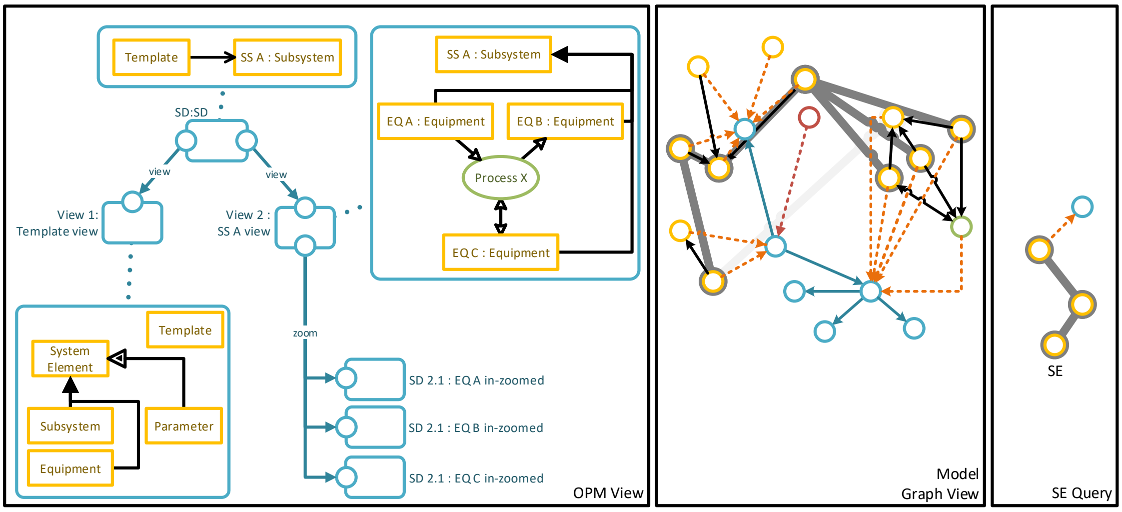


SOURCE: from the author.

Queries to manipulate data:

Figure A.6 illustrates the Graph query of the Share Aura. The left panel shows the Specialist OPM View of a model example. The middle panel contains the graph model itself. The greyish line, which does not represent an actual graph connection, illustrate the successive stereotypes linked. The Right Panel, shows the query, it looks to all the things that derives from the System Element Template Thing.

Figure A.6 - Share Query.



SOURCE: from the author.

A.3 Knowledge

Opening a notebook presents the inner information stored in the pages. Pages together can then form a macro vision of the information. This metaphor is used here, to create an aura meaning that is responsible to allows the specialists to inspect system elements.

Association to CE sessions:

When a specialist wants to inspect inner data of the system elements, the Knowledge Aura represents the opening of the internal knowledge related to the selected System Element, showing parameters and interfaces. The stereotype that indicates the internal information is the Parameter entity. The Knowledge Aura possibilities to navigate, and inspect System Element's parameters, sharing its mains proprieties and doing small value or state changes.

Artefact Interactions:

From the System Elements Use Scenarios, we refined the Knowledge metaphor to deal with the system elements noun, with the interface is in show state, in four states: Tied, Remote (Open), Navigation and Free. In Tied, the artefact controls the noun aura with overlay, the aura only shows the parameters described as externals (in OPM is environmental) - the aura follows the artefact. In Remote, the artefact controls the noun on distance, into a nearby embodiment - the aura locks on the surface and is remote controlled. In Navigation, the Knowledge aura allows to inspect/navigate the parameters - the artefact can select from the shown menu. In Knowledge Remote State, the aura also opens to shows the inner. In Free, the aura does not have an artefact associated - the only interactions are gesture move or attaching an artefact.

Figure A.7 shows the interaction/transition mapping, with the relational events (action verbs) that makes transitions.

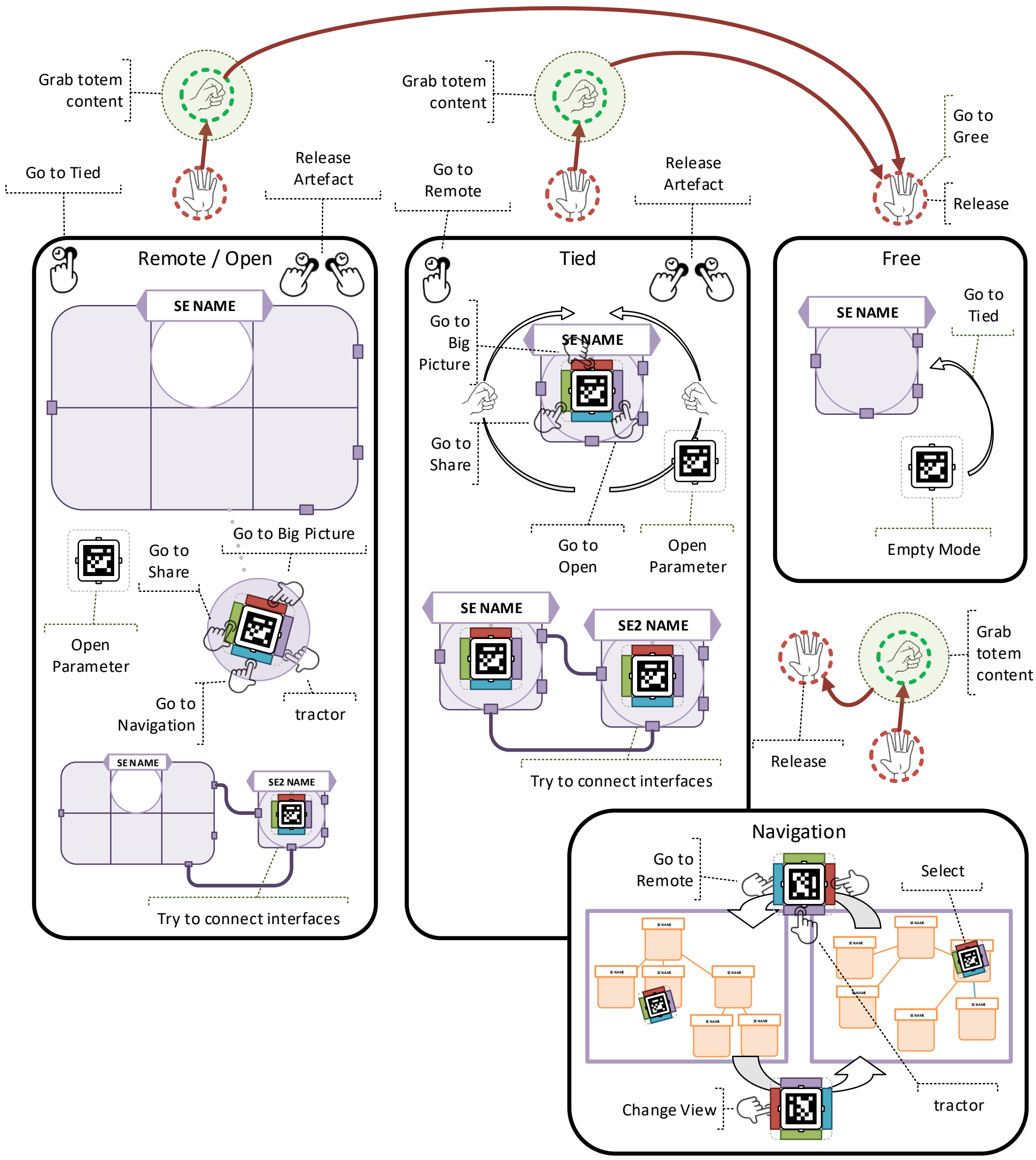
Figure A.7 - Knowledge Verbs.

	Interactions	Knowledge Noun States			
		Tied	Remote (Open)	Navigation	Free
Knowledge Verbs	Button_Red	Go to Big Picture	Go to BigPicture	Change View	
	Button_Blue		Go to Navigation	Go to Remote	
	Button_Green	Go to Share	Go to Share		
	Button_Purple	Go to Open	Aura tractor	Aura tractor	
	Button_Hold	Go to Remote	Go to Tied		
	Button_DoubleHold	Release artefact	Release artefact		
	Gesture_Grab	Hold Aura	Hold Aura		Hold Aura
	Gesture_Release				Release Aura
	Artf_EmptyProx	Show one more Parameter - Go to Navigaton	Show one more Parameter - Go to Navigaton	Select option	Go to Tied
	Arft_AuraProx	Try to connect interfaces	Try to connect interfaces		
	Artf_PlaceAbove	Show one more Parameter - Go to Navigaton	Show one more Parameter - Go to Navigaton	Select option	Go to Tied
	Artf_Move	Follow			

SOURCE: from the author.

Figure A.8 illustrate all verbs, and the noun. As this thesis copies the building blocks metaphor, the System Elements are represented as blocks.

Figure A.8 - Knowledge Example of all Verbs.



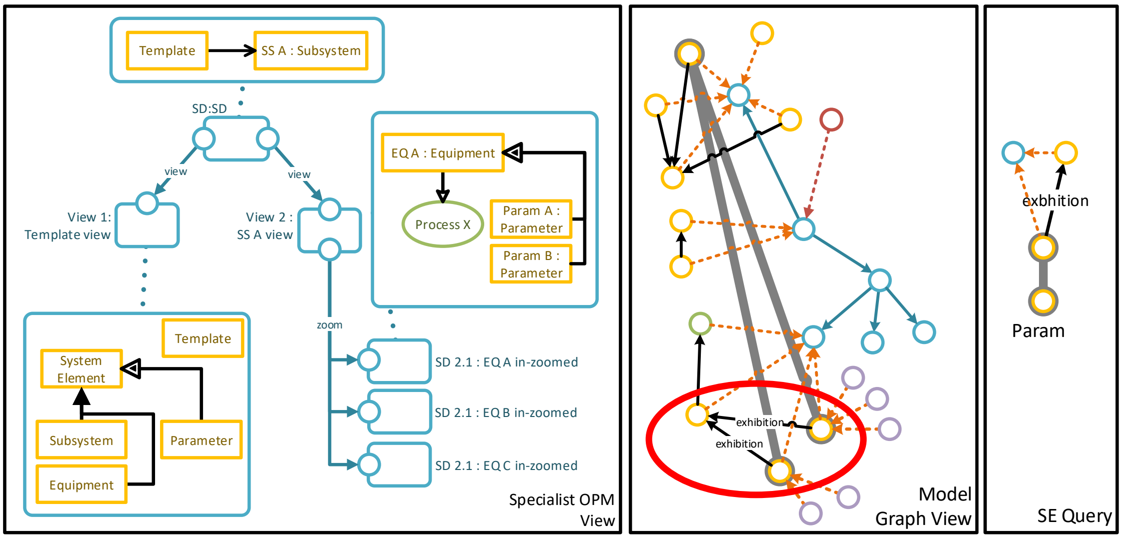
SOURCE: from the author.

Queries to manipulate data:

Figure A.9 illustrates the Graph query of the Knowledge Aura. The left panel shows the Specialist OPM View of a model example, it shows an EQ A Zoomed model with two parameters. The middle panel contains the graph model itself with a red ellipse indicating the two-exhibition links with the parameters. The greyish line, which does not represent an actual graph connection, illustrate the stereotypes linked. The Right Panel, shows the query, it looks to all the things that derives from the

Parameter Template Thing, that has a model connection and an exhibition link.

Figure A.9 - Knowledge Query.



SOURCE: from the author.

A.4 Controls

Older physical gear, pre-digital era, used to exhibit its changeable proprieties (parameters), or controls, only through: buttons, levels, knobs, etc. The Controls were tangible representations directly associated with the tangible feedback. This metaphor is used here, to create an aura meaning that is responsible to allow the specialist to do on-demand tuning on the system element's parameters.

Association to CE sessions:

The Control Aura is associated with the Knowledge Aura. The Knowledge Aura hosts the Control Auras of a given context, and they mean the chosen parameter to expose during a cluster study or presenting the solution. The main three groups of CE parameters are: (i) discrete values, (ii) continuous values, and (iii) textual values. The discrete values can indicate operational modes, or options of a system element. The continuous values can indicate numerical properties as weight, length, son on. The textual values can indicate important information, or associated requirements.

Artefact Interactions:

From the Parameter Use Scenarios, we refined the Control metaphor to deal with the parameter noun in four states: Tied, Remote, Navigation and Free. In Tied, the artefact controls the noun aura with overlay, the aura only shows the - the aura follows the Knowledge base aura. In Remote, the artefact controls the noun on distance, into a nearby embodiment - the aura locks on the surface and is remote controlled. In Navigation, the Control aura allows to inspect/navigate the parameters states (values) - the artefact can select from the shown menu. In Free, the aura does not have an artefact associated. Figure A.10 shows the interaction/transition mapping, with the relational events (action verbs) that makes transitions.

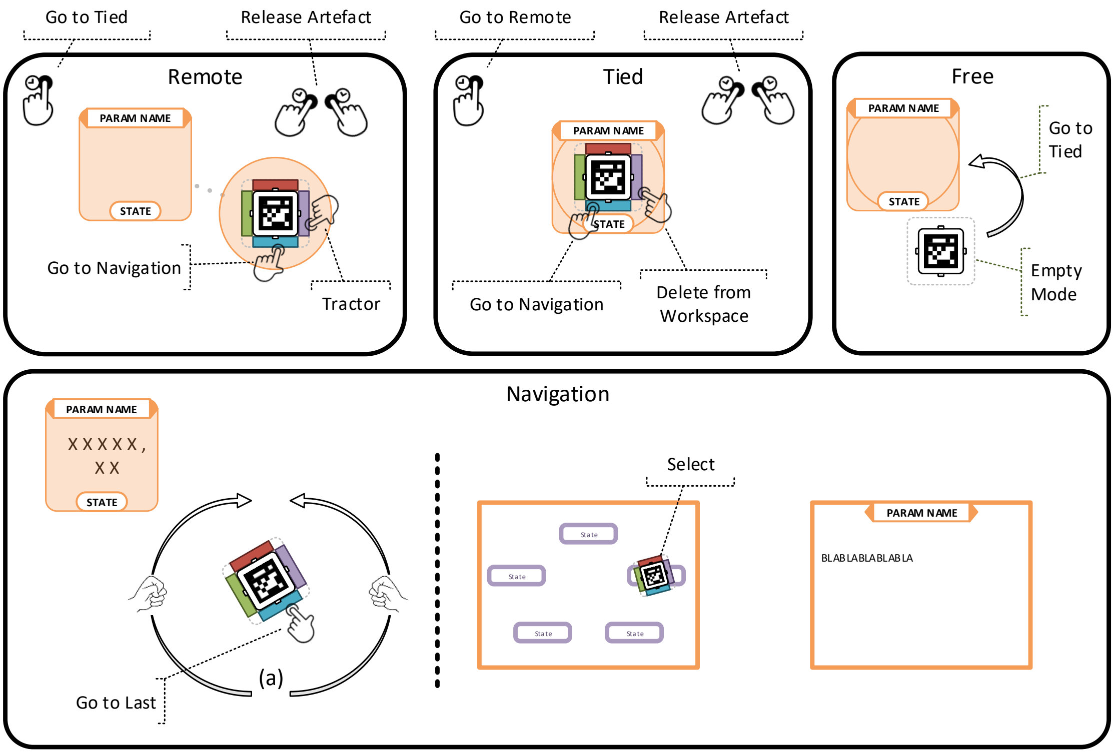
Figure A.10 - Controls Query.

Interactions		Controls Noun States			
		Tied	Remote	Navigation	Free
Controls Verbs	Button_Red				
	Button_Blue	Go to Navigation	Go to Navigation	Go to Last	
	Button_Green				
	Button_Purple	Delete from Workspace	Tractor		
	Button_Hold	Go to Remote	Go to Tied		
	Button_DoubleHold	Release artefact	Release artefact		
	Gesture_Grab				
	Gesture_Release				
	Artf_EmptyProx				Go to Tied
	Arft_AuraProx				
	Artf_PlaceAbove				Go to Tied
	Artf_Move			Change Value	

SOURCE: from the author.

Figure A.11 illustrate all verbs, and the noun. As this thesis copies the building blocks metaphor, the System Elements are represented as blocks.

Figure A.11 - Controls Example of all Verbs.

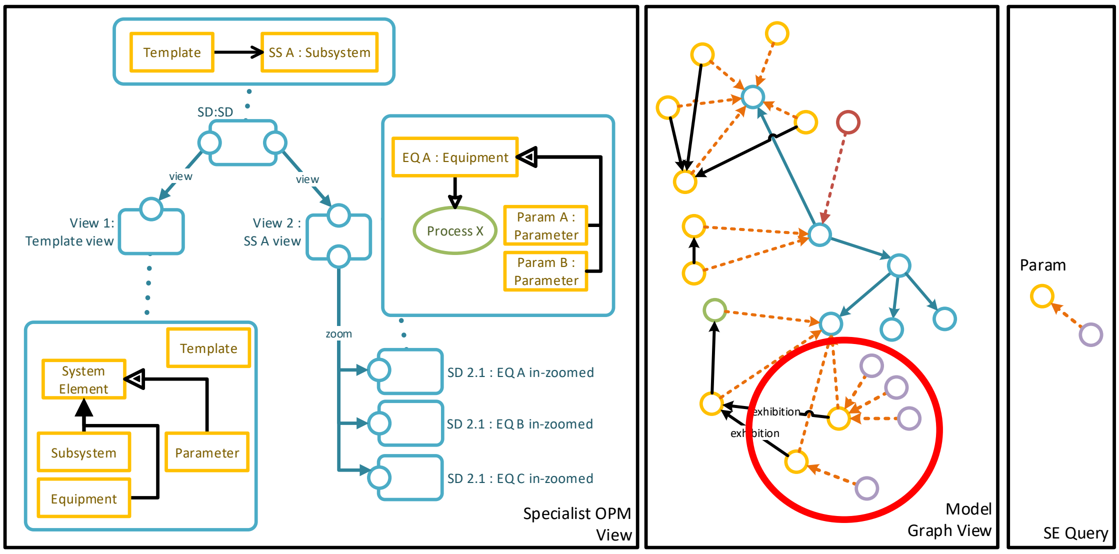


SOURCE: from the author.

Queries to manipulate data:

Figure A.12 illustrates the Graph query of the Controls Aura. The left panel shows the Specialist OPM View of a model example, it shows an EQ A Zoomed model with two parameters. The middle panel contains the graph model itself with a red ellipse indicating the two-exhibition links with the parameters, and in purple the state (value) links. The Right Panel, shows the query, it looks to all the relate parameter state things.

Figure A.12 - Controls Queries.



SOURCE: from the author.

This Tangible Interaction Vocabulary only contains simple atomic inputs. It is possible in further future works to extend to voice control, and combinations of interactions.

APPENDIX B - TANGIBLE USER INTERFACE ELEMENTS TAXONOMY

This appendix presents a proposal for a TUI Artefact Taxonomy to help developers and decision makers to evaluate and compare the features. This proposal refers to the Rigor Cycle Contributions. Our proposal of TUI Artefact Taxonomy relates: the artefact nature, what it is made of, the input and output artefact technologies, the environment technologies, the connections, the awareness towards the environment, and towards the user.

Table B.1 contains a description of each element of the artefact taxonomy topic and category.

Table B.1 - TUI Artefact Taxonomy.

Topic	Category								
Artefact Nature	**Metaphor**	none - no metaphor	noun - it represents a thing	verb - it represents a behaviour	noun and verb - it represents both a thing and a behaviour	full - it directly represents the virtual system			
	Style	passive - the artefact does not have electronics	active - the artefact has electronics						
	Purpose	instrument - the artefact represents a transformational tool	object - the artefact represents the context	instrument and object - the artefact embeds both the tool and the context					
	Instance	spatial - interprets spatial position and orientation	constructive - interprets construction modules	relational - interprets command symbols that relates	constructive-relational - considers both grouping and its symbols	associative - interprets each artefact interdependently associating a behaviour			

(Continue)

Table B.1 - Continuation

Topic	Category								
Artefact Material	**Parts of**	volumes - based on groups of, simple or transformed, Euclidean solids	hinges - containing movable mechanisms	plugs - containing fitting shapes	handles - able of carrying or raising	straps - containing fixing or pulling parts	wheels - containing scrollable parts (active or passive)		
	Shape	plastics (industrially made or 3D printing)	wood	paper	metal	foam	Styrofoam	fabric (cloth)	
	Metaphor	static - the shape is not changeable	manually incremented - the shape can be changed by adding new construction parts	controllable material - the material changes itself					
Artefact Input Technology	**Sensor Data**	orientation	positioning	depth distance	weight	temperature	gesture commands		
	Sensor Type	magnetic	resistive	capacitive	inertial	visual	global positioning	contact	
Artefact Output Technology	**Actuator Action**	movement	temperature change	sound	light	spin / torque	wind		

(Continue)

Table B.1 - Continuation

Topic	Category								
	Actuator Type	motor	heater / cooler	vibrator	speaker	LED	laser	pump	LCD panel
Artefact Connections	**Data Source**	artefact - each artefact contains the data from its context	facility - the facility handles the artefact's context	cloud - the artefact reads the context from a cloud-based information provider	hybrid - the data is speeded through the artefact and, facility, and / or cloud				
	Processing Place	artefact - the artefact fully processes the interaction and data	facility - the facility processes the interaction and the data	cloud - the artefact sends to the cloud to process the data	hybrid - the processing is speeded through the artefact, facility, and / or cloud				
Artefact's Environment Technology	**Data gathering**	visible light feed	infrared feed	depth	communication protocol				
	Feedback-Loop	monitor	projector	glasses	laser	magnetic	mechanical	wind	sound

(Continue)

Table B.1 - Continuation

Topic	Category								
	Reaction presence	direct (first person) - the feedback is overlapped, and it is seen into the artefact (or surroundings)	indirect (third person) - the feedback is overlapped but it is not directly seen into the artefact						
Artefact awareness towards the Environment	**Tangibles' Spatial Awareness**	none - all artefacts work in isolation and are unaware of the others	mutual perception - the artefacts recognize each other	environment awareness - the artefacts recognize each.					
Artefact awareness towards the User	**Embodiment**	full - the output is overlapped into the input device	nearby - the output takes place near the input device	environmental - the output is provided by the environment, away of the input device	distant - the output is in other media, or geographically apart				
	Tangible Assigned Functionality	permanent - each artefact has one unchangeable function	programmable - functions can be assigned or removed	transient - the functions are volatile, context-dependent					

(Continue)

Table B.1 - Continuation

Topic	Category							
	Detectability of Interaction	simple skill - detects only one simple skills to interact	composite skills - allows groups of contextual skills to interact					
	Feedback	continuous - the feedback action depends of a continuous value	discrete - the feedback action has a trigger	filtered				
	Simultaneous Use	single - the user can manipulate only on artefact	multiple - the user can manipulate multiple artefacts, if they do not hinder each other					

APPENDIX C - PUBLICATIONS

C.1 Structuring a Cross-Reality Environment to support a Concurrent Engineering Process for Space Mission Concept

Structuring a Cross-Reality Environment to support a Concurrent Engineering Process for Space Mission Concept

6th International Conference on Systems & Concurrent Engineering for Space Applications

- SECESA 2014 -

08-10 October 2014

Vaihingen Campus, University of Stuttgart
Germany

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INTRODUCTION

Space Mission Concept tasks requires the use of several modelling and simulations resources. The ECSS (European Cooperation on Space Standardization) Modelling and Simulation Technical Memorandum [1] indicates that simulations can support life-cycle tasks as: (i) design, (ii) feasibility and performance analysis, (ii) functional validation, (iv) software validation, (v) equipment validation, (vi) AIV (Assembly, Integration and Verification), and (vii) training & operation and further tasks. Such Memorandum also recommends that the multidisciplinary engineering team consolidate a mission and system concept using a virtual system model with a generic spacecraft, ground and environment models containing key parameters of each required domain, as: power, AOCS (Attitude and Orbital Control Systems), mission analysis, mechanical, thermal, etc.

Traditionally, each specialist engineer and discipline has a specific modelling and simulation tool set and environments, and these are placed into each engineer's computational workspace environment. These workspaces are not shared, in sessions or development, usually only a repository keeps the engineers shared information. This modelling and simulation toolset and computational environments might include: Matlab/Simulink, SciLab, STK, Orbiter, SINDA/FLUINT, CAD (Computer-Aided Design) applications, PSpice, Modellica, AMESim, LabView, MS. Excel, etc.; as well as their own nature of simulation: continuously, by events, electronic, mechanic, computational, etc.

The way each specialist engineer interacts with the tool set are, usually, based in WIMP (Windows, Icon, Menu and Pointer) metaphor, instead of a metaphor closer to the simulated system/sub-system. The WIMP metaphor extracts the abstraction of the desired system to an amount of tables, graphics, and in the best case diagrammatic representations, which allows navigation and exploration in two dimensions, for example, creating a Simulink model consists in search for functional blocks, to drag and drop into a main workspace area, interconnect the blocks, point and click to attribute setting by menus and text fields. On the other hand, a CAD based simulation (thermic, mechanic, CFD - Computational fluid dynamics, etc.) has a metaphor closer to the real system, as it represents the necessary three-dimensional system model, allowing point and click in the "three-dimensional" space in order to attribute setting.

NUI (Natural User Interfaces) researchers defines that collaborative works, as concurrent engineering, demands virtual and transparent software coupling, in real time work, using a shared visualization media [2]. So each specific engineer

C.2 Structuring Spatial Cross Reality Applications using openFrameworks and Arduino (Construção de aplicações de Realidade Cruzada Projetiva utilizando openFrameworks e ARDUINO)

Chapter

1

Construção de aplicações de Realidade Cruzada Projetiva utilizando openFrameworks e ARDUINO

Christopher Shneider Cerqueira e Claudio Kirner

Abstract

This chapter aims to show a Projective Cross-Reality environment development. The chapter consists of the following sections: correlated works that motivated this chapter, equipment used, application development steps using the open-source framework openFrameworks with the Arduino hardware interface, and some use trends. The development steps consists of: building of a basic application using openFrameworks; color tracking using an openCV wrapper; projection and camera calibration; and inclusion of a hardware in the interaction loop.

Resumo

Este capítulo apresenta o desenvolvimento de um ambiente de realidade cruzada projetiva. Inclui seções de: exemplos correlatos que motivaram o capítulo, equipamentos utilizados, as etapas de desenvolvimento da aplicação utilizando o frameworks open-source, openFrameworks com a interface de hardware Arduino, e tendências de uso. As etapas de desenvolvimento incluem: a construção de uma aplicação básica com o openFrameworks; o rastreio de cores utilizando um wrapper do openCV; a calibração da projeção e câmera; e a inclusão de hardware no loop de interação.

1.1. Introdução

Há diversas naturezas de interação, nas quais o ser humano envolve-se para manipular elementos do mundo real que podem ser "aumentados" por elementos virtuais. Os elementos dos mundos real e virtual se cruzam com elementos computacionais (sensores e atuadores), habilitando várias modalidades de mundos, como: mundo real tangível, realidade aumentada [Kirner 2011], realidade virtual [Kirner 2011], mundos virtuais distribuídos [Schroeder 2008], mundos ubíquos [Weiser 1993] e realidade cruzada [Kirner et al 2012].

C.3 Using Virtual, Augmented and Cross Reality in INPE's Satellite Simulators (Utilização de Realidade Virtual, Aumentada e Cruzada em Simuladores de Satélites no INPE)

Capítulo

1

Utilização de Realidade Virtual, Aumentada e Cruzada em Simuladores de Satélites no INPE

Christopher Shneider Cerqueira, Italo Pinto Rodrigues, Carlos José Alves Moreira, Valdemir Carrara, Ana Maria Ambrosio, Claudio Kirner

Abstract

The National Institute for Space Research – INPE (in Portuguese "Instituto Nacional de Pesquisas Espaciais") is the major research center of the space sector at Brazil. Among the main research and development activities at INPE, is the Space Engineering and Technology ETE (in Portuguese "Engenharia e Tecnologia Espaciais"), which covers, in the institute, new space technologies and space systems development. Nowadays, ETE post-graduation has been providing studies and surveys on interaction technologies, as Augmented, Virtual and Cross Reality, to support the institute's satellite operations and developments activities in the future. This chapter describes some of the initiatives undertaken in the ETE post-graduation sector.

Resumo

O Instituto Nacional de Pesquisas Espaciais (INPE) é o principal centro de pesquisas do setor espacial no Brasil. Dentre as principais atividades de pesquisa e desenvolvimento no INPE, encontra-se a Engenharia e Tecnologia Espaciais (ETE), área de atuação voltada para o desenvolvimento de sistemas e tecnologias espaciais. Atualmente, a pós-graduação em Engenharia e Tecnologia Espaciais tem realizado pesquisas e estudos com tecnologias de interação, como Realidade Aumentada, Virtual e Cruzada para apoiarem as atividades de operações e desenvolvimento de futuros satélites do instituto. Este capítulo apresenta as iniciativas atuais realizadas na área da pós-graduação da ETE.

1.1. Introdução

A área de Engenharia e consequentemente, seus processos e produtos, são os primeiros setores a serem beneficiados por novos desenvolvimentos em interação, antes mesmo do consumidor final. Novas metodologias de interação indicam novos caminhos para solucionar problemas, permitem novas abordagens, novas maneiras de visualizar e

C.4 Structuring on-demand Software User Interfaces based in Spatial Augmented Reality to Control Hardware (Arduino) (Construção de interfaces on-demand baseadas em Realidade Aumentada Projetiva para Controle de Hardware (Arduino)

Capítulo

1

Construção de interfaces *on-demand* baseadas em Realidade Aumentada Projetiva para Controle de Hardware (*Arduino*)

Christopher Shneider Cerqueira, Claudio Kirner, Ana Maria Ambrosio

Abstract

This chapter aims to present the structure Spatial Augmented Reality Interfaces, created on-demand to control hardware. Usually, the Augmented Reality (AR) interfaces are created before the software is deployed, however, at an engineering environment (and other), there are cases that the AR interface must be able to be created and expanded in execution time. In order to accomplish this on-demand requirement, it is necessary to track changes in the real structural elements and attach, in execution time, corresponding virtual elements to it. This chapter shows the steps to create this type of environment.

Resumo

Este capítulo trata da estruturação de interfaces baseadas em Realidade Aumentada Projetiva (RAP), on-demand para controle e hardware. Geralmente, a construção das interfaces baseadas em Realidade Aumentada (RA) é realizada antes da liberação do produto para uso, porém num ambiente de engenharia (ou outros), podem ocorrer casos que a interface de RA precise ser criada e expandida de acordo com o seu uso. Para isso é necessário rastrear alterações na estrutura real e anexar, em tempo de execução, os elementos da estrutura virtual correspondente. Esse capítulo mostra os passos para criar esse tipo de ambiente.

1.1. Introdução

As definições iniciais de Realidade Aumentada (RA) contemplam a necessidade do registro tridimensional de imagens, levando muitos a pressupor que RA deve somente conter interfaces com interação 3D. Porém, uma definição mais atual, dada por Kirner (2011) já exclui a necessidade do registro de conteúdos exclusivamente em 3D:

C.5 A Model Based Concurrent Engineering Framework using ISO-19450 Standard

A Model Based Concurrent Engineering Framework using ISO-19450 Standard

7th International Conference on Systems & Concurrent Engineering for Space Applications

- SECESA 2016 -

5-7 October 2016

Universidad Politécnica de Madrid (UPM)
Spain

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INTRODUCTION

The engineering of complex systems increasingly involves interconnected elements that are not necessarily from the same domain. Generally, those "engineered systems" takes into account more than one nature of knowledge, as: electrical, mechanical, chemical, logical, computing, etc. and they are known as Coupled Multidisciplinary Complex Systems. The Space Engineering, in special, deal with a highly coupled interdisciplinary complex system to achieve the needs of the stakeholders, using knowledge from disciplines as: electrical and electronics, mechanical, propulsion, programmatic, electronics, software, communication, aerodynamics, space dynamics, control, data distribution. [1]

In order to organize the development of Space Systems, space agencies divide the life-cycle in phases, from the elicitation and understanding of the stakeholder's needs to the satellite disposal, passing through the development, integration and operation phases. [1] [2] [3]

The system design choices made during the life-cycle in first phases have a strong impact into the design, cost, and schedule of the system to be developed. The first architectural choices must have a certain level of preciseness in order to avoid further design changes and bigger impact on the next developing phases. In this sense, the first conceptual decisions used to take several months because of the several meetings and the excess of required reports. Each discipline specialist (engineer or not) propose their concepts (in reports), which in later meetings will be turned in the designs of alternatives solutions [1]. The System Engineering Handbook of NASA[1] says that the first phase can take years, and the information required to the architecture alternatives are pointed through several loosely connected papers that investigate design options to meet certain mission criteria [2]. To speed-up the conceptual decisions, two approaches can be found in the literature: System Engineering and Concurrent Engineering.

System Engineering can be summarized as an organization of engineering practices added with management practices to improve the traceability, reuse, organization and collaboration of systemic data. These practices have several branches of possible approaches; one of them is the Model Based System Engineering (MBSE). The essential and common element of the MBSE's life-cycle activities and processes are the virtual (or physical) models. Models are a formal specification of a function, structure or behaviour that mimics an application of a system [4]; models have to

[1] NASA stands for National Aeronautics and Space Administration

C.6 Creating and maintaining a workshop for graduate course in space engineering and technology and its usefulness to the training of future researchers

Creating and maintaining a workshop for graduate course in space engineering and technology and its usefulness to the training of future researchers.

By Yassuda, Irineu dos Santos[1]; Oliveira, Mônica Elizabeth Rocha de[2]; Lopes, Igor Mainenti Leal[2]; Morais, Marcelo Henrique Essado de[2]; Gondo, Suely Mitsuko Hirakawa[2]; Oliveira Junior, Eloy Martins[2]; Cerqueira, Christopher Shneider[2]; Nono, Maria do Carmo[2].

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Starting on an initiative of the students, the Workshop of Space engineering and technology (WETE) has the proposal to promote the exchange of experiences, disseminate the research lines and interests of the different courses of the Space Engineering and Technology graduate course of the National Institute for Space Research (INPE. The event is an opportunity for students of the graduate Program in Space Engineering and Technology to produce, write and publish own first scientific works and also to organize an event to disseminate knowledge. Each year, a new Commission is nominated to project the event; organize tasks and look for financial and institutional support to carry out the Workshop. WETE has been held annually since 2010, despite some difficulties that persist in happen every year.

Key Words: Future Researchers, Space Education, Space Workshop.

1. Introduction

The National Institute for Space Research (INPE) has the mission to produce high quality of space science and technology and terrestrial environment areas, and to offer unique products and services for Brazilians benefit.
INPE's headquarters is located in Sao Jose dos Campos, but it also has facilities in other places around the country (Figure 1). The Institute develops research in the areas of Space and Atmospheric Sciences, Space Engineering and Technology, Earth observation by satellites, Meteorology and Environmental Changes, [1].

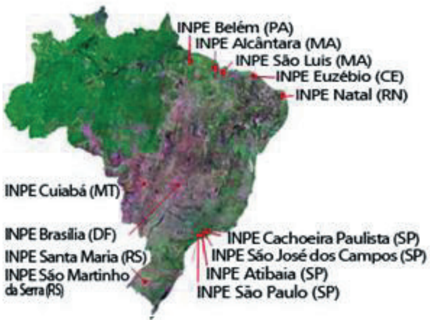

Fig 1. INPE's facilities around Brazil [1].

Although the INPE is not a full-dedicated academic institution, it has strong and large graduate courses on its research and technological areas, at master, doctoral and post-doctoral levels. This academic structure, developed from 1960's, is very important for the Institute, and the graduate students are involved in several important research projects developed by the institution [3].
The Institute offers, nowadays, the following graduate courses, all of them related to professional research and technological areas of the Institute: Astrophysics, Space Engineering and Technology, Space Geophysics, Applied Computing, Meteorology, Remote Sensing, and Earth Systems Science.
The INPE's graduate course, as a whole, is regulated by a committee composed by representatives of students of each course. In addition, each course has its own rules, which is made by a local Council elected by professors belonging to that course.
Due to the multidisciplinary nature and complexity related to the development of satellites, the course in Space Engineering and Technology is divided in four sub-areas, as following: Space Mechanics and Control; Combustion and Propulsion; Sciences and Technology of Materials and Sensors; Engineering and Management of Space Systems.
Each one of these sub-areas has its own rules, student representative and council of professors. In consequence, there are also a committee composed by these student's representatives, as well as a board of professors for the Space Engineering and Technology (SET) as a whole.
In middle of 2009, during one meeting between the student's representatives of each sub-area of SET graduate course, the representatives realized that they were used to discuss about rules and administrative proceedings, but that they had only little notion about the academic studies carried out from the others or by the sub-areas they were working in.
They also understood that if their 4 sub-areas belong to the same main area (SET) so that sub-areas must have points of intersection that should be better explored.
So, they decided to promote and internal event for each sub-area to speak up to the others and, in consequence, to

C.7 Towards an Automated Hybrid Test and Simulation Framework to Functional Verification of Nanosatellites' Electrical Power Supply Subsystem

Towards an Automated Hybrid Test and Simulation Framework to Functional Verification of Nanosatellites' Electrical Power Supply Subsystem

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Abstract

Tests in the space systems development life cycles are necessary to early verify requirements fulfillment, ensuring that the systems developed are correct. Nowadays, the efforts to develop miniaturized satellites and their test suite is increasing. Additionally, it is growing the initiatives is adopting MBSE (Model Based System Engineering) to automate the processes of: model design, simulation and model transformation. In MBSE development approach, models are the focus of the activities. The models describe requirements, functionalities and interfaces of a system, and their subsystems, considered here as "input models". In the context of an Electrical Power Subsystem (EPS), the design engineers have to (i) generate models representing solar array, battery, voltage regulators, loads, etc., for implementation solutions, and (ii) provide a verification plan, derived from requirements, to ensure the correctness of the developed functionality. In this scenario, the following question raises: "*how to interconnect the "input models" with verification plans, developed solutions and test executions?*" This paper aims to describe the structure of an automated verification framework to nanosatellite's EPS, using COTS (commercial-of-the-shelf) tools, such as MATLAB/Simulink®, MS. Excel®, and Arduino. We propose the models are as granular as in the verification plans (it is not possible to test internal behaviors from a black box artifact), so, each model represent an element in a unique file and a sequencer will integrate them, as a DSM (Design Structure Matrix) in Excel. In the context of the proposed framework, the subsystem verification enables three test configurations: fully simulated, fully simulated considering physical interface model, and hardware-in-the-loop (HIL). One advantage of the proposed framework is to reuse models from the start of the mission development, providing the reuse of these models throughout the life cycle, minimizing costs. The paper shows also results of development of the framework using an EPS behavioral model.

Keywords:
Automated Functional Testing, Simulation, Verification, Pico and nanosatellite, Electrical Power Subsystem, Hardware-in-the-loop.

1. Introduction

Developing Space Systems is a great challenge which involve the evolution of a need concept through multiple phases of product and process development until launch, and its proper use. Nanosatellites belong to the field of satellites designed to scientific research, alumni studies, technology validation and other

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Preprint submitted to Latin American IAA CubeSat Workshop *January 18, 2016*

C.8 A Framework for Automated Model Validation Applied to Picosatellite Electrical Power Subsystem

7º Workshop em Engenharia e Tecnologia Espaciais

São José dos Campos/SP - 23 e 24 de agosto de 2016

A Framework for Automated Model Validation Applied to Picosatellite Electrical Power Subsystem

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Abstract. *This paper aims to describe the structure of a framework for an automated pico and nanosatellite model validation, using commercial tools. It was proposed that the models are as granular as in the verification plans (it is not possible to test internal behaviors from a black box artifact), so, each model represent an element in a unique file and a sequencer will integrate them, as a DSM (Design Structure Matrix) in Excel. The framework enables the subsystem verification in different configurations as fully simulated models and HIL (Hardware-In-the-Loop). The paper also presents the application of the framework using a EPS (Electrical Power Supply) behavioral model and the results of this application.*

Keywords: Testing, Modeling & Simulation, Verification & Validation.

1. Introduction

Developing Space Systems is a great challenge which involve the evolution of a need concept through multiple phases of product and process development until launch, and its proper use. Nano and picosatellites belong to the field of satellites designed to scientific research, human resources training and technology validation in space environment. The development of pico and nanosatellite is of low cost; however, many of them do not succeed

An alternative approach to develop pico and nanosatellites systems is the intensive use of simulation models into a MBSE (Model-Based System Engineering) philosophy. Into this context, models help to: (i) define concepts, (ii) understand scenarios, (iii) derivate requirements, (iv) develop function models, (v) test prototypes, (vi) support acceptance and integration, (vii) train operation group, and (viii) test commands before send to the space segment [ECSS 2010a].

Working with models allows performing test in the models in earlier phases, focusing the big picture of its use, instead of test only at an AIT (Assembly, Integration, and Test) phase [Eickhoff 2009, ECSS 2010a].

This work shows, in the following sections, a framework to speed up the test of models into a MBSE environment, to verify model consistency with its required

C.9 Two Independent Processes of Verification Applied to a Satellite Simulator

7ºWorkshop em Engenharia e Tecnologia Espaciais
São José dos Campos/SP - 23 e 24 de agosto de 2016

Two Independent Processes of Verification Applied to a Satellite Simulator

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Abstract. *The process of a satellite simulator software verification demands high-efficiency in meeting realistic set of functional requirements. Based on this, the manual verification process becomes impracticable, thereby requiring an automated process. The satellite behavior that is represented here into tables of cause-effect rules requires to assure that the logic implemented in the simulator conforms to the logic of the cause-effect tables. Therefore, this survey suggests two different processes, and compare which one is most efficiently in detecting errors in the software. This processes involves the union of two techniques, Conformance and Fault Injection (CoFI) and Model Checking combined as a method to translate the tables of cause-effect into finite state machines as first input to automating the processes. The comparison will define which process generates the best logical coverage of the models and create test cases more efficient in finding more errors before not seen through the manual verification process.*

Keywords: Software Verification, Modeling & Simulation, Conformance Test, Systems Verification, Model-Based Test.

1. Introduction

Satellite operational simulators can be used throughout the life cycle of a satellite mission, as illustrated in Figure 1, generating benefits such as decrease of risk and cost. During the early phases, simulators are developed in the context of a specific domain or subsystem (e.g. Data Handling, Attitude Orbit Control Subystem (AOCS), Power, Thermal, Structures, etc.) or to address issues critical to the complete (integrated) system / mission. So they are typically used to support the mission analysis and mission product specification

C.10 Using ISO-19450 to Describe and Simulate a Smallsat Operational Scenario

8º Workshop em Engenharia e Tecnologia Espaciais São José dos Campos/SP - 09 e 10 de agosto de 2017

Using ISO-19450 to Describe and Simulate a Smallsat Operational Scenario

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Abstract. *Among the Concept Studies activities, one of the firsts is: Operational Scenarios Discovering. The scenarios allow the identification of the main functions and related entities to accomplish the desired space mission. Usually this activity is manually done, by hand drawing in paper/boards, and later using a drawing software tool. Discover entities and functions is not a trivial activity, not assessing, or even identifying, can cause rework and misguided architectures. The scenarios discovery requires successive refinements and the help of a methodology may turn this task feasible supported by a modelling tool. Entities and functions turn part of models that are refined until the architecture and concepts be delivered to the stakeholders. This paper presents an experiment using the Object Process Methodology, stated in ISO-19450, to describe an operational scenario of the first CTEE's program smallsat.*

Keywords: operational scenario, concept of operation, modelling and simulation, Object Process Methodology, concept studies.

1. Introduction

First phases of Space Engineering involve the study of the operational scenarios that the spacecraft system will pass through its operational phase, performing the designed mission. In Concept Studies, such operational scenarios provide the myriad of entities and functions that the system must deal with and accomplish, to later, compose the architecture and concepts design options. The Design Team, helped by the clients/stakeholders, identify scenarios available to: (i) identify the mission's elements, (ii) the entities, (iii) the infrastructure, and (iii) the operational processes. [ECSS, 2016]

These operational scenarios are usually build using loose modelled models, hand-drawn into paper, whiteboards, and so on. The information is then formalized in drawing tools, to later be submitted in the Mission Design Review (MDR). To reuse and be a seed to further designs, this loose model must be rewritten at a modelling environment, using some sort of modelling formalism, that allows retrieving the information and be transformed into other study domains. [CERQUEIRA 2016]

C.11 Describing Model Behaviour using OPM to an Operational Satellite Simulator (Descrição do comportamento de modelos para um Simulador Operacional de Satélites em OPM)

São José dos Campos/SP - 09 e 10 de agosto de 2017

8º Workshop em Engenharia e Tecnologia Espaciais

Descrição do comportamento de modelos para um Simulador Operacional de Satélites em OPM

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Resumo. *Uma das tendências da Engenharia Espacial é ser auxiliada por simuladores em todo o seu ciclo de vida. Na fase operacional, o simulador operacional é utilizado como ferramenta para mimetizar, no caso, um satélite em órbita, apoiando as atividades em solo. O simulador operacional precisa representar, em modelos, toda a convergência da experiência multidisciplinar e para isso precisa encontrar uma forma de expressar o comportamento com a exatidão necessária, e ao mesmo tempo clara para que não especialistas da área de computação possam: entender o modelo, validá-lo e utilizá-lo. Com base nisso, este artigo retrata um experimento realizado durante o Curso de Inverno de 2017, onde foi testado o OPM (Object Process Methodology), como linguagem diagramática para representar o comportamento de um subsistema de coleta de dados de um satélite. Neste experimento, inicialmente foram estruturadas as operações lógicas, dada a referência lógica de um simulador operacional, e posteriormente, foi realizada a validação destas operações utilizando um subsistema real.*

Palavras-chave: Object Process Methodology, OPM, OPCat, modelagem, simulação, simulador operacional

1. Introdução

Com o aumento gradual da complexidade de sistemas, se tornou cada vez mais difícil a compreensão e desenvolvimento das interações entre processos. Uma das abordagens para entender a complexidade de um sistema foi a modelagem e simulação em ferramentas computacionais. Essa abordagem permite criar um modelo com as características necessárias para um estudo de um certo problema, e a posterior execução

C.12 Alfa Project Mission Definition (Definição da Missão do Project Alfa)

8º Workshop em Engenharia e Tecnologia Espaciais

São José dos Campos/SP - 09 e 10 de agosto de 2017

Definição de Missão do Projeto Alfa

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Resumo.

Com o objetivo de proporcionar aos alunos do curso de pós-graduação em Engenharia e Tecnologias Espacial do INPE o contato com uma missão espacial real, assim como apoiar a convergência nos projetos de pesquisa da pós-graduação e atrair novos recursos, nasceu o Programa de Capacitação Tecnológica em Engenharia Espacial – CTEE. Baseado em nanossatélites, o primeiro sistema desenvolvido pelos alunos será o CubeSat Alfa. Este trabalho aborda a fase de definição dessa missão, desde a identificação dos objetivos da missão e stakeholders, captura e análise de necessidades, criação de concepções de missão, e a definição da missão. O trabalho utilizou entrevistas, análises e discussões de viabilidade, conceito de operação (CONOPS) e as lições aprendidas de outros projetos similares para compor o documento "Descrição de missão", que foi adaptado a partir da norma europeia ECSS-E-ST-10 Anexo B. O principal resultado do trabalho é a metodologia criada para a definição da missão Alfa. Devido ao andamento do Projeto durante este trabalho, apenas resultados parciais da aplicação dessa metodologia serão apresentados.

Palavras-chave: CubeSat; Definição de missão; Projeto Alfa.

1. Introdução

Desde 2003, quando o padrão CubeSat foi criado por professores das Universidades de *Stanford* e *Calpoly*, a utilização dessa tecnologia para fins educacionais tem se mostrado muito promissora. Dessa forma, o nanossatélite é utilizado para exercitar na prática conceitos aprendidos nas aulas de engenharia aeroespacial, mecânica, elétrica, computação, entre outras. Com baixo custo e curto tempo de desenvolvimento, esse tipo de projeto se mostrou uma opção viável para alunos do curso de pós-graduação em Engenharia e Tecnologia Espacial do INPE terem contato com uma missão espacial real, contribuindo também para outros objetivos como apoiar a convergência entre os

C.13 Data Collection Subsystem Modelling and Simulation using Simulink

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Data Collection Subsystem Modeling and Simulation Using Simulink

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Abstract. *TThis article presents the result of an experiment developed during the short internship of the Winter Introductory Course on Space Engineering and Technology at INPE which supported the SIMCBERS simulator modeling and verification. It was implemented a performance model of the Data Collection Subsystem using Simulink. The results that came from this experiment were very satisfying, because it was possible to demonstrate, in an easy and quick implementation of the Subsystem in a graphic language, how to verify the performance requirements and to validate the behavior models of a subsystem.*

Keywords: Modeling & Simulation, Verification & Validation, Data Collection Subsystem (DCS).

1. Introduction

The Winter Course on Space Engineering and Technology takes place at Brazilian Institute of Space Research (INPE) every winter term. Its main goal is to give to undergrads basic information on space engineering and technology. The activities include seminars to present INPE's research areas and a short internship in which the student can develop a practical activity. [CI 2016]

The practical activity of the short internship, developed in 2016 under our tutoring, consisted of implementing and to simulating a Subsystem Model of the CBERS-4 Satellite Operational Simulator (SimCBERS), under development, and to compare the results against the results of the existing simulations. The developed activity included, mainly, three areas: (i) Modeling and Simulation, (ii) Verification and Validation, (iii) Satellite Subsystem.

The main goal of the proposed activity was to validate the concept adopted to model the subsystem, now using another platform, in this case Simulink, as a way to

C.14 Initial Risk Management in Educational and Technological Space Missions (Gerenciamento de riscos na fase inicial de uma missão espacial de iniciativa educacional e tecnológica)

8º Workshop em Engenharia e Tecnologia Espaciais

São José dos Campos/SP - 09 e 10 de agosto de 2017

Gerenciamento de riscos na fase inicial de uma missão espacial de iniciativa educacional e tecnológica

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Resumo. *Missões espaciais enfrentam grandes riscos e desafios tecnológicos, científicos e gerenciais. Cada projeto é único e uma abordagem correta é essencial para seu sucesso. O objetivo deste artigo é apresentar o gerenciamento de riscos na fase inicial da missão espacial Alfa, uma iniciativa do programa de Capacitação Tecnológica em Engenharia Espacial. Os resultados evidenciam as abordagens utilizadas de simplificação de norma aplicável, inclusão de boas práticas de gerenciamento de incertezas e aplicação de planejamento em ondas sucessivas, adequadas às necessidades do projeto.*

Palavras-chave: Riscos; Incertezas; Planejamento em ondas sucessivas; Capacitação Tecnológica em Engenharia Espacial; Missão Alfa.

1. Introdução

A exploração espacial envolve enormes riscos e enfrenta desafios de engenharia, científicos e gerenciais sem precedentes, quase todas as missões têm características únicas e despertam um interesse público [Sauser, Reilly, & Shenhar, 2009]. Um dos mitos mais comuns na disciplina de gerenciamento de projetos é o pressuposto de que todos os projetos são iguais e podem ser gerenciados com o mesmo conjunto de processos e técnicas, mas na realidade os projetos diferem entre si e a adequação da abordagem correta é fundamental para o sucesso do projeto [Shenhar et al., 2005].

Ward e Chapman [2003] sugerem transformar o gerenciamento de riscos em gerenciamentos de incertezas do projeto, devido a que a abordagem tradicional de gerenciamento de riscos encoraja uma perspectiva de risco somente como ameaça e associado a eventos e não a fontes mais gerais de incerteza significativas. A abordagem proposta abrange gerenciar ameaças, oportunidades e suas implicações, além de explorar e compreender as origens das incertezas do projeto antes de procurar gerenciá-las.

Projetos relacionados a trabalhos inventivos envolvem fortes elementos de descoberta, mudanças de escopo e os requisitos tendem a surgir e evoluir à medida que o projeto se concretiza. O planejamento de projetos pela abordagem de ondas sucessivas [Githens, 1998] é uma abordagem iterativa faseada para o desenvolvimento de projetos inventivos, que equilibra processo estruturado com flexibilidade. Em um ambiente de mudanças, os gerentes de projetos devem desenvolver estratégias robustas para responder a ambientes dinâmicos, alavancando riscos e oportunidades para criar valor ao projeto.

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