UNIVERSITY OF BELGRADE
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# APPLICATION OF VIRTUAL WORLDS IN AGENT THEORY RESEARCH AND ENGINEERING EDUCATION

- Doctoral Dissertation -

Belgrade, 2022.

УНИВЕРЗИТЕТ У БЕОГРАДУ
ЕЛЕКТРОТЕХНИЧКИ ФАКУЛТЕТ

Владимир М. Петровић

# ПРИМЕНА ВИРТУЕЛНИХ СВЕТОВА У ИСТРАЖИВАЊУ ТЕОРИЈЕ АГЕНАТА И ИНЖЕЊЕРСКОМ ОБРАЗОВАЊУ

- Докторска дисертација -

Београд, 2022.

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**Dissertation title:** "Application of Virtual Worlds in Agent Theory Research and Engineering Education"


**Abstract:**

The focus of this doctoral dissertation is on exploring the potentials of virtual worlds, for applications in research and education. Regarding this, there are two central aspects that are explored in the dissertation. The first one considers the concept of autonomous agents, and agent theory in general, in the context of virtual worlds. The second aspect is related to the educational applications of virtual worlds, while especially focusing on the concept of virtual laboratories. An introduction to basic terminology related to the subject is given at the start of the dissertation. After that, a thorough analysis of the role of agents in virtual worlds is presented. This, among others, includes the analysis of the techniques that shape the agent's behavior. The development of the virtual gamified educational system, specially dedicated to agents is then presented in the dissertation, along with a thorough description. While, in the end, analysis of the concept of virtual laboratories in STE (Science, Technology, and Engineering) disciplines is performed, and existing solutions are evaluated according to the criteria defined in the dissertation.



**Keywords:** artificial intelligence, agent theory, autonomous agents, virtual worlds, virtual laboratories, robotics, computer games, education

**Scientific field:** Electrical Engineering and Computer Science

**Scientific subfield:** Artificial Intelligence

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**Наслов докторске дисертације:** “Примена виртуелних светова у истраживању теорије агената и инжењерском образовању”

**Апстракт:**

Фокус ове докторске дисертације је на истраживању потенцијала виртуелних светова за примене у истраживањима и образовању. У вези са тим, постоје два главна аспекта која су обрађена у дисертацији. Први аспект се тиче концепта аутономних агената, као и теорије агената у целини, а у контексту виртуелних светова. Други аспект је везан за примену виртуелних светова у образовању, при чему је посебан акценат стављен на виртуелне лабораторије. На почетку дисертације је дат кратак увод који се тиче терминологије и појединих појмова везаних за област којом се ова дисертција бави. Након тога је представљена систематична и темељна анализа улоге агената у виртуелним световима. Између осталог, ово укључује и анализу техника потребних за обликовање понашања агената. Потом је у дисертацији детаљно представљен развој оригиналног виртуелног образовног система посвећеног агентима. На крају, анализиран је концепт виртуелних лабораторија у НТИ (наука, технологија, инжењерство) дисциплинама и извршена је евалуација постојећих решења у складу са критеријумима који су дефинисани у дисертацији.

**Кључне речи:** вештачка интелигенција, теорија агената, аутономни агенти, виртуелни светови, виртуелне лабораторије, роботика, рачунарске игре, образовање

**Научна област:** Електротехника и рачунарство

**Научна подобласт:** Вештачка интелигенција

**УДК број:** 621.3

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*"You're unlikely to discover something new without a lot of practice on old stuff, but further, you should get a heck a lot of fun out of working out funny relations and interesting things."*

Richard P. Feynman (1918. – 1988.)

# Introductory Notes

We will hereby describe the organization of the dissertation, briefly elaborate on its content, and present its contribution, as well as the impact and metrics of the published papers related to the doctoral dissertation.

## Dissertation Outline

The text of the dissertation is organized through four main chapters. Although they are highly interconnected, each chapter of the dissertation is aimed to be as much self-contained as it is possible. Following that manner, each chapter ends with a list of relevant references. All the references in chapters are carefully chosen and organized in APA style. Furthermore, great consideration is given to a precise and detailed citing of the selected references.

Chapter 1 represents an introductory text about the concept of virtual worlds. The overall aim is to briefly introduce a potential reader to the origins, taxonomy, and research potentials related to this subject, which are necessary as a solid foundation for the rest of the dissertation.

Chapter 2 is dedicated to the agents and their role in the virtual worlds. Among others, this chapter will provide a thorough and detailed analysis of techniques for the shaping of their behavior, as well as the unique wider theoretical framework of the elaborated subject. One could notice that

AI (Artificial Intelligence) has a long tradition as a scientific field, with tremendous achievements accomplished in the decades behind us. At the same time, in the last few decades, we have witnessed the rising popularity of interactive computer games and multi-user virtual environments, resulting in millions of users inhabiting these virtual worlds. This chapter deals with the intersection of AI and virtual worlds, focusing on autonomous agents and among others exploring the potential implications toward human-level AI agents. It offers a unique multidisciplinary approach to the subject, in order to give a comprehensive view of the elaborated problems and the way they are interrelated. Benefits coming from this kind of broad study are twofold: on one hand, research on advanced agents in the virtual worlds is the necessary ingredient of their further evolution; and on the other hand, the virtual worlds represent an excellent platform for research on numerous problems related to the challenging field of AI.

Chapter 3 will represent the newly developed AViLab (Agents Virtual Laboratory) software system, specially dedicated to agents. The already mentioned development and increased popularity of interactive computer games, metaverses, and virtual worlds in general, has over the years attracted the attention of various researchers. Therefore, it is not surprising that the educational potential of these virtual environments (e.g., virtual laboratories) is of particular interest to a wider scientific community, with numerous successful examples coming from different fields, starting from social sciences, to STEM disciplines. However, when it comes to agent theory, which is a highly important part of the general AI (Artificial Intelligence) research focus, there is a noticeable absence of such educational tools. To be more precise, there is a certain lack of virtual educational systems dedicated primarily to agents. That was the motivation for the development of the AViLab gamified system, as a demonstration tool for educational purposes in the related subject of agent theory. The developed system is thoroughly described in this chapter. The current version of the AViLab consists of several agents (developed according to the agenda elaborated in the chapter), aiming to demonstrate certain insights into fundamental agent structures. Although the task imposed to our agents essentially represents a sort of “picking” or “collecting” task, the scenario in the system is rather gamified, in order to be more immersive for potential users, spectators, or possible test subjects. This kind of task was chosen because of its wide applicability in both, gaming scenarios and real-world everyday scenarios. In order to demonstrate how AViLab can be utilized, we conducted an exemplar experiment, described in the chapter. Alongside its educational purpose, the AViLab system also has the potential to be used for research purposes in the related subjects of agent theory, AI, and game AI, especially regarding future system extensions (including the introduction of new scenarios, more advanced agents, etc.).

Chapter 4 is dedicated to the more detailed analysis of educational aspects of virtual worlds. Special emphasis will be given to the virtual laboratories concept. Namely, laboratory exercises are an extremely important aspect of science and engineering education. They often represent an inevitable part of the curriculum and educational process itself. Different lab experimentation scenarios enable students to get deeper insights into the theoretical foundations, and at the same time interconnect gained theoretical knowledge with practical applications. Therefore it is not surprising that their virtual alternative is in the focus of scientific interest. For the purpose of analysis, we defined evaluation criteria necessary for the assessment of the selected virtual laboratory solutions, that will be described in this chapter. While investigating the concept of virtual laboratories in this chapter, special emphasis will be given to robotics, as its multidisciplinary nature gives us a solid foundation for a deeper understanding of the mentioned evaluation criteria and the core ideas behind the concept of virtual laboratories. Furthermore, the mentioned emphasis on robotics is also motivated by the expertise gained through the research work on the concept of the virtual laboratory for mechatronic systems (developed by the joint effort of the team of researchers at the School of Electrical Engineering, University of Belgrade).

## Impact, Metrics, and Contribution

During the research process, as a direct result of working on this dissertation, several papers are published in eminent international journals, as well as at international conferences. The following list of these papers includes only articles indexed by Scopus and Web of Science (WoS SCI list) scientific bases, as the most relevant. Furthermore, all relevant data (in full form) regarding each paper are listed, including the appropriate (or last available) journal impact factor and appropriate journal ranking.

Consequently, one should notice that (as it is expected) large quantities of the text in this dissertation are directly reproduced from some of those publications. One should also notice that in the following chapters, we will not especially cite and underline the extracted text from the mentioned authored papers (already listed here), as this is considered to be somewhat unnecessary and would tend to make a certain confusion and decrease in overall readability of the dissertation.

**At this point, we will just briefly mention the main contributions of the published journal papers, as they represent a core material supporting the doctoral dissertation:**

- The main contribution of the paper [1] is reflected in the development of the unique, original, gamified virtual educational system for introduction to agent theory fundamentals.

- The main contribution of the paper [2] represents a unique multidisciplinary study on the role of agents, their autonomy, and intelligence, in the context of virtual worlds.

- The main contribution of the paper [3] is reflected in a unique analysis on the subject of virtual laboratories in STE (Science, Technology, and Engineering) disciplines.

**As of 20.02.2022, the listed papers are cited:**

**728 times** according to the Google Scholar database,

and **370 times** according to the Scopus database.

**International Journals:**

[1] **Vladimir M. Petrović**, Branko D. Kovačević, "AViLab – Gamified Virtual Educational Tool for Introduction to Agent Theory Fundamentals", *Electronics*, 11(3):344, 2022.

***(section:** Computer Science & Engineering**; special issue:** "Virtual Reality & Scientific Visualization")*

**Journal impact factor '20 = 2.397**

| | |
|---|---|
| Ranked 104/162 | in "Computer Science, Information Systems" |
| Ranked 138/273 | in "Engineering, Electrical & Electronic" |
| Ranked 79/162 | in "Physics, Applied" |

[2] **Vladimir M. Petrović**, „Artificial Intelligence and Virtual Worlds – Toward Human-Level AI Agents“, *IEEE Access*, Volume 6, pp. 39976-39988, 2018.

**Journal impact factor '18 = 4.098**

| | |
|---|---|
| Ranked 23/155 | in "Computer Science, Information Systems" |
| Ranked 52/264 | in "Engineering, Electrical & Electronic" |
| Ranked 19/87 | in "Telecommunications" |

***Note:* In December of 2018., this paper entered the list of 100 most popular papers in the entire IEEE Xplore digital library.**

[3] Veljko Potkonjak, Michael Gardner, Victor Callaghan, Pasi Mattila, Christian Guetl, **Vladimir M. Petrović**, Kosta Jovanović, "Virtual Laboratories for Education in Science, Technology, and Engineering: a Review", *Computers & Education (Elsevier)*, Vol. 95, pp. 309-327, 2016.

**Journal impact factor '16 = 3.819**

| | |
|---|---|
| Ranked 11/105 | in "Computer Science: Interdisciplinary Applications" |
| Ranked 7/235 | in "Education & Educational Research" |

***Note:* In April of 2018., "Elsevier Educational Journals" announced that this paper entered the list of "Top Cited Research in Technology and Education", regarding the papers published in 2016.**

**International Conferences:**

[4] **Vladimir M. Petrović,** „An Inexpensive Design of Agent's Behavior During a „Picking Task“ in a Simulated 2-D Virtual Game-Like Evironment“, *Proceedings of the IEEE 2021 Zooming Innovation in Consumer Technologies Conference*, pp. 16-20, May 2021.

[5] **Vladimir M. Petrović**, Branko Nikolić, Kosta Jovanović, Veljko Potkonjak, "Development of Virtual Laboratory for Mechatronic Systems", *Advances in Robot Design and Intelligent Control (Proceedings of the 25th Conference on Robotics in Alpe-Adria-Danube Region (RAAD 2016))*, Springer International Publishing AG, pp. 622-630, 2016.

*"Nobody ever figures out what life is all about, and it doesn't matter. Explore the world. Nearly everything is really interesting if you go into it deeply enough."*

Richard P. Feynman (1918. – 1988.)

# Chapter 1

## A Brief Introduction to Virtual Worlds: Origins, Taxonomy, and Research Potentials

In this chapter, we aim to briefly introduce a potential reader to basic terminology, origins, taxonomy, and research potentials of virtual worlds (in general), which should serve as a solid foundation for a better understanding of the related subjects elaborated in the rest of the dissertation. One should notice that some of the standpoints elaborated in this chapter, will be repeated in other parts of the dissertation. At the same time, some of the topics mentioned in this chapter will be more thoroughly elaborated in other parts of the dissertation.

The idea of artificial or virtual reality (a simulated world where people can interact), has attracted a lot of attention several decades ago. At that time, virtual reality was defined as the HCI (human-computer interface) that includes simulations and interactions in real-time, using multiple sensors with the aim to provide a proper excitation of human senses (vision, hearing, touch, smell, and taste) (Burdea & Coiffet, 1994). Head-mounted displays, 3-D sound, sensing gloves, force-touch feedback, etc., were implemented in order to make a realistic illusion of presence at some virtual location and to provide users with the sense of immersion (Burdea & Coiffet, 1996; Burdea, 1999; Lloyd, Beis, Pai & Lowe, 1999; Adams & Hannaford, 1999). However, expectations and demands coming from the virtual reality concept were much higher than the technological capabilities at that time (Ellis, 1994; Bainbridge, 2007).

Development of computer graphics in combination with internet technology heavily influenced the evolution of one different sort of virtual interaction – computer games. At this point, one should notice, that when it comes to modern computer games and their content-rich environment, we must go deep into the past in order to understand the very roots of their existence and development. Namely, different sorts of games have attracted the attention of humans for centuries. This fascination can be traced all the way to ancient history. The illustrative examples are board games such as The Royal Game of Ur (Middle East), or Senet (Egypt), which are dated to 2000-3000 BC. Board games, card games, and all different kinds of their variations developed during the centuries, representing not only an entertainment tool but a problem-solving platform as well. Consequently, these games became an object of interest of many researchers coming from different areas of science. Therefore it is not surprising that analyzing the game dynamics, and deep understanding of algorithms related to successful game playing become rooted in the very foundations of AI (Artificial Intelligence) as a scientific field. The successful playing of complex games such as Chess (Campbell, 1999; Campbell, Hoane, & Hsu, 2002), Checkers (Schaeffer, Lake, Lu, & Bryant, 1996; Schaeffer et al., 2007), Go (Silver et al., 2016), and many others, occupied the attention of the AI community to the present day.

The development of computer technology, enabled a world of games to rapidly evolve and expand, providing the players with much more visual stimulants than a playing board or a deck of cards. Massively multiplayer online role-playing games (MMORPGs) became especially widespread. One of the most illustrative examples is WoW (World of Warcraft) – with millions of open accounts, and more importantly millions of active subscribers as well. Some studies have shown that the population of players belongs to a broad age range, with demographic characteristics that widely vary (Yee, 2006). The popularity of this sort of virtual interaction can also be recognized in the fact that according to some research studies, students spend up to 20 hours a week playing various online computer games (Thompson, 2011). Population size and diversity of users involved in these gaming worlds represent a very valuable potential for different research studies. It is reported (Yannakakis, 2012) that leading game developing companies (such as Blizzard and EA Games) collected and analyzed large data sets considering the player's behavior. Other companies also recognized the potential of gaming – e.g., IBM investigated the way successful playing of WoW leads to the improvement of strategic thinking techniques and leadership capabilities (IBM, 2007).

Further evolution of 3D computer games at one point led to something more socially complex – the development of MUVEs (multi-user virtual environments). These virtual environments, or "virtual worlds" as they are often called, attracted massive attention. One of the first examples (if not the first one) of MUVEs was "Active Worlds" developed and launched in the mid-90s. This platform is still active today, with the latest stable version released in 2019. There were many other successful examples too, such as There, Open Wonderland, or probably the most widely-known platform of this kind Second Life (bearing in mind its large-scale nature, Second Life can also be classified as a metaverse, or simply speaking a cluster of virtual worlds). Hundreds of thousands of users, represented via avatars (animated human-like characters), found in them a place to simultaneously interact and socialize (Messinger, Stroulia, Lyons, Bone, Niu, Smirnov, et al., 2009; Kumar, Chhugani, C. Kim, D. Kim, Nguyen, Dubey, et al., 2008).

At this point, one should notice that when the term "virtual world" is used, there is often a sort of confusion (or even misunderstanding) on the exact meaning. It should be noticed that some researchers use the term "virtual world", as a broader classification when referring to both – interactive computer games and MUVEs/metaverses (Kumar, et al., 2008). Of course, although they are very similar, it should not be forgotten that computer games and MUVEs/metaverses have different objectives (Messinger, et al., 2009). However, bearing in mind that virtual worlds can be defined (Kumar, et al., 2008) as computer-based simulated environments, in which users can interact between themselves or with artificial agents, this kind of terminology is rather justified and will be followed further in the dissertation. Therefore, by the term “virtual world”, we will consider a wide range of simulated virtual environments, no matter their size-level (micro or macro-level). Computer games, MUVEs, and metaverses will also be simultaneously used as terms, depending on what should be pointed out in a particular sentence.

As it could be noticed from the previous text, virtual worlds (in general) offer numerous possibilities for all kinds of scientific research, covering an entire spectrum of scientific disciplines. From social sciences to STEM disciplines, there are numerous illustrative examples of virtual worlds utilization for research & education purposes. According to the overall aim of the dissertation, we will focus on what we consider as two main aspects of these above-mentioned potentials of virtual worlds.

The first one is related to the research regarding the theory of agents, the concept of autonomous agents, and AI (including game AI) in general. Since we will thoroughly discuss these topics in the following chapters, we will not go into further details at this point, in order to avoid unnecessary redundancy.

The second aspect (often interconnected with the first one) is the educational potential of virtual worlds. This educational potential is utilized in many different manners, related to various interesting concepts, such as edutainment, serious gaming, or virtual laboratories. At this point we will elaborate this subject in a more general sense, therefore briefly analyzing the educational role of MUVEs, particularly on the Second Life example (as the “roof” representative of virtual worlds technology). While a more focused analysis of educational potentials (especially regarding the virtual laboratories concept) will be thoroughly discussed in some of the following chapters of the dissertation.

As we have already mentioned, Second Life can be observed as one of the most popular representatives of MUVE technology. Therefore, it is not surprising that we can identify many examples of its educational applications. It is recognized in the literature as a metaverse with the largest number of educational applications (Warburton, 2009). Regarding this, it is also reported (Barkand & Kush, 2009), that at one point more than three hundred higher-education institutions across the globe, conducted some sort of education & research activities in Second Life. According to (Messinger, et al., 2009), the list of those institutions included among others eminent universities, such as Harvard University, Princeton University, Stanford University, Vassar College, Delft University of Technology, etc.

What is particularly interesting, is the versatility of those educational applications, which is reflected in a number of different fields which utilize the Second Life platform. Social sciences somewhat naturally found an effective e-learning tool in the form of Second Life metaverse. However, other scientific fields also followed this trend. As an example, one could notice a number of reported applications in the field of medical-related education. Considering this, we could mention the “Nutrition Game”, created by Ohio University (see Boulos, Hetherington, & Wheeler, 2007), which represents one of the illustrative examples recorded in the literature. The aim of the researchers was to create a learning environment in which users can get knowledge about health-related impacts of fast-food diet, through experimentation related to eating habits. Another medical-related example recorded in the literature (Boulos et al., 2007; Wiecha, Heyden, Sternthai, & Merialdi, 2010) is an interactive laboratory dedicated to the field of genetics, called the “Gene Pool”. According to the authors of the above-mentioned papers, users of the “Gene Pool” were enabled to participate in a content-rich, immersive experience, aiming to help them learn the fundamentals of DNA structures.

A very interesting study was presented in (Prattichizzo, 2009), aiming to use Second Life for popularizing the highly multidisciplinary robotics field. Furthermore, the authors recognized metaverse as an effective tool for examining human-robot interaction. This study included creating the virtual RAS (Robotics and Automation) building at the virtual IEEE island in Second Life. A visitor of the RAS building can experience different kinds of robotics demo simulations, covering different aspects of robotics.


***Figure 1.1:*** *The IEEE RAS location at Second Life (figure extracted from Prattichizzo, 2009).*

Besides Second Life, other MUVEs, such as OpenSimulator, or Open Wonderland also found their educational perspective through numerous applications. However, we will not go into a further detailed analysis related to this subject, as this would go outside of our main focus, especially considering the rest of the dissertation.

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*"I would rather have questions that can't be answered than answers that can't be questioned."*

Richard P. Feynman (1918. – 1988.)

# Chapter 2

## Agents in Virtual Worlds

The popularity and continuous development of previously mentioned virtual interactive worlds, consequently enabled new research directions to be opened in various scientific fields (Bainbridge, 2007), including the field of Artificial Intelligence (Forbus & Laird, 2002). Among others, these virtual worlds are recognized as a fruitful ground for research in autonomous intelligent agents (Laird, 2001b), which will be the focus of this chapter.

Besides the field of AI itself, the development of intelligent agents can be identified as highly beneficial for virtual worlds as well. Therefore, this topic will be critically investigated from different perspectives, practical on the one side, and more abstract on the other – with the desire to elaborate and integrate valuable insights coming from both, the academic community and commercially oriented industry.

The chapter is organized in the following order. In Section 2.1, the role and significance of AI in virtual worlds will be discussed. Section 2.2 will provide an analysis of a number of AI techniques aiming to provide an autonomous intelligent behavior of agents. In Section 2.3 virtual agents will be placed in a wider theoretical framework, aiming to provide a unique approach to the subject of potential implications and requirements leading toward human-level AI agents. Concluding remarks will be elaborated in Section 2.4. In the end, a rich source of carefully chosen references used for this research study will be listed.

## 2.1 The Role of AI in Virtual Worlds

It should be noticed that despite the partial overlap, virtual worlds and earlier mentioned virtual reality represent very different concepts (Bainbridge, 2007). One of the crucial differences is reflected in the fact that MUVEs and modern computer games share a common property that differentiates them from old virtual reality ideas – most of the user sensation comes from the graphics displayed on the computer monitor. Advanced 3D graphics can be identified as the main ingredient of the tremendous success of virtual worlds in the past. However, despite the fact that state-of-the-art 3D graphics acts very persuasive, it is questionable if it can fully provide two elements that are identified in (Burdea & Coiffet, 1994) as a key issue – immersion & interaction. One should notice that these two elements are mutually dependent. As it was defined in (Dede, 2009), immersion represents a subjective impression that the user participates in a realistic experience. In order to achieve a higher level of immersion, graphical visualization is necessary but not a sufficient requirement.

Therefore, there is often a point of view that the role of graphics in these virtual worlds came to the point where it can no longer represent a crucial enhancement of the user's experience (Laird, 2001b; Anderson, 2003). Not to mention that in the competitive game industry, a high level of graphics long ago became quite expected (Johnson & Wiles, 2001; Cass, 2002). Consequently, stepping up to the next level of believable and realistic experience implies that research efforts must be more oriented toward the behavior of the game inhabitants, rather than on the visual appearance of the environment. It is even reported that with the more complex visual appearance of the simulated world, the necessity for more complex NPCs (non-player characters) is increasing (Zyda, 2005). Artificial intelligence is recognized as a crucial element that can largely contribute to virtual worlds (Forbus & Laird, 2002) since AI can make NPC's behavior more appealing and natural. A higher level of life-like behavior certainly affects the user's immersion to a large degree. Therefore, it is no surprise that the overall quality of the implemented AI is recognized as one of the main evaluation criteria of the successful games (Forbus & Laird, 2002; Johnson & Wiles, 2001; Nareyek, 2004; Laukkanen, Karanta, Kotovirta, Markkanen, & Rönkkö, 2004; Lim, Dias, Aylett, & Paiva, 2012). This is followed by a number of dedicated books dealing with the practical issues related to it (e.g., Steve Rabin's "AI Game Programming Wisdom" series).

In the early days of the field, the range of AI techniques used in games was very limited, focusing mostly on simple AI. Reasons were various: from the fact that some AI techniques are extremely complicated and require too much computational power, to the simple fact that sometimes advanced AI in games is considered unnecessary. Not to mention that graphics used most of the CPU power, in that way leaving a very small amount of processing resources for AI. This trend was changed to a great extent over the years, however, some of the issues remained. Numerous efforts were made in the past, in order to reduce a strong gap between academic AI and game industry developers (Forbus & Laird, 2002; Johnson & Wiles, 2001; Luck & Aylett, 2000), since these two are often burdened with different natures of their goals. Still, despite the different approaches, computer gaming worlds probably represent the "largest commercial application of artificial intelligence" (van Lent, Fisher, & Mancuso, 2004). The great potential that lies in applying academic AI research to virtual worlds is not beneficial only for their future development, but also for the field of AI itself. As it was observed (Forbus & Laird, 2002), virtual worlds with their rich content represent a challenging platform for advanced AI research, especially in the domain of autonomous intelligent agents.

### *2.1.1 Game Agents – NPCs*

Observing the past, one could notice that the behavior of game agents, or NPCs as they are usually referred to, was among the main focuses of game AI. Although there are some variations on what exactly qualifies as the NPC, the broadly accepted definition is that NPCs are all virtual world characters that are not controlled by a human user (no matter if they are acting as opponents, collaborators, or neutrally oriented supporting characters). As it was reported by some authors, an obvious distinction considering the commercial game AI on the one side and academic AI on the other could be noticed (Anderson, 2003; Cass, 2002; Nareyek, 2004). NPCs are maybe the best indicator of differences between the two, considering the nature of their goals.

The purpose of AI in games is rather simple – to create a better, more realistic gaming experience for users. This does not necessarily include the making of an advanced AI system. In a number of scenarios, NPCs are not designed to actually be intelligent, but rather to give an illusion of intelligent behavior. One could consider it as a sort of "smart" cheating. In the developer's point of view, this approach is rather logical and even encouraged (Cass, 2002), because in a very large percent simple illusion of intelligence can have the same effect as a more complex AI. Furthermore, in the majority of cases, it is less cost-effective and algorithmically simpler. So-called "suspension of disbelief" (Bates, 1992), has its roots in the widely known "Eliza effect" (Weizenbaum, 1966). Although the focus of this chapter is not on the illusion of intelligence, some aspects must be discussed in order to provide a deeper understanding of the topic in general. One of the illustrative examples that are describing this phenomenon can be found in many different games where the human user has computer-controlled opponents. In a common scenario, a group of hostile agents is acting in some environment and they are talking to each other: "Watch for your back", "Set up a perimeter", etc. Of course, they are randomly yelling these phrases, while at the same time acting absolutely independently without any intelligent collaboration. However, if this communication between NPCs is carefully designed, it can often produce a sense of intelligent behavior for a human user participating in a game, in that way increasing his level of immersion into the virtual gaming environment.

Another aspect of "cheating" is the omniscience of the NPCs. It is especially noticeable when a computer-controlled enemy is playing against a human player in some game scenario – in the majority of cases enemy agents possess unrealistic capabilities, especially when it comes to searching or decision-making speed. Related to the previous, one more aspect to be considered is the game difficulty. If the NPC is almost unbeatable, then the majority of players will lose their interest very fast. The same thing will happen if NPCs are too easy to beat. In order to prevent this kind of scenarios developers are trying to achieve a balance by designing opponents that are not stupid, but at the same time not too smart. In other words, aspects of cheating must be carefully implemented, in order to give an illusion of intelligent behavior. This challenging task is thoroughly analyzed by some authors (Lidén, 2004). Even though this kind of approach is inspired by gaming needs, an analog example (with a different motivation) can be found in academic AI. Alan Turing, which is widely considered as one of the founding fathers of AI, described a sort of intelligence test (later well known as Turing test) and in his seminal work (Turing, 1950) he analyzed the situation where machines are not making any mistakes: "It is claimed that the interrogator could distinguish the machine from the man simply by setting them a number of problems in arithmetic. The machine would be unmasked because of its deadly accuracy." In order to prevent this, a simple solution is proposed – machines should make intentional mistakes in order to deceive a human interrogator (Turing, 1950). We will later return to the Turing test in the context of NPCs.

## 2.2 Techniques Used for Shaping the Behavior of Game Agents

As it was already mentioned, NPC's behavior is commonly shaped with some of the AI algorithms. It is noticed that academic AI and game AI have different views on what qualifies as artificial intelligence (Millington & Funge, 2009). While the game industry mostly observes NPC's AI in a broad sense, including even some problems that have different nature, the academic community is often referring to NPC's AI in a more narrow sense, focusing only on the autonomous and intelligent behavior (Spronck, Ponsen, Sprinkhuizen-Kuyper, & Postma, 2006). In this section, special emphasis will be on algorithms and techniques used for decision making and learning, as they represent essential topics regarding the underlining idea of the chapter. We will briefly describe chosen techniques, provide examples (commercial and academic) of their implementation regarding the topic of intelligent agents, and discuss some of the benefits and drawbacks coming with their implementation.

### *2.2.1 Approaches Based on More Traditional Methods*

A number of successful AI programs were developed with Rule-based Systems, so it is not surprising that they are used for control of NPC's behavior since the very beginning of the game AI. Their structure consists of available knowledge (data) and a set of rules (if-then logic). Properly used, rule-based systems can provide a decently high degree of control and sufficient robustness. However, they are rarely used as a dominant method since in the majority of cases there are simpler and more efficient techniques to achieve desired behavior (Millington & Funge, 2009).

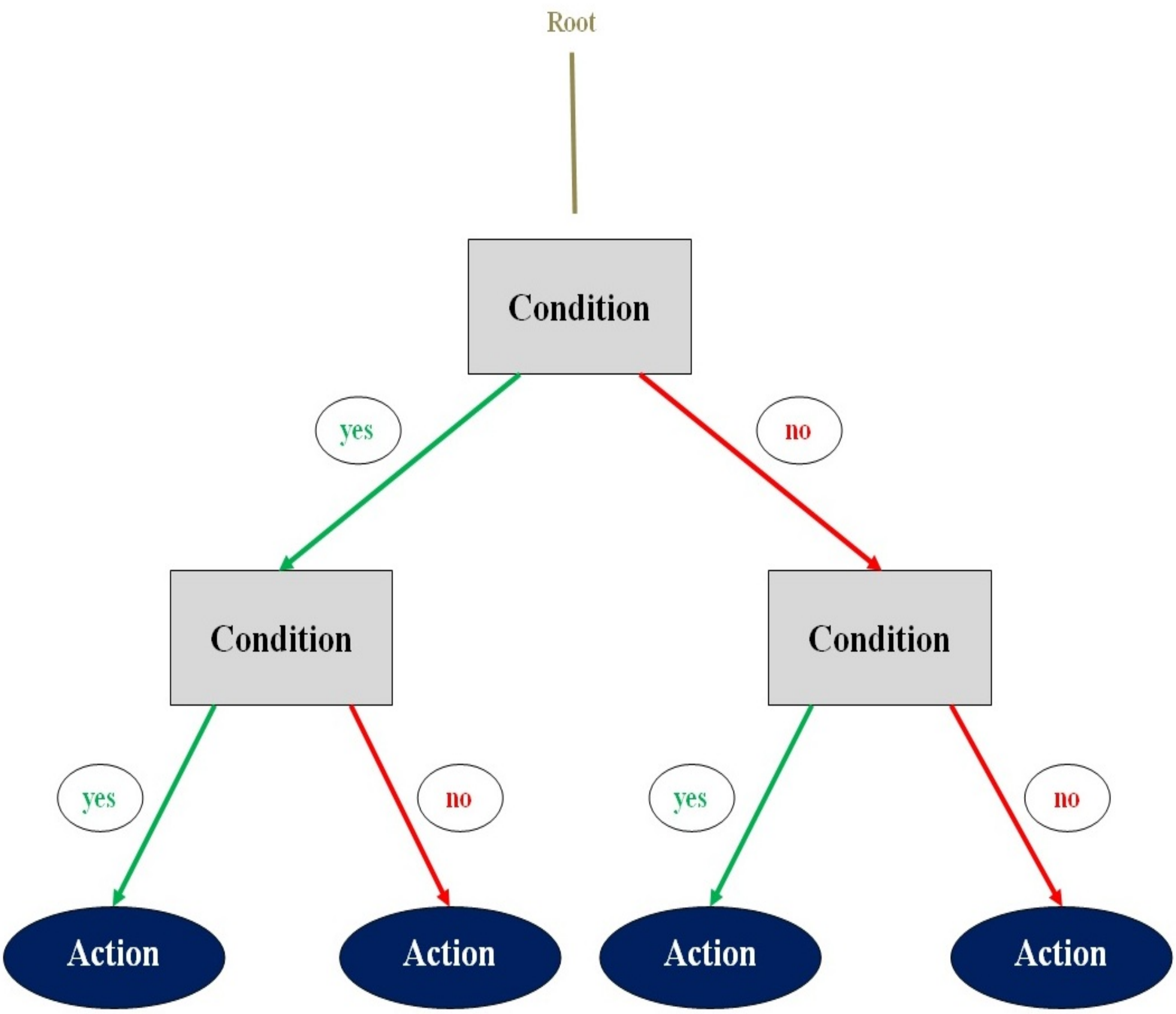


***Figure 2.1:*** *UML-like representation of an example of Decision Trees method implementation.*

According to (Millington & Funge, 2009), Decision Trees (example shown in Figure 2.1) are among the simplest decision-making mechanisms used in the game AI. In short terms, this hierarchical tree-like structure is organized in branch nodes and leaf nodes, where leaf nodes represent possible decisions. As it is described in (Alpaydin, 2010), it implements a divide-andconquer strategy. Decision trees can be used alone or in combination with other decision-making techniques. This algorithm is reasonably fast, easy to modify, and simple to understand, as it was mentioned at the start. Besides the already mentioned decision-making application, one of the most common techniques for inductive inference (Mitchell, 1997), decision tree learning is also rooted in the decision trees method. As one of the main advantages, this method offers high robustness considering the missing data. A number of decision tree learning algorithms are described in (Alpaydin, 2010; Mitchell, 1997). An interesting example, considering computer games, is the Black & White. Creatures in this game use AI software architecture called Belief-Desire-Intention derived from the theory of human practical reasoning (Bratman, 1987). It is based on several learning methods, such as the widely known ID3 decision tree learning algorithm (Quinlan, 1986), as well as neural networks and reinforcement learning. Depending on whether the creature does something wrong or right, the player can slap it (penalty, negative stimulus) or stroke it (positive stimulus). Creatures remember players' feedback and then according to it adapt their behavior.

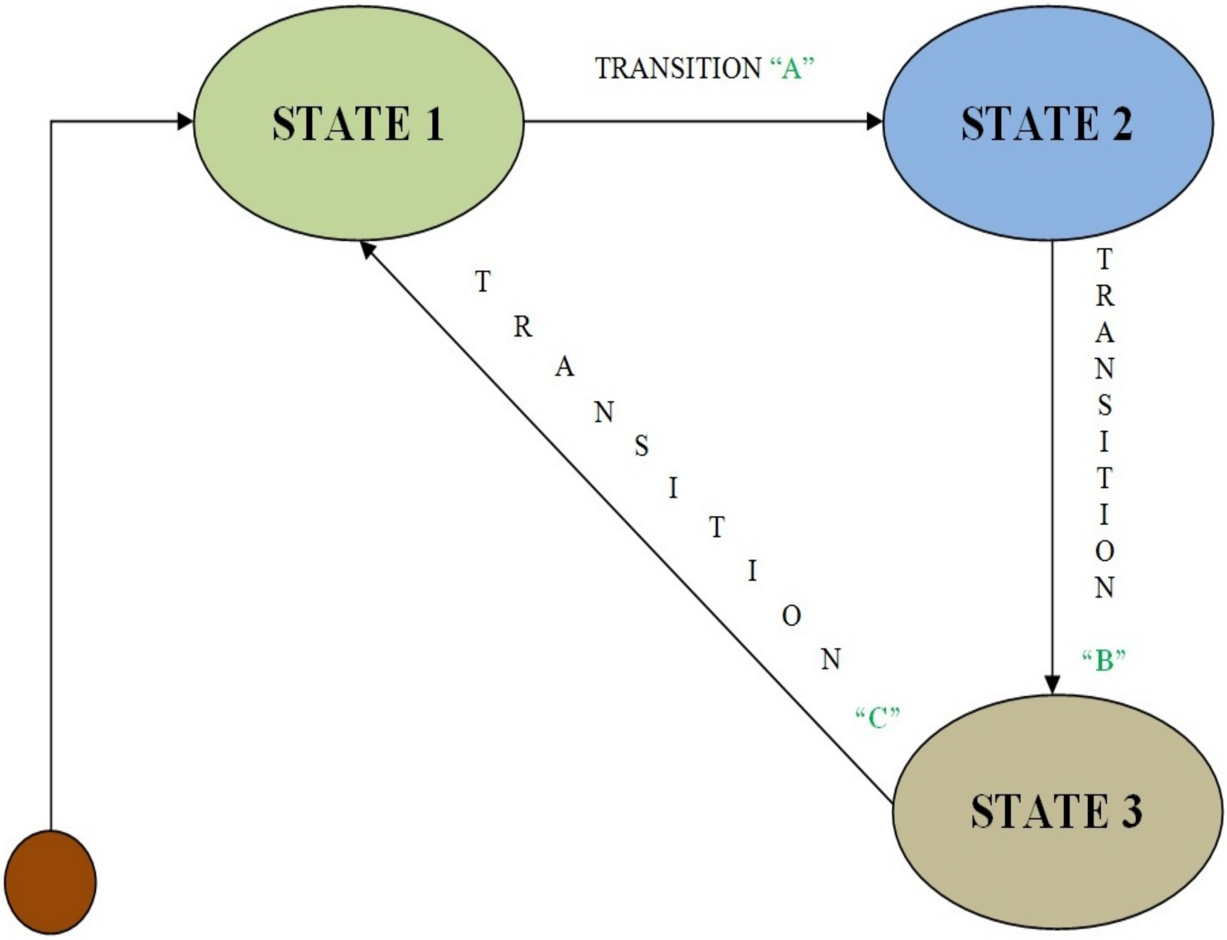


***Figure 2.2:*** *UML-like graphical representation of a simple FSM.*

Finite State Machines represent a well-known computational model. Although not always the most optimal solution, it is probably the most widely used technique in game AI development. A number of successful computer games, such as Half-Life series or Quake series used FSMs as a basis for the control of NPCs. The idea is rather simple: at any time, only one of a finite number of states is possible, and depending on the inputs that state could be changed. FSM is defined by its initial state, list of possible states, and transition conditions. FSMs use Boolean logic, thus a state can be active or inactive (true or false). Switching between the states changes the behavior of the NPC. FSMs are easy to implement, efficient (especially when it comes to simple NPC's behavior), compact, and very powerful algorithms, which makes them rather favorable in game development (Cavazza, 2000; Fu & Houlette, 2002). A UML-like graphical representation of a simple FSM is presented in Figure 2.2. However, they are often criticized for being too inflexible, causing them to behave inaccurately in complex and unpredicted scenarios. Further on, one of the main disadvantages in this approach is that number of states can rapidly overgrow, if we exaggerate the complexity of the desired behavior. This could be partially avoided by introducing sub-states into the systems, in that way creating hierarchical finite state machines (HFSMs) (Harel, 1987).

Several variations of FSMs are possible, including Fuzzy State Machines where fuzzy logic is used as an alternative for the Boolean logic. As a consequence, unlike the FSMs, the system could be in more than one state at a time. To be more precise, different levels of membership can be assigned to states. The introduction of multiple states, as well as fuzzy logic in general, gives a sense of more natural and realistic NPC's behavior. Although reasonably simple to implement, it must be taken into account that too many fuzzy states could lead to the rapid growth of the system complexity known as "combinatorial explosion". It should also be noted, that besides the fact that FuSMs have many advantages compared to standard FSMs (e.g., NPC's behavior is less predictable), the method is weaker in the terms of the problem generalization. There are numerous examples of FuSMs and fuzzy logic in virtual worlds reported in the literature (Anderson, 2003; Johnson & Wiles, 2001), especially when it comes to strategic and tactical games (e.g., Civilization: Call to Power).

Besides state machines, scripting is used in the majority of virtual worlds, when it comes to building an AI system. It should be noted that scripts are considered to be static and often tend to be very complex, which implies their problem with predictability and difficulty scaling (Spronck, Sprinkhuizen-Kuyper, & Postma, 2004). In order to solve this, dynamic scripting was described in (Spronck et al., 2006). This unsupervised online machine learning technique, which is based on reinforcement learning, aims to adapt AI to changing circumstances online, while the game is being played (Spronck et al., 2006; Spronck et al., 2004; Ponsen, Munoz-Avila, Spronck, & Aha, 2006). The algorithm is successfully tested on the Neverwinter Nights commercial game (Spronck et al., 2006). We will later return to the interesting topic of learning in computer games.

Behavior Trees gained their popularity in game AI community, with Halo 2 (see (Isla, 2005) for more implementation details). In the following years, BTs became the dominant method in game AI with a number of different implementations. Although not always the most efficient (traversal problem), this method represents a powerful tool for achieving complex NPC's behavior and a high level of control. In a certain way, BTs synthesize several exiting AI techniques and their strengths (Millington & Funge, 2009). BTs are functioning in a modular manner, having tasks/behaviors instead of states that are used in state machines. Although having some similarities with the earlier mentioned HFSMs (Millington & Funge, 2009), the approach is rather innovative. BTs solve many of the drawbacks found with state machines, such as maintenance issues. Removing or adding the specific state entails changes in the conditions of other states related to it. Depending on the number of states that are affected, this can be rather problematic as it increasingly opens the possibility for errors. With BTs possibility for errors is reduced, as nodes are behaving independently and therefore are not affected by changes in other parts of the system. Easy to maintain, reusable, scalable, extensible, and customizable (Marcotte & Hamilton, 2017), it is not surprising that behavior trees became a favorable tool for controlling of NPC's behavior.

Developers often use rather creative approaches in order to provide life-like behavior of the agents. The Sims is considered to be one of the games that heavily influenced the field of game AI. In this life simulation computer game, players can give orders and observe the life of a number of autonomous NPCs, called the Sims, while they interact with the environment. As it was observed in (Cass, 2002), the Sims "turned the concept of an AI inside out", with its "Smart Object" approach. The uniqueness of this concept was reflected in the fact that a large quantity of intelligence, especially regarding decision-making, is not incorporated in the NPCs per se. Namely, NPCs are equipped with the needs, but all the information considering the interaction with some object is in the object itself.

### *2.2.2 Non-Standard Approaches – Impact of Academic Research*

In complex virtual worlds, NPCs are faced with thousands of possible interactions. This makes the implementation of advanced AI very difficult (Spronck et al., 2006). Therefore, it is not surprising that virtual worlds mostly rely on previously described standard approaches, which are well proven and thoroughly tested. For a long time, more advanced AI methods that were primarily considered academic were avoided. These algorithms were often highly complicated, computationally expensive, and problematic for implementation when compared to state machines. Earlier in the text, we sporadically mentioned learning on several occasions. Observations on a wide range of possible machine learning applications to computer gaming worlds, in general, can be found in (Galway, Charles, & Black, 2008). NPCs that can learn and adapt, represent one of the intriguing topics to the academic community, since the ability to learn is one of the main characteristics of intelligent behavior. However, implementing learning algorithms (especially in real-time) to NPCs is still not widely applied in commercial computer games, and represents a problematic endeavor for developers. The main reason lies in unpredictability. A high level of autonomy and unpredictable behavior that often comes with advanced AI and machine learning is considered undesirable in games (Nareyek, 2004), as it can spoil playability. From all the previously said, it is clear why advanced AI algorithms were not considered as the best fit for real-time constrained systems, such as interactive computer games. After all, the goal of the game designers was to make AI only as complex as it was needed, so their reluctance toward the more complicated and often non-deterministic approaches was not surprising. Further on, programmers often did not know how to implement often abstract academic AI techniques in a practical manner (Cass, 2002). However, neural networks, evolutionary algorithms, and other bio-inspired methods, gradually found their place in some scenarios of game AI. At this point, one should notice that even the broad utilization of advanced AI does not imply that standard algorithms such as state machines are unnecessary. As it was noticed in (Nareyek, 2007), advanced AI systems very often need to use some of these standard algorithms at different system levels.

One of the illustrative examples when it comes to using academic methods in commercial games is the F.E.A.R., a blockbuster FPS (first-person shooter) game. Among others, the game AI system exploits the STRIPS (STanford Research Institute Problem Solver) logic, a pioneering automated planner developed almost a half-century ago at Stanford University (Fikes & Nilsson, 1971). Detailed explanations of F.E.A.R.'s AI concept can be found in (Orkin, 2006). It is also important to mention SOAR cognitive architecture (Laird, Newell, & Rosenbloom, 1987), which was used for extensive academic research on AI-based virtual characters. The Soar Quakebot, NPC tested in Quake II game, aimed to provide more reactive and flexible behavior (van Lent & Laird, 1999; Laird, 2001a; Laird & Duchi, 2001). The decision-making of SOAR-based intelligent agents was rooted in a perceive-think-act cycle (van Lent & Laird, 1999). Further, prediction and anticipation capabilities were developed (Laird, 2001a; Laird, 2002), since anticipation is recognized as one of the key features of intelligent behavior. It is reported that Soar Quakebot successfully challenged even human opponents with intermediate-level playing capacities (van Lent & Laird, 1999).

It could be noted that Bayesian theory represents a cornerstone of today's machine learning. Therefore it is not surprising that its application to game AI attracted the attention of academics. One of the early papers in the field (Le Hy, Arrigoni, Bessière, & Lebeltel, 2004) investigated Bayesian programming for learning NPC behaviors in the Unreal Tournament. Developers took care of computational costs, which is a very important issue for potential commercial applications. Several studies were carried out considering StarCraft. This real-time strategy computer game, published by Blizzard Entertainment, gained massive popularity all around the world. The Bayesian model is developed in (Synnaeve & Bessière, 2011), in order to predict the opening strategies in the game. Further on, the same authors introduced a Bayesian probabilistic model for enabling NPCs to make tactical decision making and predict opponent's attacks (Synnaeve & Bessière, 2012). A thorough analysis of game AI experimentation for NPCs in StarCraft is presented in (Ontatnon et al., 2013).

Reinforcement Learning represents one of the major machine learning areas of research. As it was described in (Sutton & Barto, 1998), RL aims to enable agents to learn by interacting with the world, without strong supervision and without the exact model of the world. Use of RL in the game AI is reported to be rather limited (Millington & Funge, 2009; McPartland & Gallagher, 2011), although this unique theory offers advantages that are highly important for the field (e.g., coping with unpredictable scenarios). There are, however, several interesting studies on the subject. Paper (Wang, Gao, & Chen, 2010) describes using of RL concept in order to develop a team of NPCs for playing the Unreal Tournament in domination scenario. The authors used modified Q-learning in order to enable NPCs to optimize decision-making strategies. When it comes to FPS games, extensive research was also done in (McPartland & Gallagher, 2011), concluding that RL can be successfully implemented in the game AI. In this study, hierarchical, rule-based, and flat RL control were also compared. The research work of Merrick and Maher (Merrick & Maher, 2006, 2007, 2009) thoroughly analyzed Motivated RL for NPCs. The work was driven by a desire to develop more adaptive characters for virtual worlds. Experimentation with MRL implemented in Second Life metaverse provided valuable results on the subject (Merrick & Maher, 2006, 2007). Bearing in mind, that users of such metaverses/virtual worlds can change the environment by adding or removing objects, NPCs that can learn and adapt represent a research topic of high interest. Some of the potential applications of RL to game AI in general, along with possible drawbacks are thoroughly analyzed in (Millington & Funge, 2009).

Neural Networks are more than successfully implemented in board games, such as Backgammon, and even highly complex Go (Tesauro 1995; Tesauro, 2002; Silver et al., 2016). When it comes to interactive computer games, using neural networks in the game AI was often considered as complicated and computationally expensive, and therefore for a long while it was not so common. However numerous successful examples of proper NN implementations during the years showed some of the benefits coming from this method. The late nineties have brought one of the first and most significant examples of neural networks applications in computer games. Creatures, a computer game recognized as one of the breakthroughs in artificial life science, used neural networks for sensory-motor coordination and behavior selection of synthetic agents (Grand, Cliff, & Malhotra, 1997; Grand & Cliff, 1998). Strongly influenced by animal biology – biochemistry and genetic algorithm principles were also used for simulations (Grand et al., 1997; Grand & Cliff, 1998). Neural networks are also implemented in several commercial racing games, such as Forza Series or Colin McRae Rally. Forza Series racing game published by Microsoft Studios developed an AI system based on neural networks, called Drivatar. By analysis of collected data and Bayesian learning, Drivatars are trying to emulate real users' driving techniques. The more some user plays the game, more data about his gaming behavior is available, thus enabling the Drivatar to have a larger degree of similarity with the user. The aim is to imitate specific features of an individual's driving style (how you brake or use gas, etc.), in that way creating AI agents that differ one from another. A team of researchers at the University of Texas developed the NERO (Neuroevolving Robotic Operatives) game. It represents an interesting example of a noncommercial machine learning-based game. The human player has a role of an instructor to a team of agents (simulated robots). Agents start the training with no skills, just the ability to learn. In order to enable agents to learn, NERO uses rtNEAT (real-time Neuroevolution of Augmenting Topologies) algorithm for evolving increasingly complex neural networks in real-time (Stanley, Bryant, & Miikkulainen, 2005). Unlike scripting where after a while weaknesses can be detected and exploited, this approach is aiming for NPCs to adapt and improve their behavior by learning. Neuroevolution, a combination of genetic algorithms and neural networks, is successfully implemented in a real-time interactive environment (Agogino, Stanley, & Miikkulainen, 2000). Authors of the NERO even suggest that this concept could be used in the future for training people in sophisticated tasks (Stanley et al., 2005). Paper (Risi & Togelius, 2017) provided a detailed survey of neuroevolution applications in games, along with the detailed analysis of benefits and drawbacks coming with this approach.

Previously mentioned Genetic Algorithms rarely represent a method of choice in commercial games, as it is considered that this approach is often too slow, and requires too many CPU resources (Johnson & Wiles, 2001; Nareyek, 2004). However, since the appearance of the Cloak, Dagger, and DNA game (created by Don O' Brien), which implemented GAs in order to develop evolving NPCs, academics investigated possible applications of GAs in the game AI. Besides already described neuroevolution, several studies were conducted based on applying GAs to popular games such as Counter-Strike or Quake III Arena (Cole, Louis, & Miles, 2004; Liaw, Wang, & Tsai, 2013). It is believed by some authors (Lucas & Kendall, 2006) that properly used evolutionary algorithms could improve the overall playability of the game, implying in that way that potential commercial applicability could eventually increase.

## 2.3 Human-Level Intelligence and Virtual Worlds – Placing NPCs in a Wider Theoretical Framework

As it was sharply noticed in (Kemp et al., 2008), "Humans are humanity's favorite subject." This deep desire to understand the essence of our existence and behavior led us to tremendous achievements in different aspects of science and art. A number of scientific fields revolved around the necessity to understand and generate human-level capacities. An illustrative example is robotics, where the idea of making a fully functional humanoid robot has its roots grounded back in history (e.g., see (Mataric, 2007; Siciliano & Khatib, 2008)), long before the field itself was even established. When it comes to the closely related field of Artificial Intelligence, incredible results were accomplished in different domains during the last few decades. So-called "weak AI" provided numerous specialized algorithms and solutions that are applied in order to enhance different aspects of technology and human life in general (Nilsson, 2005; Laird & van Lent, 2001). However, the development of human-level AI (or "strong AI", as it is often referred) is still a dream, like it was in the very beginning. Some of the AI pioneers, such as Marvin Minsky and Herbert Simon, were very optimistic in the early days of the field, predicting that human-level AI will be achieved by the end of the 20th century, which will eventually enable machines to do everything that humans can (Simon, 1965; Minsky, 1967). These predictions were not fulfilled, in that way opening numerous discussions that question why we still can not engineer human-level machine intelligence, is human-level intelligence necessary, and at the end is it even achievable. This is rather understandable considering the fact that not just that we did not achieve the human-level AI, but we are struggling to reach the capacities of organisms that we consider far simpler. An illustrative example given in (Clark, 1996) still applies today – despite the tremendous technological advancements we still do not have an autonomous mobile system that has the effectiveness and sophistication of a "simple" cockroach.

Computer games possibly represent one of the most illustrative success stories of Artificial Intelligence systems which are comparable with humans (Schaeffer, 2001). If we take a look at computer systems that can play board or card games, remarkable results are accomplished in the last few decades, considering not just perfect-information but imperfect-information games (e.g., Poker (Bowling, Burch, Johnson, & Tammelin, 2015)) as well. Chess was the subject of research for decades since Shannon's seminal paper (Shanon, 1950). When IBM's Deep Blue system (Campbell, 1999; Campbell, Hoane, & Hsu, 2002) defeated Garry Kasparov in the epic chess battle rematch, public hype considering the AI was at the pick. A number of other examples can be listed too, such as Checkers (Schaeffer, Lake, Lu, & Bryant, 1996; Schaeffer et al., 2007), or earlier mentioned Backgammon (Tesauro, 1995; Tesauro 2002) and Go (Silver et al., 2016), where computer systems reached the level of top-human performance. Further, the AlphaZero algorithm was reported to have remarkable results playing Chess, Shogi, and Go (Silver et al., 2017). Although the superiority of some of these systems was not based solely on AI techniques (Lucas & Kendall, 2006), research in these games influenced the entire field of AI, strongly pushing new ideas and approaches. However, if we take earlier mentioned Checkers as an example, despite the obvious complexity of this game, which is, among other things, reflected in the fact that this game has nearly 500 billion possible positions (Schaeffer et al., 2007), this is still a finite number of combinations. Besides that, classic board games are mostly perfect information, meaning that all participants of the game have insight into everything that has happened before they make a decision (Lucas & Kendall, 2006; Bowling et al., 2015). Unlike these finite, deterministic, constrained gaming spaces, humans (as well as other living beings) live and make decisions in a world of uncertainness, with limited information available, where an infinite number of interactions occur every day. Therefore, it is somewhat logical that in order to get closer to human-level intelligence, we need more than a gaming board or a deck of cards. No matter how complicated and challenging these previously mentioned problems are, they represent only one fragment of human intelligence. In their seminal work (Laird & van Lent, 2001), Laird and Van Lent recognized interactive computer gaming worlds as a perfect testbed for research of the human-level AI. This view, later supported by other authors (Schaeffer, 2001; Schaeffer & Jaap van den Herik, 2002), opens up an interesting perspective in different areas of AI research.

Namely, it is obvious from the previous sections of the chapter that virtual worlds indeed provide us with a possibility to effectively research numerous problems related to intelligent autonomous agents, and consequently, different segments of human-level AI problems. At the same time nature of mechanisms on which the virtual worlds are built, could impose severe limitations for full utilization of their potential on this subject. Further in the text, several aspects of Laird's suggestion will be analyzed, together with possible implications. In order to get a deeper understanding of the potential of virtual worlds on previous matters, the question of human-level AI from the perspective of selected theories must be briefly addressed first.

### *2.3.1 Evolution, Embodiment Theory, and Situatedness – Following the Bio-Inspired Ideas*

Classical AI, also called GOFAI (Good Old-Fashioned Artificial Intelligence) (Haugeland, 1985), showed a lot of shortcomings in pursuing human-level AI. One of the main reasons is recognized in the fact that classical AI theories and expert systems are deeply grounded in information and symbol processing (Pfeifer & Bongard, 2007). This approach proved itself as powerful and very efficient, considering numerous problems and applications. However, it is often disputed when it comes to achieving strong AI (Pfeifer & Bongard, 2007; Pfeifer & Scheier, 1999), as the nature of human intelligence lies on different cornerstones.

A conclusion that there is a possibility, that we misinterpreted the very foundations of intelligence, was recognized by many scientists (e.g. (Clark, 1996)). To have a deeper understanding of this, we must seek into some of the essential parts of human evolution. How did humans become intelligent? Many possible theories and therefore many speculations are generated by the scientists in the relevant fields. Evolution theorists tried to recreate our past and to discover key events and processes that influenced the development of human intellectual capabilities, in that way deferring us from other known primates.

One could certainly notice that changes in physical characteristics caused the changes in intellectual capabilities and vice versa. Early theories recognized bipedalism as a possible first change in the evolution of humans (Rodman & McHenry, 1980; Raven & Johnson, 2002), dating a bipedal walking in the earliest known hominids (Zollikofer et al., 2005; Lovejoy, 2009). As a consequence of the adopted bipedalism, human body structure departs from apes in many ways (Raven & Johnson, 2002; Lovejoy, 1988). Bearing in mind the fact that bipedal walking is one of the key characteristics which are separating humans from other primates (Lovejoy, 1981; Richmond & Strait, 2000), and that bipedalism is so unusual for mammalians in general (Lovejoy, 1981), it is natural to question a reason for this kind of behavior. A number of different, and often opposite theories were made – e.g., some studies reported that bipedalism appeared as an energetically efficient solution compared to quadrupedal locomotion (Rodman & McHenry, 1980), while others denied it (Lovejoy, 1988; Taylor & Rowntree, 1973). However, the final answer to this complex problem is still remaining unsolved. What is certain is the fact that bipedalism preceded brain expansion (Raven & Johnson, 2002). Therefore, one could conclude that bipedalism heavily influenced human behavior, and therefore affected the shaping of our intelligence. Upright walking changed the human perspective of the environment and changed the way humans interact with it (Raven & Johnson, 2002). Free forelimbs enabled many useful activities such as manufacturing and using of tools, and manipulating the environment in general, in that way decisively influencing the human evolution.

Considering just a brief look at some of the evolution cornerstones mentioned in the previous text, it is obvious that human intelligence is inseparable from a human body, and vice versa. As it was noticed in (Clark, 1996), "the biological mind is, first and foremost, an organ for controlling the biological body."

This kind of approach is perhaps most vividly reflected in the Embodiment Theory, which appeared as a response to classical AI. A number of scientists consider embodiment as a necessary condition for developing any sort of true intelligent behavior (Pfeifer & Bongard, 2007; Ziemke, 2003), analyzing this problem not just from the human perspective but with illustrative examples coming from different orders of animals as well. Regarding that, Pfeifer and Scheier described embodiment (Pfeifer & Scheier, 1999) as: "A term used to refer to the fact that intelligence cannot merely exist in the form of an abstract algorithm but requires a physical instantiation, a body." Of course, this definition should not be understood in a simplified sense, bearing in mind the deeper meaning regarding the connections among neural and physical processes (Pfeifer & Bongard, 2007; Pfeifer, Iida, & Gomez, 2006).

The necessity to find an alternative to classical AI approaches was underlined in the pioneering research of Rodney Brooks (collection of the most important papers is given in (Brooks, 1999). His work in the field of autonomous robotics insisted on the physical grounding hypothesis, instead of the traditional symbol system hypothesis. Brooks thoroughly analyzed the main characteristics of both approaches in his seminal work (Brooks, 1990). The physical grounding hypothesis is based on the premise that representations of an intelligent system must be deeply grounded in its physical surrounding, unlike the traditional paradigm where the AI system is based on a "system of symbols" and its manipulation,  In (Brooks, 1990), Brooks elaborated why are physically grounded mobile robots superior to symbol-based robots, supporting his ideas with a number of developed prototypes. Among others, situatedness and embodiment (Brooks, 1991c) are enhancing robots' adaptability to the changing environment, an attribute so characteristic for humans. It is further noticed that besides its morphology, the behavior of some entity is also influenced by the environment in which it acts (Pfeifer, Lungarella, & Iida, 2007). As it was elaborated in (Brooks, 1991a), "Intelligence is determined by the dynamics of interaction with the world."

### *2.3.2 Potential Implications to Virtual Worlds and NPCs*

If we observe previously described paradigms (sub-section 2.3.1) in the context of current computer games technology, we can easily notice the research potential behind these ideas, but also all the shortcomings which are constraining their full implementation into the interactive virtual worlds. Namely, NPCs appear in the form of human-like avatars or some creatures, and behave according to their capabilities within the virtual environment, at the same time affecting the environment in some way. However, their embodiment and situatedness are simplified. As it was noticed in (Isla & Blumberg, 2002), NPCs are "virtually embodied", or more precisely graphically embodied. They are not built and therefore are not acting in the manner living beings are. Further, the virtual worlds themselves are focused on a visual resemblance, and they lack some of the crucial real-world characteristics. This is a very important issue since the evolution of human intelligence is strongly connected with recognizing and interacting with the dynamic 3-D world, its structures, and other living beings (McCarthy, 2008). If we want to follow the earlier mentioned principles of embodiment and situatedness in a more real-world manner, then some adjustments of the virtual world mechanisms should be ensured. NPCs should probably be provided with a virtual dynamical embodiment and more strictly set virtual situatedness, all within interactive virtual environments modified to support such characteristics. This should not be understood in a simplified manner – as a mere introduction of some dynamical properties. More importantly, NPCs should be enabled (as much as it is possible) to sense the world around them and interact with other entities and the dynamic interactive surrounding in a way that resembles how living beings act in the real world. After all, situatedness is recognized as one of the key requirements in order to define something as an agent, meaning that it has to be capable to receive inputs from sensors, and accordingly in some way affect its environment (Jennings, Sycara, & Wooldridge, 1998). Regarding this, so-called "sensory honesty" (Isla & Blumberg, 2002; Isla, Burke, Downie, & Blumberg, 2001) represents one of the highly significant issues, since it is very rarely implemented in virtual worlds – NPCs are mostly built to be omniscient, without any real understanding of the world that is surrounding them.

Bearing in mind the briefly elaborated principles of subsumption architecture and embodiment theory, one should be careful – applying these principles adjusted to virtual worlds should not lead toward just purely reactive AI agents, but rather enable them to integrate and exploit different AI techniques and AI functionalities to a larger degree. It should also be noticed, that considering the complexity of humans and following the ideas elaborated in (Brooks, 1991b), previously mentioned principles should be gradually applied by experimenting with artificial agents inspired with simpler organisms at first.

When it comes to already-mentioned dynamical properties, thorough research studies on dynamically simulated graphical models were done in the past (Terzopoulos & Fleischer, 1988; Wilhelms, 1987; Nealen, Müller, Keiser, Boxerman, & Carlson, 2006). Dynamically simulated characters were presented in (Brogan, Metoyer, & Hodgins, 1998), as an alternative to motion caption and key-framing motion generation methods. In this research, two virtual environments were developed and populated with NPCs, simulating bicycle racing and a heard of ships. Animations of some chosen human movements based on dynamics are also thoroughly researched in (Hodgins, Wooten, Brogan, & O'Brien, 1995; Wooten & Hodgins, 1996; Faloutsos, van de Panne, & Terzopoulos, 2001). One should notice that majority of the studies dealing with dynamical models in virtual environments, primarily aimed to provide a more realistic graphical sensation. An illustrative example of experimenting with physics-based NPCs in a virtual world, under a different agenda, can be found in (Terzopoulos, Tu, & Grzeszczuk, 1994). In this seminal work, the virtual marine was filled with virtual 3D fish models, providing in that way some original insights into the field of artificial life. Simulated models were built according to simplified biomechanical and hydro-dynamical principles, together with emulated sensors and real fish behavior patterns.

Previously described academic studies provided important insights on dynamically modeled animations. When it comes to the commercial virtual worlds, most of them use some sort of physics engine rooted in the classical mechanics theory, whether they are based on rigid body physics or mass aggregate approach (Millington, 2007). Illustrative examples are the Havok engine (used by Second life, Halo, Half-Life, etc.), or the PhysX engine (used by Active Worlds, Mafia II, etc.). Despite the fact that physics engines offer whole spectra of possibilities, virtual worlds tend to be rather static (Lopes & Bidarra, 2011) considering objects inside them, as well as the nature of interactions between players and NPCs with the environment. As it was noticed in (Pfeifer et al., 2007), it is still problematic to precisely model and simulate real-world properties. Besides obvious complexity, bringing some real-world properties through physics-based models and advanced sensorial systems is also very computationally expensive. Introducing physically complex objects is severely increasing a number of interactions (Luck & Aylett, 2000). Further, with the increased number of simulated objects and interactions, CPU resources are dramatically running out (Kumar et al., 2008). Therefore, it is not surprising that the nature of the virtual worlds and interactions in them is still constrained, not modeled accurately enough, and not in the scale that is needed to fully apply principles behind the physical grounding hypothesis.

At this point, one should be careful in order to avoid a possible misunderstanding of some of the previously exposed analyses. Namely, the goal is not to replicate the world in all of its diversity and complexity (not to mention that this is impossible to do), but rather to identify and emulate some of its essential characteristics, as well as they can be emulated. Human-level intelligence could be too dependable on various internal and external factors to be replicated in that way (Nilsson, 1998). However, following the analogy from the humanoid robotics example presented in (Zlatev, 2001) – exposing NPCs to some of the essential real-world conditions and equipping them with some of the essential mechanisms and interaction patterns characteristic for living beings, could trigger an evolutionary leap in their autonomy and intelligence. In other words, it could be one of the necessary “baby” steps toward the development of human-like intelligence and cognition mechanisms, or it could at least enable us to better understand the foundations of human intelligence.

Besides previously described aspects, social behavior and therefore social interaction with other living beings is also recognized as the key element of the origin of human intelligence (Reynolds, 1976). As it was observed in (Raven & Johnson, 2002), humans are the only living beings that are using symbolic language, which among others enabled us to transfer our knowledge through generations. There will be no thorough analysis on these matters further in the text, as this topic deserves a survey of its own in order to be properly analyzed. However, in the author’s view, a brief discussion considering some aspects of the topic must be provided in the following lines. Considering this, it is not surprising that agents, which can communicate in a human-like manner, represented the subject of extensive research over the last few decades. Consequently, virtual worlds served as a perfect testbed for the development of these chatterbots, as they are often called (e.g., “roboatars” tested in the Second Life (Burden, 2009), etc.).

One of the benefits is reflected in the fact that virtual worlds provide NPCs with a large number of human users to interact with. Another benefit comes from the fact that various challenging scenarios can be designed and tested in these virtual worlds. Annual Loebner Prize competition is organized, aiming for computer-controlled characters to pass the Turing test through textual communication. Since it was introduced (Turing, 1950), the Turing test caused a lot of different interpretations (French, 2000; Proudfoot, 2011), and a lot of opposite opinions considering its validity and efficiency (e.g., “Chinese room” discussion (Searle, 1980)). Argumentation about its relevance is not in the focus of this chapter. However, what should be noted is that absence of the embodiment is recognized as one of the reasons which are disabling NPCs to pass the Turing test (Gomez, Fountas, & Fidjeland, 2013). Bearing in mind that we use symbolic language to describe the world around us, the way we sense it, and its phenomenon, the following logical question is imposing itself. Is it reasonable to expect that any disembodied computer system, which can not interact and sense the world in a human-like manner, could be capable to perform fully human-level intelligent conversation without any tricks?

At the end of this section, it should be noticed that there is no ultimate solution that guarantees progress toward achieving human-level AI agents. In order to get close to the human-level intelligence, or at least achieve some segments of it, different theories, hybrid solutions, and techniques must be integrated in order to fully exploit their strengths and at the same time minimize their weaknesses. Besides that, virtual worlds themselves as well as NPCs acting in them should be carefully designed in order for these methods to be effective.

## 2.4 Concluding Remarks

This chapter aimed to provide a unique perspective on the subject of AI agents in virtual worlds. The primary purpose was not to bridge the gap between AI academics and the commercial-based gaming industry, but rather to gather important insights coming from both sides, critically evaluate them, interconnect them and point out the multidisciplinary richness and the research potential of the elaborated problems. Therefore, the author is hoping that this research study will serve as a valuable source of information for a wide range of experts. A special emphasis of the chapter was on human-level AI research in the context of autonomous intelligent agents in virtual worlds.

When it comes to AI agent problems that can be investigated in virtual worlds, the number of possible applications is constrained only by the imagination of the research community (Bowling, Fürnkranz, Graepel, & Musick, 2006), and current technical limitations. Therefore, it is important to mention, that implementation of techniques and theories presented in this chapter is often constrained with CPU resources. This is especially regarding some of the real-time related problems, that agents often meet (Dignum, 2012). Such technical issues were recognized, but not analyzed in detail, as they are not in the main focus of the chapter. After all, following Moore's law, these constraints are significantly diminishing during the years, and therefore are not compromising the theoretical value of underlining research ideas.

In the earlier mentioned paper (Laird & van Lent, 2001), Laird suggested that at one point in the future, computer games will have to evolve, inevitable concentrating on advanced AI agents with the need to even match human-level intelligence in order to provide next level of realistic experience for users. If one carefully observes previous sections of the chapter, as well as the required properties of artificial systems defined in (Castillo, Lopez, Bedia, & Lopez, 2015), in an ideal scenario those agents should be among other enabled with several essential capabilities: appropriate reasoning about its environment and their role in it, learning and intelligently interacting with the dynamic environment including a successfully coping with uncertainties, and predicting the events and behavior of other dynamic entities in a dynamic environment. This requires numerous methods and theories to be integrated during development (Figure 2.3). The practical justification of Laird's suggestion is reflected in several beneficial aspects to the further development of virtual worlds. As it is noticed in (Khoo & Zubek, 2002), human users are more engaged when competing with other humans, than with computer-controlled opponents that often behave too predictable. Therefore, a need for intelligent autonomous agents that can provide more immersive and life-like virtual world experiences seems rather obvious. Computer-controlled AI opponents that can behave in a human-like manner are reported to be more challenging and enjoyable (Soni & Hingston, 2008). Another aspect can be related to the fact that virtual worlds are becoming more dynamic and complex, with the increased population of human users and NPCs as well. Therefore, there is a need for autonomous agents that can cope with unpredicted scenarios (Khoo & Zubek, 2002).

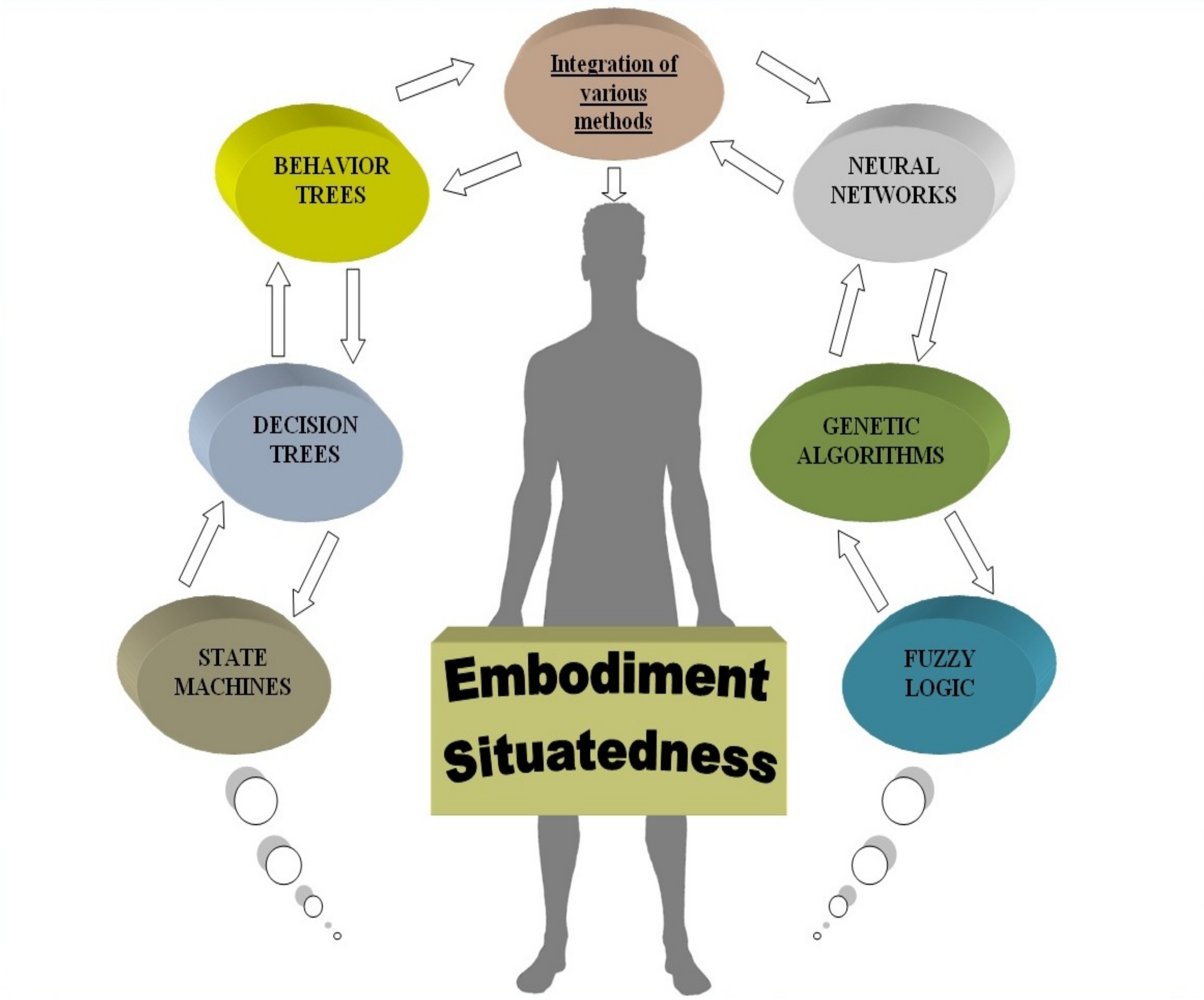


***Figure 2.3:*** *Future Human-Level AI virtual agent.*

Laird's predictions are gradually progressing, as human-level characters are drawing increased attention. Earlier mentioned real-time strategy game StarCraft, represents an illustrative example. Accordingly, StarCraft AI competitions are organized aiming to create agents with the ability to successfully play the game and compete with humans and other scripted NPCs (Robertson & Watson, 2014; Farooq, Oh, Kim, & Kim, 2016). As Samuel sharply noticed (Samuel, 1960), "Programming computer to play games is a stage in the understanding of the methods that must be employed for the machine simulation of intellectual behavior." Bearing in mind the massive popularity of StarCrafft, it is not surprising that it is recognized as a suitable testbed environment. The potential of this game as a platform for research of human-like NPCs (see (Freed et al., 2000)) has been recognized since the early days of the game. Although there is a long way until virtual characters reach top human performance in this complex virtual world, StarCraft represents a research topic of high interest. Supporting this, it should be noted that DeepMind and Blizzard research teams are actively working on the reinforcement learning environment developed on the basis of the StartCraft II (Vinyals, 2017). With further advancements in deep learning (LeCyn, 2015), including human-level control (Mnih et al., 2015), agents are getting close to some segments of human capabilities. It should also be mentioned that cognitive and behavioral modeling (Castillo et al., 2015; Bohil & Biocca, 2007; Kasap & Magnenat-Thalmann, 2008; Bakkes, Spronck, & van Lankveld, 2012), attracted a lot of attention in the last few years. Although this interesting, highly multidisciplinary topic was not a subject of analysis in this chapter, one should recognize cognitive models as a potentially powerful method that can be used in the development (especially on a higher level) of future human-like agents. Cognitive models derived from available players' gaming data can enable exploration of various key properties listed in (Kasap & Magnenat-Thalmann, 2008), such as "adaptation to environmental constraints" in that way increasing agent's autonomy.

A number of researchers noticed that very few academics directly attacked the question of general intelligence (see (Laird & van Lent, 2001; Minsky, Singh, & Sloman, 2004)). Regarding this, some authors rightfully claim that human-level AI is researched in the computer games domain with more effort than in any other, especially with general game playing (Togelius & Yannakakis, 2016). Research in the human-level intelligent characters can benefit the entire AI field. Therefore, this chapter was dealing with a crucial aspect of Laird's seminal work (Laird & van Lent, 2001) – the fact that interactive virtual worlds could represent a powerful testbed for pursuing human-level machine intelligence. These worlds are already characterized by a number of real-world elements and problems. More importantly, they are becoming more complex and dynamic, with real-time decision-making and other human characteristics increasingly required. Further, computer characters in these worlds are exposed to numerous interactions with human users, between themselves, and with their surroundings. In the author's opinion, this makes virtual worlds a rather unique testbed for different segments of AI research and their potential integration – e.g., state-of-the-art humanoid robots can not be safely exposed to such interactions, and in such scale within the real world (especially regarding the interaction with humans and other living beings).

There are different, often extremely opposite opinions regarding the possibility of achieving human-level artificial intelligence. After all, research in human-level AI represents a tremendous endeavor. This is reflected in the fact that it is not problematic only to achieve all of the human main capabilities, but also to properly integrate them (Swartout et al., 2006). Many researchers are certain that human-level AI will eventually be achieved, but it requires new approaches to be implemented and integrated together with the existing ones (McCarthy, 2007; Zadeh, 2008). Even if it should be proven in the future, that this tremendous endeavor is not possible, one could be certain that research in human-level AI is not only helping us to better understand principles of human intelligence but is also producing numerous "side-effects" across almost all scientific fields. Regarding this, the aim of this chapter was not to claim the achievability of human-level AI, but rather to explore frontiers and to underlain benefits and shortcomings of current state-of-the-art virtual worlds and intelligent agents inhabiting them, in the context of human-level AI research.

In the end, the author is fully aware that there is no analysis that could be attributed as thorough enough. Regarding this, there are several topics and theories that are not included and elaborated in this work. It should also be clear that there was no intention to disregard or reduce the importance of theories that are not analyzed in this research. Chapter and its theoretical content are exposed and organized in the manner that in the author's opinion best covers the underlining ideas behind this research study.

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*"Study hard what interests you the most in the most undisciplined, irreverent and original manner possible."*

Richard P. Feynman (1918. – 1988.)

# Chapter 3

## AViLab — Gamified Virtual Educational Tool for Introduction to Agent Theory Fundamentals

Over the last few decades, we have witnessed extensive development and popularity growth of interactive computer games, metaverses or MUVEs (Multi-User Virtual Environments), and similar virtual environments. According to several research studies – although there are distinctions between them, in a more general sense, all these environments can be called "virtual worlds" (Kumar et al., 2008; Bainbridge, 2007; Petrović, 2018). These virtual worlds have millions of users interacting in them on a daily basis. Some studies have shown that students (aside from social networks activities) spend up to 20h a week in these environments (Thompson, 2011).

Therefore, it is rather expected that they are recognized as a fruitful ground for various research directions (Bainbridge, 2007). What is of particular interest for this chapter is the educational potential of these environments and related technologies. This potential is widely recognized in the academic community, starting from social sciences, to STEM disciplines. It could be noticed that virtual laboratories represent one of the most fruitful educational applications of virtual worlds technologies. Laboratory exercises represent an extremely important part (and in most cases inevitable part) of the education process in science, technology, and engineering disciplines, enabling students to conduct experiments, gain deeper knowledge, and visualize theoretical foundations of their learning process.

Although there are many successful examples of virtual laboratories and demonstration tools in different scientific disciplines, it can be noticed that there is very little work on the subject, when it comes to the theory of agents, which will be elaborated in the next section of the chapter. At this point, agents and agent theory should be briefly clarified as terms. Namely, the term agent is used in many different research disciplines. However, in this dissertation, as could be noticed, we are oriented toward the field of AI, and the way agents, as well as their autonomy, intelligence, and theoretical foundations, are defined from the AI perspective. Therefore, it should be also underlined that autonomous agents and agent theory in general, are long ago proclaimed as one of the central topics in the field of AI (Jennings, Sycara, & Wooldridge, 1998). At the same time, agents represent an extremely important part of the virtual worlds and their development process, and consequently game AI. Since the early beginnings of the field, some authors even observed game agents (NPCs) as an essential part of the interactive gaming worlds (Doyle, 1999; van Lent et al., 1999). The illustrative examples of the intersection between academic research and virtual worlds can be found in seminal research presented in (Laird & van Lent, 2001; Laird, 2002), where computer games and agents inhabit them are even promoted as a platform for human-level AI research. The autonomy of agents, as well as implications of agent technology in virtual worlds in general, are thoroughly researched in (Petrović, 2018), where a broad source of valuable information can be found.

Bearing in mind all the previously said, it could be concluded that an agent's importance is twofold, regarding not just the academic community but commercial applications as well. Considering this, one could also notice that there is thorough and fruitful academic research on agent theory, which over the years resulted in the development of various agent and multi-agent simulations related to numerous applications. At the same time, there is extensive research on the development of agents for commercial-based games (with many examples well described in (Risi & Preuss, 2020)). However, as was mentioned earlier, it could be noticed that there is a certain deficiency when it comes to developing gamified systems specially dedicated to educational purposes in the field of agents.

Therefore, this chapter will present the AViLab (Agent Virtual Laboratory) virtual gamified system, the development of which is inspired by the previously elaborated standpoints. It aims to contribute to filling the observed deficiency related to agent-oriented educational systems. AViLab in a certain sense follows the "serious gaming" manner and primarily aims to serve as an illustrative tool for the demonstration of agent theory fundamentals, experimentation, and visualization of theoretical concepts. Furthermore, this system also has the potential to be used for research purposes. Due to the manner in which it was designed, the system could also be easily extended in the future, enabling a different kind of agent research.

The rest of the chapter is organized as follows. In Section 3.1, related work will be described, providing important reference points to the potential reader. Section 3.2 will present the working principles of the AViLab, including the system details, current agent structures, task description, and other important system details that will be systematically explained. Section 3.3 presents an example of laboratory exercise conducted in the AViLab, presenting one of the ways in which AViLab can be utilized. Section 3.4 gives concluding remarks and a brief discussion. The chapter ends with a list of relevant references.

## 3.1 Background Research

Over the years, virtual laboratories have placed themselves as an important addition to the learning processes, or even a full substitution for the real laboratories. An extensive study, presented in (Tzafestas, Palaiologou, & Alifragis, 2006), compared students accessing real, remote, and virtual laboratories in the field of robotics and concluded that students entering a virtual laboratory showed comparable results to the ones entering the real laboratory, with no significant difference in their results. A very visually appealing virtual laboratory in the field of chemistry was presented in (Gervasi, Riganelli, Pacifici, & Laganà, 2004), describing several practical implementations of the developed system, such as the Boyle Law demonstration. Virtual laboratory for metrology learning is presented in (Ballu et al., 2016), underlining one of the obvious advantages of virtual solutions considering many fields – real laboratory equipment is often very expensive, while virtual laboratory presents a more affordable option. Virtual laboratory in the field of biotechnology is presented in (Abramov et al., 2017) while pointing out another advantage of such solutions, which is a high level of availability and location independence. Availability feature is shown to be particularly important during complex circumstances, such as the recent world COVID-19 pandemic, enabling users to conduct experiments in a safe manner (Kapilan, Vidhya, & Gao, 2021).

Many illustrative examples are coming from engineering disciplines. Research presented in (Goodwin, Medioli, Sher, Vlacic, & Welsh, 2011) analyzed virtual laboratories as a successful low-cost replacement for experiments in control engineering. An interesting example is coming from the field of mechanical engineering (Aziz, Chang, Esche, & Chassapis, 2014), where a game-based virtual learning environment was presented, enabling students to perform different experiments related to the fundamentals of gearing. Virtual laboratory for mechatronic systems, dealing with robotics and hydraulics, was elaborated in (Petrović, Nikolić, Jovanović, & Potkonjak, 2016), pointing out the need for broader implementation of such systems in engineering fields. One of the early examples in the robotics field can be found in (Jaramillo-Botero, Matta-Gómez, Correa-Caicedo, & Perea-Castro, 2006), where the developed ROBOMOSP system was aimed to be used in a multipurpose manner (as a research tool, for the training of operators, for learning the mathematical and physical principles of industrial manipulators). A thorough review and a valuable source of information, related to the subject of virtual laboratories in STE (Science, Technology, and Engineering) disciplines, can be found in the next chapter of the dissertation, where many of the laboratories mentioned in this section, will be analyzed in a more detailed manner.

However, although there is a number of illustrative examples regarding developed virtual laboratories in science, technology, and engineering disciplines, it could be noticed that there is a rather limited amount of work on the subject in the field of agent theory. To be more precise, while there is a number of examples of incorporated agent technology, it could be noticed that there are very few cases of developed virtual laboratories and similar education and research environments, dedicated exclusively and primarily to agents. One of the rare examples of virtual laboratories dedicated especially to agents is presented in (Strippgen & Christaller, 1994; Strippgen, 1997). The environment called INSIGHT aimed to explore the behavior of autonomous agents in an immersive environment, such as a golf court. Another illustrative example comes from (Jung & Milde, 1999), where an environment with different kinds of agents (anthropomorphic, robotic, etc.) was proposed, aiming to cover the educational aspect, among other things. Namely, it is reported that the developed environment was used as a part of the University Course, enabling students to have a practical demonstration and insight into certain aspects of agents theory, AI, artificial life, etc. However, as we already pointed out, the number of this kind of educational environments, dedicated to agents, is very limited.

All the previously analyzed can serve as a clear indicator of the necessity of developing systems such as our AViLab, bearing in mind the importance of virtual laboratories and similar environments across the many scientific fields and at the same time an obvious deficiency of such systems dedicated to agents.

## 3.2 The AViLab System

In this section, we will present a concise description of our AViLab system. The main focus will be on, what we consider to be, essential details important for the potential reader. We will start by introducing an audience to software tools used in our development process and then continue with a detailed description of the defined task, algorithms, and control logic.

### *3.2.1 Software System Introduction*

The AViLab gamified educational tool has its development roots in the initial work on a single agent presented in (Petrović, 2021). Development is performed by using a Unity's game engine, Microsoft Visual Studio IDE, and a C#. These software platforms offer a plethora of features and possibilities, in that way enabling us to develop efficient, as well as illustrative simulations.

During the development, we insisted on a few basic principles of the system that needed to be fulfilled:

- Computational efficiency: This means that the system (including the agents) must be optimally developed, and therefore omit any unnecessary computational expense, in order to rationally use available computer resources.

- Generalization: Chosen tasks must have reasonably wide applicability.

- Immersiveness and Visualization: A "serious gaming" approach, meaning that the developed system must be visually appealing to human users, while at the same time embodying theoretical concepts.

- Flexibility: Applied software tools should enable us to relatively easily modify our system (scenery, agents, task, etc.), if necessary. In that sense, an object-oriented approach is an essential requirement for system development (a valuable, and still up to date reference related to the very principles of the object-oriented approach can be found in (Gamma, Helm, Johnson, & Vlissides, 1994)).

- Extensibility: Different agents and different task scenarios could be added to the AViLab system in the future.

One should notice that at the moment, the AViLab software system is not publicly available or open-source, as we do not want to jeopardize current and future related research and publications, as well as educational applications. However, further in the text, we will try to thoroughly describe details of the system, in order to provide all the essentials for the potential reader.

At this point, we briefly comment that our system's GUI (part of it can be seen in Figure 3.1) is designed in a very user-friendly manner, giving basic information to a potential operator, such as system description, details about specific agent design, task description, operating instructions, etc. In addition, a potential user has the option to return to the main menu at any moment with the back button, or by simply pressing the ESC button on the device keyboard if the simulation is in progress.

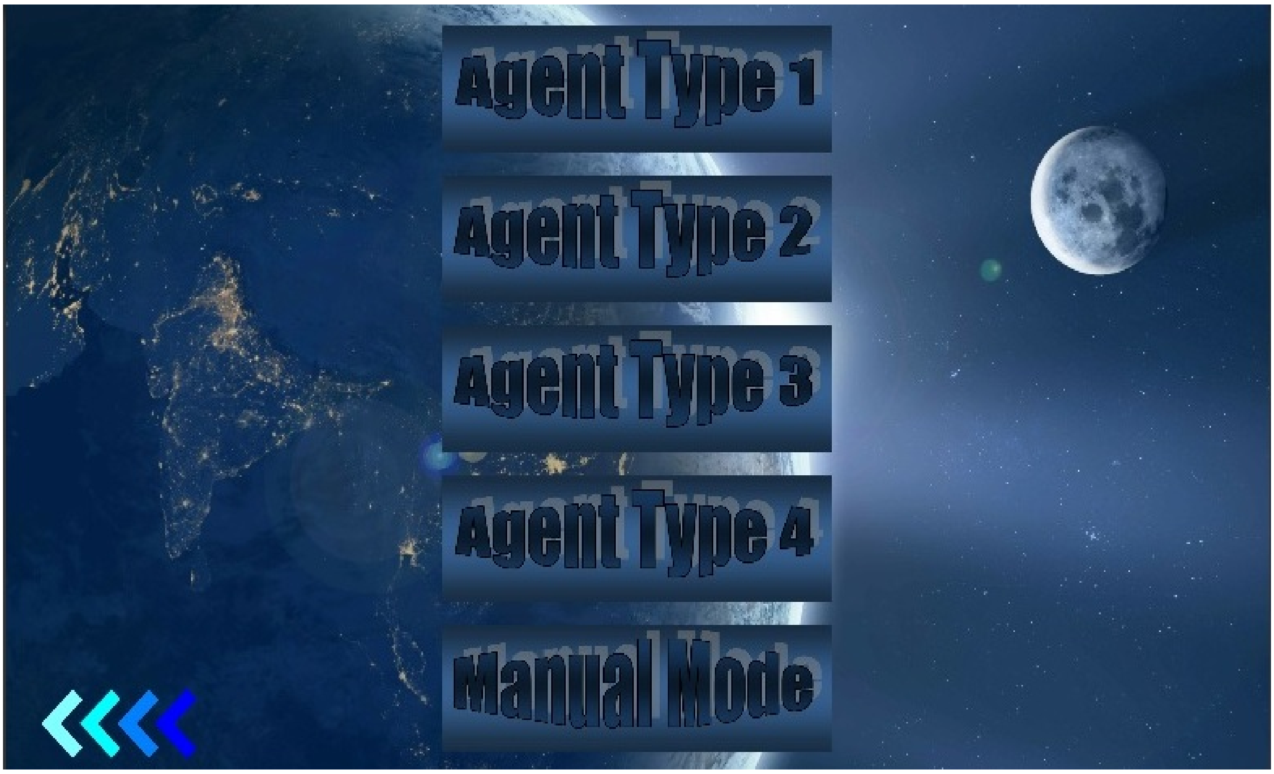


***Figure 3.1:*** *The operation modes page of the AViLab system's GUI offers to start one of the developed agents or enter a manual mode.*

### *3.2.2 The Imposed Task*

The basic task used in our system essentially represents a sort of "picking" or "collecting" task. This kind of task is chosen because apart from its numerous applications in gaming scenarios, it has wide applicability in real-world scenarios as well. Illustrative examples come from the field of robotics: household mobile robots that perform some sort of garbage collection, service robots designed for cleaning up some hazardous area, or service robots picking the balls from the golf court (e.g., (Pereira, Ribeiro, Lopes, Whitney, & Lino, 2012)), etc. Furthermore, with a change of scenery, this task could be easily modified to a "Search-and-Rescue" scenario.

In simulated scenarios offered by our AViLab, agents or human users are faced with the task in which they have to eliminate alien enemy satellites (increasing their score by one, each time they eliminate an alien satellite) in a game-like space world. These alien satellites are randomly placed across the simulation world. We have developed two different main modes of spawning of satellites, aiming to cover two different scenarios—the so-called "static" and "dynamic" mode. Regarding the static mode, upon each new simulation cycle, a predefined number (which can be altered according to our needs) of alien satellites is spawned simultaneously at random positions across space. Therefore, the environment is set at the beginning of the simulation, and only changes in the environment are caused by the agent (or human) actions during the simulation. On the other hand, in the dynamic mode, a certain number of satellites is spawned simultaneously at the start of the simulation, while others are spawned "one by one" in equal time intervals during the simulation. In that way, a more dynamic environment is provided. Both modes use variations of an algorithm, specially designed for our AViLab system, which searches across the game space for collision-free positions and then spawns enemy satellites at those positions.

The developed algorithm behaves in a very intuitive manner (Figure 3.2): it starts with generating a random position in the virtual gaming world, then checks its availability through calculation, and spawns satellites if available, or returns to the first step if not. It should be kept in mind that upon the start of each new simulation cycle, a set of new random locations is generated and selected. The introduction of randomness into the process of locations selection is providing us with a more realistic emulation of real-world scenarios. Furthermore, as a consequence of the previously elaborated, we can avoid scenarios in which an agent or human can deliberately or accidentally exploit the predictability and immutability of the enemy locations in order to increase its performance score. Some of the previously elaborated are already emphasized in (Petrović, 2021) and are out of great significance in experiments where we want to track the performance of the agents or humans, or even compare them between themselves.

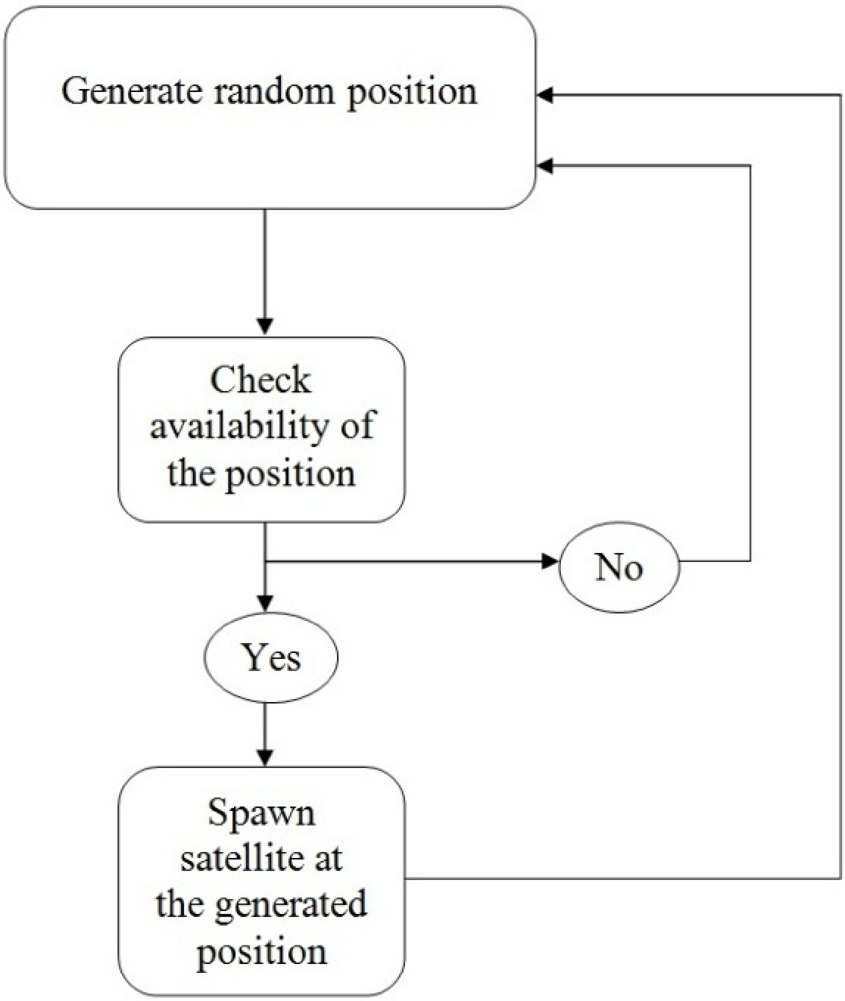


***Figure 3.2:*** *UML-like presentation of the basic logic behind the spawning algorithm.*

Besides the described main spawn modes, there is an option to entirely customize alien satellites spawning (before the start of simulation), as this can be useful for certain demonstration purposes and scenarios.

### *3.2.3 Modes of Operation*

The current version of the AViLab system offers five modes of operation. As was mentioned earlier in the text, during the R&D process, we insisted on some development principles (defined in Section 3.2.1). One of our starting points was also to put the main accent on relatively basic structures of agents because we wanted to demonstrate some of the fundamentals related to agent theory. Namely, due to various fruitful research directions related to both academic and gaming industry agent applications, as well as the fact that competitiveness of the field itself cause advanced AI and machine learning to often take the central research focus, we have an impression that more simple solutions based on the relatively fundamental principles and features of agents are sometimes superficially processed or not investigated thoroughly enough. This is a particularly important issue bearing in mind that educational tools should serve to gradually build knowledge on a matter of interest, starting from the basics. Furthermore, one should also notice the long-ago elaborated principle, that depending on a situation, the main goal is not to always build the "smartest" possible agent, but the most optimal one (Lidén, 2004).

Upon entering the "operation modes" page of the AViLab system's GUI, one can choose to activate one of the four agents or enter the manual mode (Figure 3.1). Four different types of agents are developed partially inspired by theoretical concepts of agent theory elaborated in one of the seminal works in the field (Franklin & Graesser, 1996). Therefore, we insisted on some of the defined properties such as reactive behavior, and pro-activeness. The idea was to enable users to explore and visualize how different, mostly basic types of agents, cope with the imposed tasks, to compare their performance, or to compare them with human users as well. Therefore, a manual mode is also introduced, which offers a human user to enter the simulation.

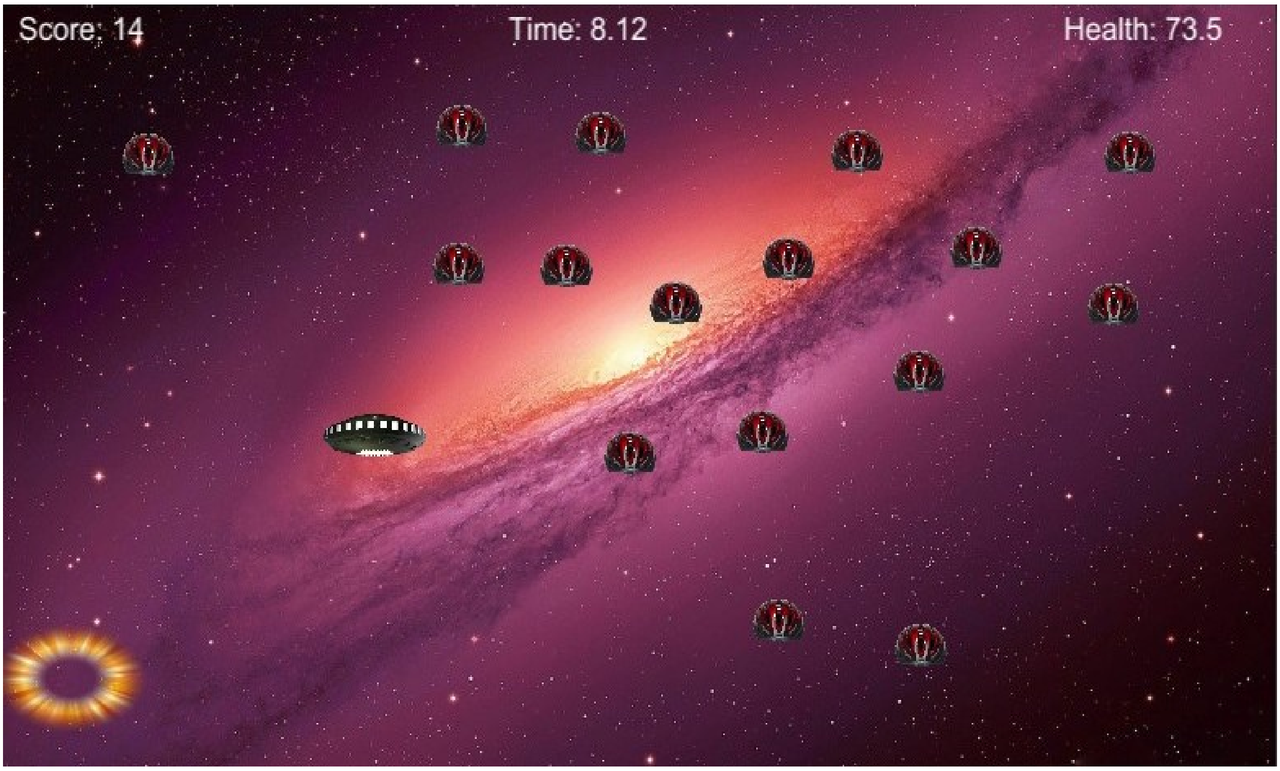


***Figure 3.3:*** *Simulated game-like scenario, where we have time and energy constraints. Agents (or humans) must return to their power base, at the lower-left corner of the screen, in order to restore their health (level of energy).*

In our previously mentioned simulated game-like environment (Figure 3.3), an agent or a human controls a spaceship, which it uses to eliminate satellites by simply touching them. For proper tracking of their performance, a display at the top of the screen (Figure 3.3) shows the number of eliminated enemy satellites (scored points), elapsed time, and energy level (health) of the agents/human users.

Agent Type 1 has a rather basic reactive design. It wanders around the simulated game world (randomly changing direction in a pre-defined time period), with no sensorial information about the positions of the alien satellites. The agent just knows that it must eliminate the enemy if it runs into it. In other words, it must react. Regarding this, it is designed on a sort of “touch sensor” principle, which allows him to make appropriate decisions (to recognize and destroy the enemy).

Agent Type 2 has no sensorial information about the positions of enemy satellites, as well. Similar to Agent Type 1, it is also based on a sort of emulated “touch sensor”, which allows him to recognize and destroy enemy satellites when it runs into them. However, it also uses sensorial information about nature and the boundaries of the space in which it acts, to systematically search the space. When we say systematically, this means that its primary goal is to cover the entire area and search every part of the space. Therefore, it “patrols” horizontally, from one side of the space to another, and upon reaching the side boundary it shifts up (shift-up value is equal to its own height) and then continues its horizontal movement to the side boundary again.

Agent Type 3 is a variation of the previous agent. It has the same features. However, it uses a different movement pattern and searches the space in a vertical manner. Therefore, upon reaching the vertical side boundary, it moves aside for the value that is equal to its own width and then continues its vertical movement to the side boundary again.

All the previously described agent types are designed in a sort of minimalistic manner (e.g., they do not have the ability to learn), according to our aim to put an accent on the behavior of rather basic structures, at the same time avoiding any unnecessary computational and design expense.

Agent Type 4 is a sort of omniscient agent. Like the previous three agents, it also does not have the ability to learn, but it has perfect information about the location of enemy satellites and the surrounding world (it detects all the enemies in the space, memorizes their locations, and then apply actions according to its agenda). The strategy that this kind of agent is applying basically represents a practical visualization of the nearest neighbor search. Namely, the agent finds the position of the nearest enemy and changes its direction accordingly. Upon reaching this position and eliminating the enemy, it changes its direction toward the next nearest satellite. It repeats this pattern until there are no more enemy satellites. This strategy is not always the most optimal solution, especially in time-limited tasks, which can be efficiently demonstrated in our AViLab system. However, we will not analyze this in our chapter.

As we mentioned earlier in the chapter, besides agents, our system also offers a manual mode. This mode enables a human user to enter a simulations scenario and try to fulfill the imposed task. A human user controls the spaceship by using the arrows on the device keyboard. This movement (as well as the movement of the agents) is designed carefully, so the speed is always the same, even in diagonal directions (at this point, one should notice that diagonal movement was a well-known “bug” in some early versions of popular computer games). It is important to emphasize that all the significant predefined parameters of the simulation scenarios are completely the same within all modes of operation (regardless of whether the agents or human users are performing the imposed task). This is very important if we want to ensure an unbiased comparison between them, when necessary.

### *3.2.4 Simulation Details and Main Control Architecture of Agents*

In this sub-section, we will describe some general simulation details, which are already partially elaborated in (Petrović, 2021) but could be applied to the AViLab system in general. At the beginning of each new simulation cycle, the previously selected agent or a human user starts to move across the surrounding space, in the form of a spaceship, and according to its own agenda. There is also a simulation time limit. At this point, it should be emphasized that depending on our needs, we could adjust the duration (time limit) of each simulation cycle. Consequently, upon reaching the defined time limit, the mission (imposed task) is aborted.

Our task also has some additional requirements which must be taken care of – such as the energy level of the spaceship. We introduced such a requirement in order to have a more applicable, and realistic task scenario (examples from everyday life include driving an automobile, or piloting a plane, where you have to take care of the fuel level and adapt your actions according to this). Accordingly, if the spaceship (which is under the control of agents or humans) runs out of energy during the simulation, it will stop performing its task. Therefore, as a consequence, it will fail to successfully achieve its task. As a penalty, its score automatically drops down to zero. To prevent this sort of scenario, during the simulation, the spaceship has to return (one or more times) to the power base, so it could restore its energy. The initial value of the energy level is defined at 100 units. For every second that spaceship spends outside the power base, the energy level decreases by four units. Similarly, upon its return to the power base, the energy level of the spaceship starts restoring every second while it is in there, increasing by four units.

Considering our current agents, the "red flag" for returning to the power base is triggered when the energy level reaches 35 units. This particular value is chosen because it enables our agents to safely return to their power bases, even when they are located at the farthest part of the simulation space. On the other hand, the "green flag" for reactivating the agent and consequently leaving the power base is triggered upon a full recharge (reaching 100 units). Of course, it should be emphasized that this kind of agent strategy, depending on the particular situation, does not always represent the most optimal solution.

All the previously mentioned simulation details and values of parameters are chosen in order to provide efficient and illustrative simulations, and at the same time enable us to have an illustrative insight into the agent's capabilities. As some of the previously mentioned parameters, they can also be altered and adjusted to different values if needed.

The general behavior cycle, applied to all four agents, can be depicted in the following manner:

- Agent starts the defined task, by going out from its power base.

- Agent moves across the simulation world (according to the designed agenda), and eliminates enemy satellites upon detection.

- Agent returns to the power base when its energy level reaches the defined critical value.

- Agent restores its energy level in the power base.

- Agent starts a new behavior cycle by going out from the power base and continuing its mission when the energy level reaches its defined value.

A simplified graphical representation of the general behavior cycle is shown in Figure 3.4. The kind of agent behavior cycle which we want to provide can be accomplished with different sorts of methods. Important theoretical foundations and insights related to the very principles of the shaping of agent's behavior are well described in (Cavazza, 2000; Khoo & Zubek, 2002), covering a thorough analysis of different methods and algorithms.

Bearing in mind the motivation and specific details related to the development of our AViLab system, we have chosen to construct an agent's control structure based on decision threes and FSMs (Finite State Machines), as the most suitable technique. FSMs are over the years widely accepted as a dominant technique for the shaping of agent behavior in computer games (Cavazza, 2000) and are well described in the available literature.

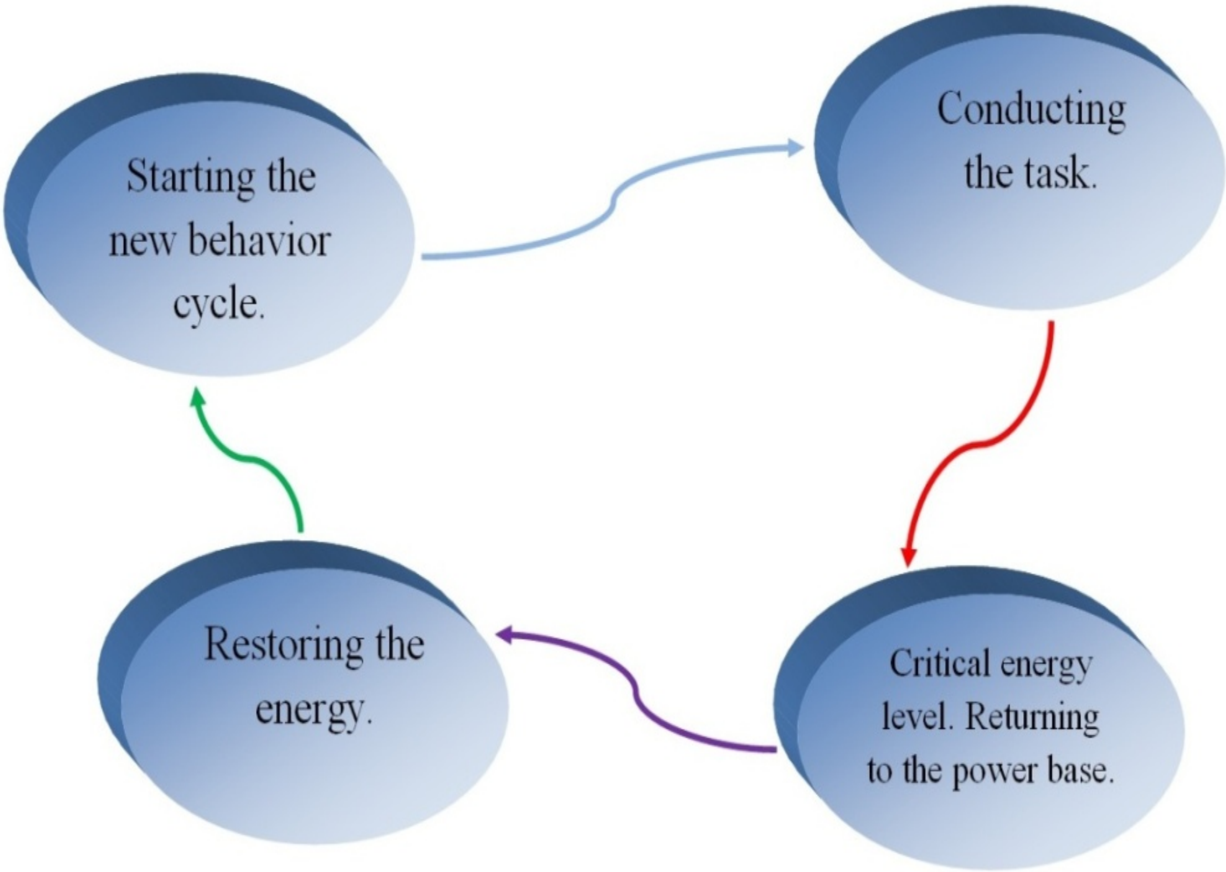


***Figure 3.4:*** *A simplified graphical representation of the general behavior cycle that is applied to agents.*

A UML-like graphical representation of the general control structure that we applied to the agents in our game-like educational system can be seen in Figure 3.5. We used a sort of hierarchical FSM as the main control framework. To be more precise, the energy levels of our agents are out of the highest priority. Therefore, when the energy level reaches a critical value, it activates a transition from the current state to the state that is higher in the hierarchy. As a consequence, the agent instantly stops its current actions, end enters a higher state. Therefore, the agent heads toward its power base in order to restore its energy. Upon reaching the defined energy level (in our case—fully recharging), another transition is activated, causing the agent to go back to the lower states and continue to perform its regular task.

At this point, one should notice that upon restoring their energy levels, agents Type 2 and Type 3 return to the place they were at before their energy reached the critical value (they previously memorize the location), and from that point continue their behavior/movement pattern. In other words, they continue their mission, right where they were stooped. In that way, we are disabling the redundant behavior –in which the agent would every time search the same part of simulation space. With agent Type 1, this “return condition” is not necessary, since it is moving in random directions. For Agent Type 4, we found that the “return condition” is also rather irrelevant.

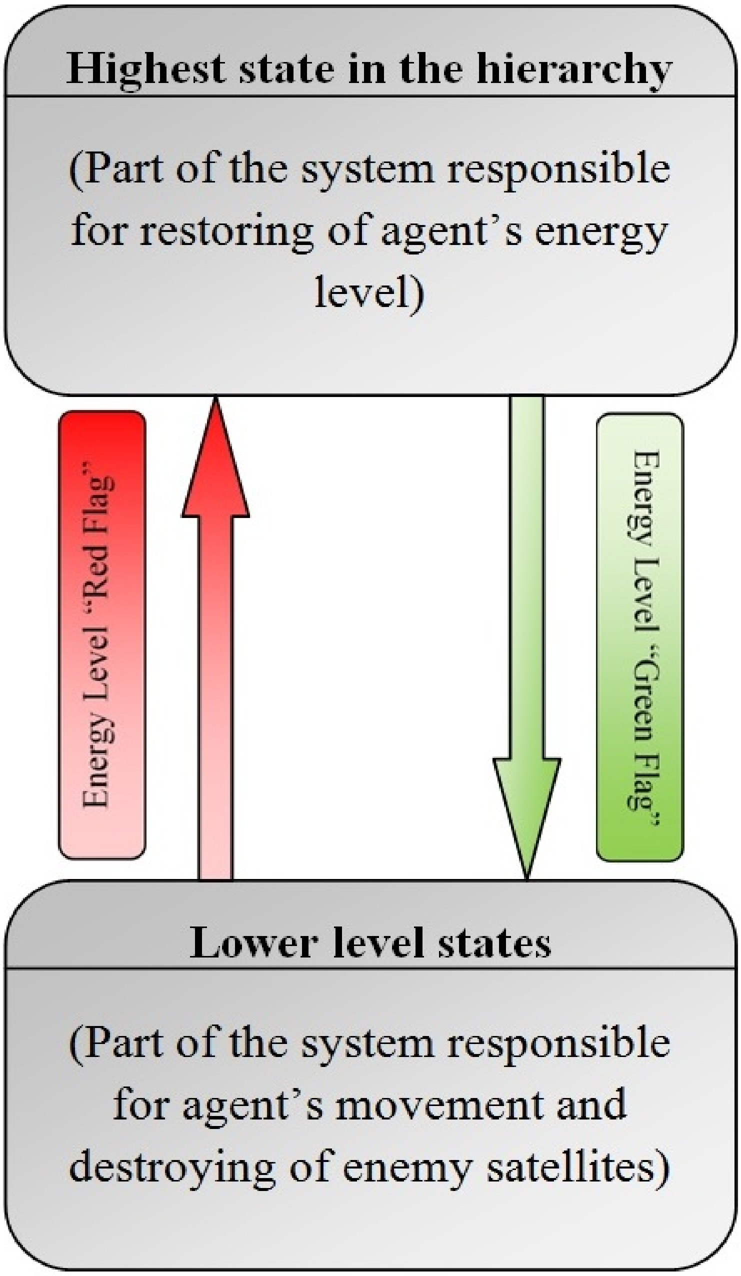


***Figure 3.5:*** *UML-like presentation of the hierarchy in the agent's control system.*

## 3.3 Example of the Experimental Setup

In this section, we will describe an example of an experimental setup conducted in the AViLab system. This kind of setup aims to show several possibilities of AViLab utilization at the same time. The goal of this experimental setup is to examine and demonstrate how successfully can relatively simple agent architectures (with limited knowledge about the surrounding world, sensorily inferior to humans, and without the ability to learn) cope with the imposed task, under specific time-limited conditions, and whether they can be compared in the terms of efficiency with the test groups of human users. In other words, we want to demonstrate and visualize the already mentioned premise, that depending on a situation the main goal does not always have to be developing of the "smartest" possible agent, but more simple solutions can also be optimal (with an often significant advantage, reflected in the fact that they are computationally and algorithmically less demanding).

Therefore, we will use agents 1 to 3. In order to have a clearer insight into the performance of agents, we will compare them to the two test groups of untrained human users. In addition, we will use two different environments (static and dynamic spawning mode). In this experimental setup, we limited the simulation cycle time to 60 s. The time limit does not allow for an agent/user to explore every single part of the space – in the case of Agent Type 2 and Agent Type 3, they cannot patrol the entire space world for the given time. We deliberately designed the experiment in such a way, because we wanted to see how agents and human users will handle the task under "tight" time conditions.

As is mentioned, we examined developed agents and test groups of human users in both, static and dynamic mode spawning scenarios. In both cases, the total number of enemy aliens was the same (set to 30), but they are spawned in a different manner as was explained earlier in the text. In order to provide a thorough insight into the performance of the developed agents and human test subjects, 50 simulation cycles are performed. The number of simulation cycles was chosen carefully, based on the work presented in (Petrović, 2021). Namely, a too-small number of simulations would probably lead to unreliable and possibly false results (e.g., an agent would be falsely superior compared to the previously untrained human user). At the same time, we must take care not to have excessive repetition of the task. As was recorded in the literature, humans tend to explore possible permutations through repetition (Coyne, 2003), and this repetition leads to learning from experience (Brinkmann, 2017). Consequently, with too many repetitions of the task, the influence of what we call "a purely untrained phase" on the overall data results would be diminished.

TABLE 3.1
PERFORMANCE DATA FOR THREE AGENTS IN THE STATIC MODE ENVIRONMENT, BASED ON THE 50 SIMULATION CYCLES.

| Parameter\User | Agent – Type 1 | Agent – Type 2 | Agent – Type 3 |
|---|---|---|---|
| Number of failed missions | 0 | 0 | 0 |
| Min score | 9 | 6 | 14 |
| Max score | 21 | 12 | 20 |
| Arithmetical mean value | 15.62 | 9.2 | 16.92 |
| Median value | 16.00 | 9 | 17 |
| Standard deviation | 3.19 | 1.49 | 1.3 |

Simulation results for all three agents in the "static mode", including a basic statistical analysis, are given in Table 3.1. With the observation of the obtained data, it can be seen that the performance of Agent Type 1 was rather constant, bearing in mind its built-in constraints. Therefore, it can be concluded that its overall design ensured a solid behavior. Agent Type 1, like the other two agents as well, never failed during the imposed task (which is according to the way they are designed). While its performance results during each simulation cycle vary – which is rather expected, bearing in mind the agent's limited knowledge about the outer world and its lack of sensorial information. Agent Type 2 had a smaller standard deviation, compared to Type 1. However, it scored significantly fewer average points, max score, and achieved a lower median value. Performance of the Agent Type 3 can be observed as the best out of these three. Although it did not achieve the max score of Type 1 in any of the 50 simulation cycles, it had a better average score and median value, followed by a significantly smaller standard deviation. Although agents Type 2 and Type 3 had similar strategies, due to the shape of the spaceship, which affected the shifting value, Agent Type 2 managed to cover more space during its "patrolling". Therefore, it managed to achieve better scores.

In order to have a better insight into the performance quality of the agents, we compared them with two test groups of human users (with each group counting 10 individuals). Namely, previously untrained human users entered the manual mode of our simulation system, where they had the same task as the agents (one group of humans entered the static spawning mode, while the other one entered the dynamic spawning mode). At this point, the term "untrained" should be clarified more precisely. Namely, this means that selected groups of human users had no prior experience in this particular game-like simulation, and at the same time, they also had a negligible amount or no experience at all, in similar types of simulations and computer games. One should also notice that both groups of human users are chosen, while taking care of gender and age diversity, as much as it was possible.

At this point, the audience should be reminded once again that simulation conditions are exactly the same, whether the agents or the human users enter the simulation scenario (e.g., human users and agents move across the space with the same speed, etc.). In that way, a fair and objective comparison is provided. There are, of course, two obvious main differences between them. The first one is reflected in the fact that all agents are sensorily inferior compared to humans, and do not have learning capabilities. The second one is reflected in the fact that, unlike the agents, human users do not have a predefined trigger for their return to the power base and restoration of the energy level (in other words – they are not safe from failing). Consequently, human users must behave in an intuitive manner, and therefore choose which recharging strategy will apply, and adapt the strategy if needed. Table 3.2 shows the obtained simulation results, regarding the test group of untrained human users in the static environment.

TABLE 3.2
PERFORMANCE DATA OF UNTRAINED HUMAN USERS IN THE STATIC MODE ENVIRONMENT, BASED ON THE 50 SIMULATION CYCLES.

| Parameter\User | HU1 | HU2 | HU3 | HU4 | HU5 | HU6 | HU7 | HU8 | HU9 | HU10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Number of failed missions | 14 | 4 | 9 | 4 | 2 | 7 | 2 | 0 | 10 | 1 |
| Min score | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 0 | 0 |
| Max score | 27 | 26 | 27 | 25 | 24 | 27 | 23 | 22 | 27 | 22 |
| Arithmetical mean value | 13.86 | 15.08 | 15.58 | 14.24 | 15.26 | 15.6 | 15.2 | 14.4 | 15.48 | 13.80 |
| Median value | 15.00 | 15.00 | 17.00 | 14.00 | 15.00 | 17.00 | 15.00 | 14 | 17 | 14.00 |
| Standard deviation | 9.67 | 6.70 | 8.52 | 6.19 | 4.77 | 7.40 | 4.16 | 4.26 | 8.85 | 4.56 |

While observing the experimentation process, it was noticed that human users differently coped with the imposed task, which was rather expected. This mainly resulted in their selection of different tactical approaches – some of them had more aggressive strategies resulting in a larger number of failures, while some had a more careful approach to the problem, aiming to reduce failures, even at the cost of lower scores. However, they all learned from experience to a certain degree and enhanced their strategies and overall performance during the time. With a closer look at the statistical parameters shown in Tables 3.1 and 3.2, we can conclude that all human users scored higher max scores than any of the three agents. They were also superior to Agent Type 2, regarding the mean and median value. On the other hand, agents Type 1 and Type 3 were, generally speaking, more successful than any of the human users in the static environment. These agents achieved higher mean values than any of the human test users. Furthermore, as can be seen from the statistical parameters, these agents had a more constant performance, which can be an extremely significant advantage for certain types of tasks.

TABLE 3.3

PERFORMANCE DATA OF UNTRAINED HUMAN USERS IN THE DYNAMIC MODE ENVIRONMENT, BASED ON THE 50 SIMULATION CYCLES.

| Parameter\User | HU1 | HU2 | HU3 | HU4 | HU5 | HU6 | HU7 | HU8 | HU9 | HU10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Number of failed missions | 10 | 4 | 13 | 4 | 2 | 5 | 0 | 1 | 12 | 1 |
| Min score | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 0 | 0 | 0 |
| Max score | 20 | 24 | 24 | 25 | 20 | 23 | 19 | 21 | 27 | 18 |
| Arithmetical mean value | 10.46 | 13.32 | 13.44 | 13.44 | 12.9 | 13.22 | 12.92 | 13.28 | 13.32 | 12.2 |
| Median value | 11 | 13 | 16 | 14 | 13 | 13 | 13 | 13 | 16 | 13 |
| Standard deviation | 6.30 | 6.41 | 8.67 | 5.97 | 4.39 | 6.22 | 3.52 | 4.81 | 8.48 | 3.93 |

We also tested agents and humans in the dynamic spawning mode. Table 3.3 shows the performance of another test group of humans, while Table 3.4 shows the performance of the agents. The second test group of human users generally achieved lower scores compared to the first one. One could also notice that agents decreased in their performance. The change of environment particularly affected the performance of Agent Type 1. However, Agent Type 3 remained overall better compared to the humans.

TABLE 3.4

PERFORMANCE DATA FOR THREE AGENTS IN THE DYNAMIC MODE ENVIRONMENT, BASED ON THE 50 SIMULATION CYCLES.

| Parameter\User | Agent – Type 1 | Agent – Type 2 | Agent – Type 3 |
|---|---|---|---|
| Number of failed missions | 0 | 0 | 0 |
| Min score | 4 | 4 | 11 |
| Max score | 16 | 10 | 16 |
| Arithmetical mean value | 9.82 | 6.6 | 13.48 |
| Median value | 10.00 | 6.5 | 14 |
| Standard deviation | 2.86 | 1.23 | 1.28 |

By further increase of the number of tested human users, it could be expected that there will be those who would in a certain measure outperform Agent 3 in both environments. Nevertheless, the results of this experiment can be observed as a decently strong indicator regarding the appropriate level of capabilities and performance of agent structures designed according to our agenda.

Summing up the obtained experimental data can lead us to a conclusion that in certain scenarios, a carefully designed and tuned control algorithm implemented in an agent’s behavior, can to a certain degree rather successfully compensate for a lack of sensorial information and complex AI. This represents a very important exercise demonstration, keeping in mind that we often meet constraints regarding the available computational resources in present highly complex virtual environments (Khoo & Zubek, 2002). One should also notice, once again, that the ultimate goal does not always represent the development of the “smartest” possible agent, but rather the most adequate for the given situation, especially when it comes to computer games applications (Lidén, 2004; Cass 2002). Therefore, in some scenarios, an inexpensive design can represent a better choice over a complex AI, regarding all the parameters. All of the previously demonstrated in this exercise is not only significant from the aspect of already mentioned gaming worlds, but also from the aspect of real-world applications, where inexpensive (yet reasonably efficient) design can be a crucial segment of the development process. In the end, it should be also underlined that both groups of human participants unanimously evaluated their experience with the AViLab system as highly positive.

## 3.4 Concluding Remarks and Future Work

This chapter presented the realization of the AViLab software system aiming to serve as the educational tool dedicated to experimentation and demonstration, regarding an agent's features and basic principles. Our main objective was to build a game-like system specially dedicated to agents while focusing on some of the fundamentals of agent theory. Bearing in mind that the concept of agents and related theory can often seem rather abstract to those that are getting introduced to the field (students, pupils, etc.), we strongly believe that systems such as our AViLab can help in visualization, practical demonstration, and a therefore better understanding of theoretical fundamentals.

As was discussed in the chapter, virtual laboratories in their essence offer many useful features. They are more affordable than real laboratory equipment. They enable the repeatability of experiments. In addition, they offer a high level of availability and location independence, as they can be installed on almost any personal computer. Furthermore, virtual laboratories can sometimes offer experimentation possibilities unfeasible or unviable in the real world.

Our AViLab system can be utilized in several ways. Users can experiment with changing the parameters while tracking down the performance of a single agent. They can compare agents between themselves, or include test subjects and compare them with agents, under a certain experimental setup (as was demonstrated in our exemplary experiment). You can also customize spawning, in order to demonstrate certain scenarios of interest. Therefore, different scenarios can be designed, depending on desired learning/experimentation/demonstration agenda. In other words, our system is suitable to be used as a demonstration tool during course lectures, as well as for laboratory exercises (designed according to the aim of the lab supervisor), aiming to provide an efficient demonstration of the important insights of the agent's technology fundamentals in illustrative, as well as an immersive manner (e.g., exploiting agent's predictability, autonomy, control architectures, etc.).

Considering future work, besides the standard parameters that we can change, such as the number of satellites, time-limit of the simulation, etc., we also plan to work on a few different variations of our simulation scenario features, as well. Consequently, this could enable us with a wider framework for demonstration. Furthermore, since our system is developed in such a way (due to an object-oriented programming approach), that in future work it can be rather easily expanded with additional modes, upgrades, and scenarios; we consider the development of a "Battle Arena" mode, where human users can compete directly against a chosen agent. A deeper pedagogical analysis of the system, oriented toward the user experience, is yet to be thoroughly researched, with a careful and broader elaboration of different experimental and demonstrations scenarios. Of course, development directions oriented toward pedagogical agents are something to be thought about in future work. However, modifications in this direction will be thoroughly analyzed, while taking care not to violate the basic principles of system development elaborated in the chapter.

In the end, one should notice once again that the developed AViLab system aims not only to serve as an educational tool but at the same time has the potential for various research applications.

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*"If science is to progress, what we need is the ability to experiment."*

Richard P. Feynman (1918. – 1988.)

# Chapter 4

## Educational Aspects of Virtual Worlds (Emphasizing the Importance of the Virtual Laboratory Concept)

In the previous chapters, we have already mentioned some aspects of virtual worlds and related technology. As it was underlined on several occasions, over the years virtual worlds and their applications became recognized as objects of interest in various scientific fields. Consequently, their potential for educational purposes is noticed and utilized in many different ways. From serious gaming to virtual laboratories – there are numerous examples of how different virtual environments can be useful in educational processes. In this chapter, we will thoroughly inspect this subject, while focusing on the role of virtual laboratories.

This chapter is dedicated to providing a thorough analysis, which should serve as a basis for deeper understanding and extensive future use of technologies related to the virtual laboratory concept. At the same time, we are focusing on a broad audience while introducing it to fundamental theoretical and practical knowledge. However, it should be noticed that we address the concept of virtual laboratories while primarily focusing on the technology perspective, therefore not analyzing and going into details regarding the pedagogy-related theories.

We begin our analysis, with Section 4.1. In this section, we briefly explain the purpose, advantages, and drawbacks of virtual laboratories. Section 4.2 introduces requirements and evaluation criteria for virtual laboratory solutions. A systematic examination of selected virtual laboratories (done according to the previously established criteria and requirements) is elaborated in Section 4.3. Within this section, different STE (Science, Technology, and Engineering) fields are analyzed, while putting a special emphasis on the engineering-related disciplines and especially taking care of the field of robotics. Disciplines related to physical sciences, technology, and engineering, have certain requirements, that defer them from some other disciplines (such as computer science), and will be elaborated in this chapter. One should notice, that only academic-based research was taken into account, therefore not considering the commercial-based simulators and training environments. One should also notice, that Section 4.3 represents the core part of the chapter. In Section 4.4, we provide a summary of the chapter, brief discussion, observations, and consequently try to determine some of the directions and possibilities for future work and advancements in the field. The chapter finishes with the list of relevant references, which is used as support for the elaborated subject.

## 4.1 Why Go Virtual? Analyzing Advantages and Drawbacks of the Virtual Laboratory Concept

As we mentioned earlier in the text, in this section we will try to concisely elaborate the motivation for applying virtual laboratories, their purpose, some of their advantages, and possible drawbacks of this technology.

### *4.1.1 Motivation*

There are different motives for virtual laboratories development. One of the aspects (which is widely known and recognized) is certainly the concept of distance & online learning, and the globalization of education in general. In the past decade and more, we have witnessed an extensive growth of online courses, pc & web-based learning platforms, and even open universities. All of the previously mentioned aimed to make education more accessible to the interested parties.

In the beginning, the development of this concept was much more progressive in social sciences, where distance learning could achieve most of the traditional learning functionalities. However, STE disciplines were more complicated, as they often required laboratory experiments as an inevitable part of the learning process. Namely, laboratory exercises are an extremely important aspect of science and engineering education. Different laboratory experimentation scenarios enable students to get deeper insights into the theoretical foundations, and at the same time interconnect gained theoretical knowledge with practical applications.

A solution to the previously mentioned issues was the introduction of alternatives to real laboratories – in the forms of remote and virtual laboratories. Remote laboratories, however, fail to solve certain requirements, which will be discussed later. Therefore, we argue for the concept of virtual laboratories, and will thoroughly discuss this matter in the following sections.

While investigating the concept of virtual laboratories in this chapter, special emphasis will be given to robotics, as its multidisciplinary nature gives us a solid foundation on defining evaluation criteria and analyzing the core ideas behind the concept of virtual laboratories. Furthermore, it can be noticed that there is a certain degree of matureness in the robotics field, regarding the concept of virtual educational tools & environments. One could notice, that this fact is not surprising, bearing in mind that the field of robotics represents almost an ideal example of synergy between different engineering disciplines and physics theories. Therefore, this could imply a broad application of the virtual laboratory principles established on the robotics example, to other STE disciplines.

### *4.1.2 Advantages and Drawbacks of Virtual Laboratories*

We mentioned earlier in the text that there are two alternatives to the traditional physical laboratories – remote and virtual laboratories. However, remote laboratories fail to solve certain issues. Namely, although they can provide distance access to the laboratory equipment, they fail to provide good scalability (e.g. at the given moment, each laboratory setup is occupied by one user/student). In addition to that, there are certain limitations in supporting more complex educational scenarios, which include user cooperation. Furthermore, the overall complexity and expense of such systems are higher compared to both virtual and real physical laboratories. Therefore, it can be noticed that in many ways, remote laboratories represent a rather inefficient solution.

As we already mentioned, this chapter is primarily focused on virtual laboratories, which can (by their nature) efficiently solve many of the previously mentioned issues. Therefore, in this sub-section, we will try to elaborate on the advantages and drawbacks of such solutions, compared to both real and remote laboratories.

***Advantages:***

We will now discuss some of the advantages, particularly important in the context of STE disciplines.

**(I) Economic perspective:**

Virtual laboratory concept enables cost-effective solution for educational & research institutions, as an alternative to the often expensive physical laboratory setups in STE fields.

**(II) Flexibility aspect:**

The virtual laboratory concept enables numerous variations of the virtual experimentation process. Furthermore, as it was recognized in (de Jong, Linn, & Zacharia, 2013), the learning process can be simplified by removing confusing details, or by other adaptations of experimental design which could make observing various phenomena much easier.

**(III) Accessibility aspect:**

A number of users/students could simultaneously occupy the identical virtual experimental setup.

**(IV) Modification aspect:**

The virtual concept enables modifying or adapting the configuration (software and hardware) of the virtual system. Very often this cannot be easily performed (or cannot be performed at all) in a real-world physical system. If we take robotic, or some other electro-mechanical system, as an example – a user/student can easily replace or modify actuators, sensors, or some other system element.

**(V) Damage toleration:**

It is not prohibited to make damage or cause a malfunction of the device in a virtual system. As a consequence, this opens up the opportunity of “learning from mistakes”, as there is no real penalty or permanent consequences. If we take robotics as an example, unlike the real world where the collision of the robot with some segment of its environment would cause significant damage or even destruction of the device, in a virtual scenario all we need is to restart the simulation.

**(VI) Revealing of the inner mechanisms/processes:**

Considering the engineering disciplines, the majority of physical laboratory electrical, and mechanical equipment have some sort of protecting housing to preserve the machines/apparatus from negative external influences. Very often this protecting housing is not so easily-removable (or even, it is not removable at all). However, the virtual concept gives us the possibility for enabling of protecting housing removing, thus exposing the internal working mechanisms.

***Shortcomings:***

Besides elaborated advantages, there are potential issues and drawbacks related to virtual laboratory solutions:

One of the issues is related to the available computational power of PC. Namely, dynamics and CAD models of particular devices/objects, as well as the system in general, could sometimes be rather computationally complex and demanding. This would be especially noticeable if insisting on such modeling would be put in the context of the metaverses.

Another potential shortcoming is related to the very essence of the virtual laboratory concept. Since the system is virtual (it only emulates some selected real-world processes), there are no real-world penalties for potential mistakes. Although this can represent a very valuable feature (as we already mentioned previously in the text), on some occasions this could also lead to a specific working attitude of a particular user/student, reflected in a certain reduced degree of responsibility, and cautiousness, while conducting laboratory experimentation.

This could be illustrated through many examples. Standing inside of the power plant, and standing in some virtual ambiance that is emulating it, simply does not provoke the same feeling. The same could be applied to a complex manufacturing facility, with a number of large industrial robots and other machinery, manipulating with large payloads. A real-world experience in such systems affects students'/trainees' attitudes, making them more focused and cautious.

In the end, it should be underlined, that depending on the field, hands-on experience with the physical real-world laboratory setup is sometimes an inevitable part of the learning process or training since current virtual solutions cannot always fully replace the physical laboratory paradigm. Nevertheless, bearing in mind the tremendous advance in all technologies related to the development of virtual laboratories, the boundaries between what could be achieved exclusively in the real world and what could be achieved in its virtual counterpart are diminishing.

## 4.2 Defining Evaluation Criteria

As a pre-condition for a thorough examination of the selected state-of-the-art virtual laboratories, some evaluation criteria and requirements must be defined. These criteria and requirements are based on a key condition (highly relevant for all STE fields, and especially relevant for engineering disciplines): ***operating a virtual laboratory for a student must feel like they are working with real authentic devices in a real authentic space***.

Bearing in mind the previously elaborated condition, we will now define some evaluation criteria and requirements (in rather logical order):

**(EC1) – UI (User interface)**

In the case, where we are emulating the existing real-world devices, every laboratory device should have a UI that is equivalent to a UI of its real-world counterpart, or as similar as possible. In the case where we are designing our own original devices, a user interface should be user-friendly and designed as it would be for a real-world application.

This requirement is not too demanding (in the majority of cases), and could be regarded as rather straightforward. One should notice, that this criterion can be out of high significance when it comes to virtual laboratories aiming to serve as a tool for operators' training.

**(EC2) – System behavior**

A simulated system should behave in the approximately same manner as its real-world counterpart.

This often includes (depending on particular STE discipline) obeying real-world physics laws, including the dynamics of a physical system. Therefore, at this point one should notice that there are two manners in which system dynamics can be solved in virtual environments, each having its own advantages and drawbacks. The first solution is using real-time physics engines. The second solution is using customized specifically developed models of physical system dynamics (illustrative examples can be found in Vukobratovic & Potkonjak, 1982; Vukobratovic & Potkonjak, 1985; Vukobratovic, Potkonjak, & Matijevic, 2003). We will not go into a deeper analysis of these solutions, in this chapter.

One should notice that the system dynamics model is not always necessary and is highly dependable on the overall purpose of the system. Consequently, this implies that this criterion does not have to be fully fulfilled in some scenarios, in order to provide a realistic behavior. An illustrative example comes from the earlier mentioned operators' training dealing with industrial manipulators. For this scenario, the dynamics model of the manipulator is unimportant (and even unnecessary). However, the kinematical model of the manipulator (which is in direct relation to the input commands/parameters and therefore the motion of the manipulator) is of key significance.

**(EC3) – Visual aspect**

Simply speaking, we must enable users/students to have a high level of realistic visual experience. This criterion could be divided into two sub-conditions.

Condition **(EC3a)** refers to looking at or interacting with the particular laboratory setup/device and workplace, while on the other hand condition **(EC3b)** refers to an entire more content-rich virtual environment (if there is one) in general. Consequently, both of these conditions require applying CAD (Computer-aided design).

**(EC4) – Multi-user, collaboration aspect**

In other words, this criterion means not just heaving a visually content-rich environment (condition EC3b), but also using/developing a 2D or 3D laboratory environment that enables efficient communication and collaboration between users/students. This requires for integration of the system into some of the existing MUVEs/metaverses, or the development of a dedicated virtual environment that could be classified as a micro-metaverse. In Chapter 1, we already elaborated thorough information and research potentials related to MUVEs/metaverses, computer games, and virtual worlds in general.

**(EC5) – Intelligent tutoring system**

In some sense, this requirement represents an extension of the previous one. In real-world laboratories, students often need guidance from a laboratory supervisor. Although a collaborative metaverse-based educational environment would enable the presence of human tutors, this is not always the most optimal solution (remember that one of the main focuses is to provide good scalability and high accessibility). Therefore, the concept of pedagogical agents, who would have a tutoring role, and intelligently guide a user/student through the educational environment, could be out of great significance, and could consequently expand and enhance the overall quality of the virtual system.

## 4.3 Analysis and Evaluation of the Selected Virtual Laboratories

The importance of virtual laboratories is reflected not only in a number of developed labs in different fields but also in wider initiatives. These initiatives aimed to provide a more general focus and research framework, not only for full virtual laboratories but for remote laboratories as well. We will briefly describe some of them, further in the text, while afterward, we will redirect the focus on specific solutions clustered by a common class to which they belong.

One of the illustrative examples is LiLa (Library of Labs), a joint effort of several European universities and enterprises (coming from different countries), coordinated by the University of Stuttgart, and supported by the European Commission. According to (Richter, Boehringer, & Jeschke, 2009), LiLa aimed to construct an infrastructure for sharing experimental and simulation setups. Furthermore, what was elaborated as the main motivation for creating such a network, was the desire of participating institutions to promote virtual and remote laboratories as a key part of education in engineering-related disciplines, especially focusing on undergraduate courses. What was particularly interesting (especially in the context of the following sections in this chapter), is the fact that Open Wonderland supported the LiLa concept.

Another interesting example is the Go-Lab Project (Global Online Science Labs for Inquiry Learning at Schools), also funded by the European Commission. According to work presented in (Govaerts et al., 2013; de Jong, Sotiriou, & Gillet, 2014), this four-year project (2012-2016) aimed to promote virtual and remote laboratories for broad use in STEM disciplines, while focusing on inquiry-learning. Furthermore, it emphasized the importance of online laboratories as a valuable addition to STEM education. The consortium of the project consisted of numerous eminent educational and research institutions across Europe, led by the University of Twente. What is of particular importance is the fact that, among others, the created portal enabled access to a collection of online laboratories related to eminent scientific institutions, such as CERN (European Organization for Nuclear Research, Switzerland), or ESA (European Space Agency, Netherlands). Furthermore, the portal was intended to support the introduction of new laboratories. This project continued its life and is credited for the present-day Go-Lab initiative.

Over the past two decades, one could notice that the virtual laboratory concept related to various disciplines was extensively promoted. Considering the very nature of the appropriate research fields, virtual laboratories are in most cases specifically tailored in order to respond to the appropriate field requirements. Consequently, they do not offer the possibility to be easily re-used as a general software framework for further applications in other disciplines. Furthermore, each specific virtual laboratory solution has its own, specific degree of complexity (regarding the theoretical and technological aspect of its development).

In the following sections, selected virtual laboratories coming from various STE disciplines will be elaborated. These examples are considered to be out of high significance for the overall focus of this chapter. One should notice, that aim was to create a balanced selection between STE disciplines. However, as we have already mentioned in the previous text, the main focus will be on the field of robotics.

The summarized assessment of the selected virtual laboratories is among other arranged through four Tables (4.1 – 4.4), with each table covering a distinctive part of our overall analysis. Furthermore, each table contains essential information related to the selected laboratories: name/acronym, participating institutions, primary field, and evaluation grades (related to the previously elaborated evaluation criteria). All of the mentioned should lead to a rather methodical and thorough analysis, and assessment of virtual laboratory solutions. At this point, one should notice, that all analyzed virtual laboratories have a very high level of functionality. However, they are evaluated from the perspective of the features that would be contained in a highly realistic virtual laboratory comparable with (and even in some sense better than) the real physical laboratory.

### *4.3.1 Virtual Laboratories Related to Physical Science*

We will start our analysis, with several examples coming from physical science. To be more precise, the main focus will be on the fields of physics and chemistry. Specifications of selected virtual laboratories coming from these fields, along with evaluation criteria, are shown in Table 4.1. While a more thorough description of each laboratory follows in the text below the table.

TABLE 4.1
BASIC INFORMATION AND EVALUATION CRITERIA REGARDING THE SELECTED VIRTUAL LABORATORIES COMING FROM PHYSICAL SCIENCE.

| Virtual Laboratory Name, or Acronym | Participating Institutions | Primary Field | EC1 | EC2 | EC3a | EC3b | EC4 | EC5 |
|---|---|---|---|---|---|---|---|---|
| CyclePad | Northwestern University (USA), University of Oxford (UK), & Xerox Cooperation (USA) | Physics | yes | yes | no | no | no | no |
| VMSLab-G | University of Perugia (Italy) | Chemistry | yes | yes | yes | yes | no | no |
| Virtual Chemistry Laboratory | Charles Sturt University (Australia) | Chemistry | no | no | yes | yes | no | no |

One of the early examples of virtual laboratory implementation, in general, was presented by the team of researchers (Forbus et al., 1999) coming from the USA and the UK. They described the CyclePad, a virtual laboratory dedicated to the research of thermodynamics principles. Although this laboratory focus on engineering students, it essentially belongs to the field of physics. Authors underlined that due to its wide applicability in general science, and engineering disciplines as well, thermodynamics represents a perfect field for the implementation of the virtual laboratory concept. Students can experiment in CyclePad, by designing different types of thermodynamic cycles (e.g. cryogenic system). Authors reported that their CyclePad laboratory was embraced by several universities for use in educational purposes on different levels of study. They also reported that at the time, their virtual laboratory enabled students to conduct more complex collaborative projects than prior to the introduction of the CyclePad educational system. Considering our evaluation criteria, and according to the information available from the above-mentioned paper of the authors, CyclePad fulfills criterion (EC1), and criterion (EC2). On the other hand in the case of CyclePad, criteria (EC3a), (EC3b), and (EC4) are not fulfilled. Criterion (EC5) is also not fulfilled in the way it was required, however, we must comment that CyclePad had an interesting "coaching" system that aimed to help students during experimentation.

The team of researchers coming from the University of Perugia (Italy), presented the VMSLab-G (Figure 4.1). This virtual laboratory is dedicated to the field of chemistry (Gervasi, Riganelli, Pacifici, & Laganà, 2004). According to the authors, students can move around the virtual laboratory space and experiment with different lab exercises dedicated to the fundamentals of molecular science. Furthermore, safety rules based on real-world chemistry laboratories are applied to this virtual environment. Several scenarios are offered in the VMSLab-G, including the Boyle law experimentation setup, IR spectroscopy, flame spectroscopy, and UV spectroscopy. What is underlined by the authors, as a core feature of the developed educational system is the molecular description of conducted experiments. Considering our evaluation criteria, and according to the information available from the above-mentioned paper of the authors, VMSLab-G fulfills criteria (EC1), (EC2), (EC3a), and (EC3b). However, criteria (EC4), and (EC5) are not fulfilled.


***Figure 4.1:*** *VMSLab-G virtual laboratory (figure extracted from Gervasi et al., 2004).*

Another interesting example comes from the field of chemistry (Dalgarno, Bishop, & Bedgood, 2003; Dalgarno, Bishop, Adlong, & Bedgood, 2009). Namely, the research team coming from Charles Sturt University (Australia), identified that their students, especially those ones engaged in distance learning, have a certain feeling of discomfort and lack of confidence when they approach laboratory setups. Their solution was to introduce students to a virtual educational environment, called Virtual Chemistry Laboratory (Figure 4.2). The aim was to prepare students for future hands-on experience in physical laboratory conditions. What is interesting is that their virtual laboratory represents an accurate 3D model of the real chemistry laboratory at their university. However, this laboratory does not allow students to actually conduct experiments. They can explore and learn about laboratory items, setups, and laboratory space in general. The authors reported that the majority of students found their virtual laboratory experience to be useful and helped them prepare for the real physical lab exercises. According to the information available from the above-mentioned papers of the authors, and the very essence of the system which is already described, Virtual Chemistry Laboratory fulfills only criteria (EC3a), and (EC3b).

***Figure 4.2:*** *Virtual Chemistry Laboratory (figure extracted from Dalgarno et al., 2003).*

#### *4.3.2 Virtual Laboratories Related to Technology and Non-Robotics Engineering Fields*

This sub-section will be dedicated to virtual laboratories which are primarily oriented towards technology and engineering disciplines, not primarily focused on robotics. Specifications of selected virtual laboratories, along with evaluation criteria, are shown in Table 4.2. While a more thorough description of each laboratory follows in the text.

Virtual laboratory solution in the field of process control was presented by a group of researchers coming from the Faculty of Chemical and Food Technology, at the Slovak University of Technology in Bratislava (Kaluz, Cirka, & Fikar, 2011). The authors argued that virtual laboratories represent a step towards the improvement of education in the field of automation & process control. They simulated certain processes in a technological plant, through several illustrative applications. Namely, based on the PID controllers and appropriate mathematical modeling, their 2D laboratory elaborated interesting problems of the tank storage system, tube heat exchanger, and stirred-tank reactor. It is important to underline that the authors paid special attention to precise dynamical models and physical properties of mentioned simulated systems. Consequently, this included linear and non-linear ODEs (Ordinary Differential Equations) during the modeling. Considering our evaluation criteria, and according to the information available from the above-mentioned paper of the authors, this virtual laboratory fulfills the criterion (EC1), and the criterion (EC2). Other criteria are not fulfilled.

TABLE 4.2

BASIC INFORMATION AND EVALUATION CRITERIA REGARDING THE SELECTED VIRTUAL LABORATORIES COMING FROM DISCIPLINES RELATED TO TECHNOLOGY & NON-ROBOTICS ENGINEERING.

| Virtual Laboratory Name, or Acronym | Participating Institutions | Primary Field | EC1 | EC2 | EC3a | EC3b | EC4 | EC5 |
|---|---|---|---|---|---|---|---|---|
| Virtual Laboratory of process control | Slovak University of Technology at Bratislava (Slovakia) | Process control | yes | yes | no | no | no | no |
| Emulation-Based Virtual Laboratories for Control System Design - VLCSD | The University of Newcastle (Australia), & Griffith University (Australia) | Control engineering | yes | yes | partly | no | no | no |
| Multiplatform Virtual Laboratory for Educational Purposes | Universitat Politecnica de Catalunya (Spain) | Control engineering | yes | yes | no | no | no | no |
| TriLab | Loughborough University (UK) | Control Engineering | yes | yes | no | no | no | no |
| Virtual Laboratory Environment | Stevens Institute of Technology (USA) | Mechanical Engineering | yes | yes | yes | yes | yes | no |
| Virtual Electric Machine Laboratory | Firat University (Turkey) | Electric machines | yes | yes | no | no | no | no |

Research presented in (Goodwin, Medioli, Sher, Vlacic, & Welsh, 2011) analyzed virtual laboratories as a successful low-cost replacement for experiments in the control engineering and presented VLCSD (Virtual Laboratories for Control System Design) system. Authors argue that their solution can provide students with applicable, real-world, industrially relevant learning experiences. VLCSD offers several interesting modules (Figure 4.3), related to real-world applications. According to this research, there is an audio quantization lab, rolling mill lab, paper machines module, continuous casting plant, and a module dedicated to rocket dynamics and control.

Each of these modules has a unique UI and defined learning objectives. The overall conclusion of the authors, elaborated through an appropriate assessment, was that the VLCSD system significantly improved students' attitudes and general knowledge in a related subject. Considering our evaluation criteria, and according to the information available from the above-mentioned paper of the authors, VLCSD fulfills the criterion (EC1), and the criterion (EC2). It also partly fulfills the criterion (EC3a). Other criteria are not fulfilled.

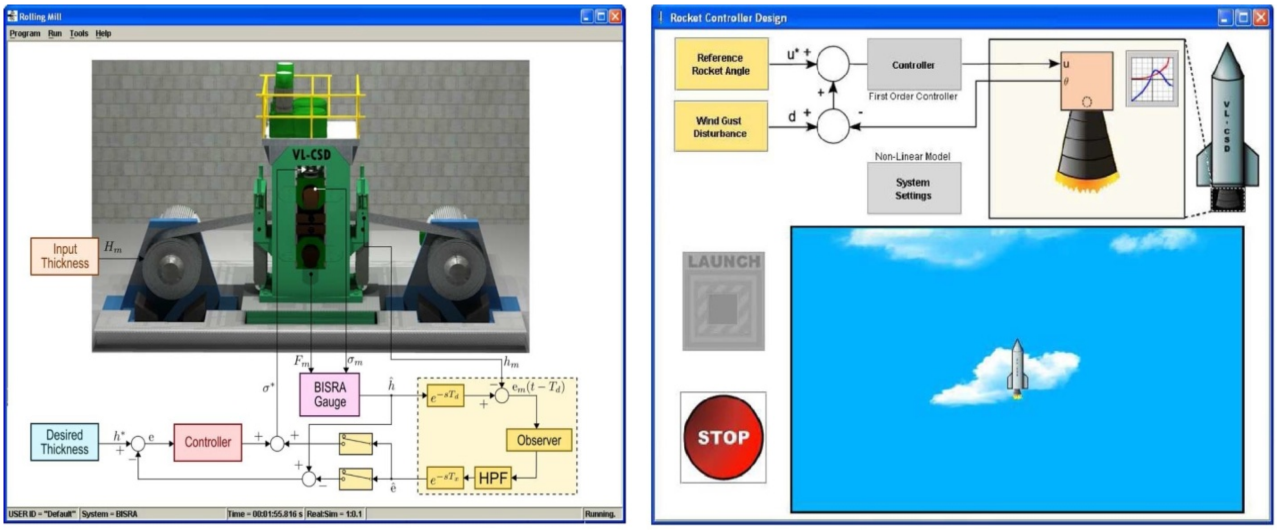


***Figure 4.3:*** *Some of the available modules offered by the VLCSD (figure extracted from Goodwin et al., 2011).*

Multiplatform virtual laboratory dedicated to the field of control systems engineering was presented by the research team coming from the Universitat Politècnica de Catalunya, Barcelona, Spain (Villar-Zafra, Zarza-Sanchez, Lazaro-Villa, & Fernandez-Canti, 2012). This virtual laboratory is dedicated to education at the university level. It is developed on Java-based tools. The authors underlined its multiplatform nature, explaining that experiments in the virtual laboratory can be conducted in any browser. Several illustrative experimental setups are offered in this laboratory, aiming to demonstrate the fundamentals of the control theory. Accordingly, students can work on magnetic levitator (which is developed as a counterpart to the existing real-world magnetic levitator), and inverted pendulum-cart system, in that way gaining important knowledge about subjects such as system nonlinearity and dynamics. What is reported in this study as a significant advantage, is the fact that virtual laboratory was available for students 24h a day. Consequently, since the students also used real laboratory setups during their learning, this reduced the usage of the real laboratory by about 80%. Considering our evaluation criteria, and according to the information available from the above-mentioned paper of the authors, this virtual laboratory fulfills the criterion (EC1), and the criterion (EC2). Other criteria are not fulfilled.

Another virtual solution dedicated to the field of control systems was elaborated through the TriLab project, presented in (Abdulwahed & Nagy, 2013). As it can be concluded from the project title, this laboratory integrated all three laboratory modes (Physical, Remote, and Virtual). The laboratory is developed with the use of the LabVIEW platform, which authors considered the most suitable regarding their overall project requirements. The main focus of this educational platform is on introducing the students to fundamentals of control engineering, such as the open-loop concept, designing, and tuning of PID algorithm, etc. The authors underlined the importance of the role of experiments in engineering education and concluded that their concept had a successful impact on the learning process of their students. Considering our evaluation criteria, and according to the information available from the above-mentioned paper of the authors, the virtual segment of the TriLab project fulfills the criterion (EC1), and the criterion (EC2). Other criteria are not fulfilled.

One of the most illustrative examples is certainly a project coming from Stevens Institute of Technology, USA (Aziz, Esche, & Chassapis, 2009; Aziz, Chang, Esche, & Chassapis, 2014), where research team developed a game-based virtual learning environment in the field of mechanical engineering (Figure 4.4). To be more precise, this learning environment was dedicated to gear train design, aiming to introduce students to fundamental knowledge related to transmission ratios, various gear configurations, their working principles, etc. All experimental setups followed the laws of physics. The authors identified three levels of visualization details: detailed, intermediary, and extended level. This enabled students (as well as their supervisors) to access content-rich laboratory space in the form of avatars, take a closer look at the experimental setup and equipment, interact with the equipment and conduct experiments. All of these details aimed to provide a feeling of immersion to the users. According to the above-mentioned papers, the "Source" game engine is used for the realization of their project, as well as the "Havok" physics engine. The research team also tested their learning environment with the undergraduate students, attending university courses on mechanisms and machine dynamics. Reported results have shown that students enhanced their knowledge to a rather large degree. Considering our evaluation criteria, and according to the information available from the above-mentioned papers of the authors, this virtual laboratory fulfills all evaluation criteria, except for the criterion (EC5).

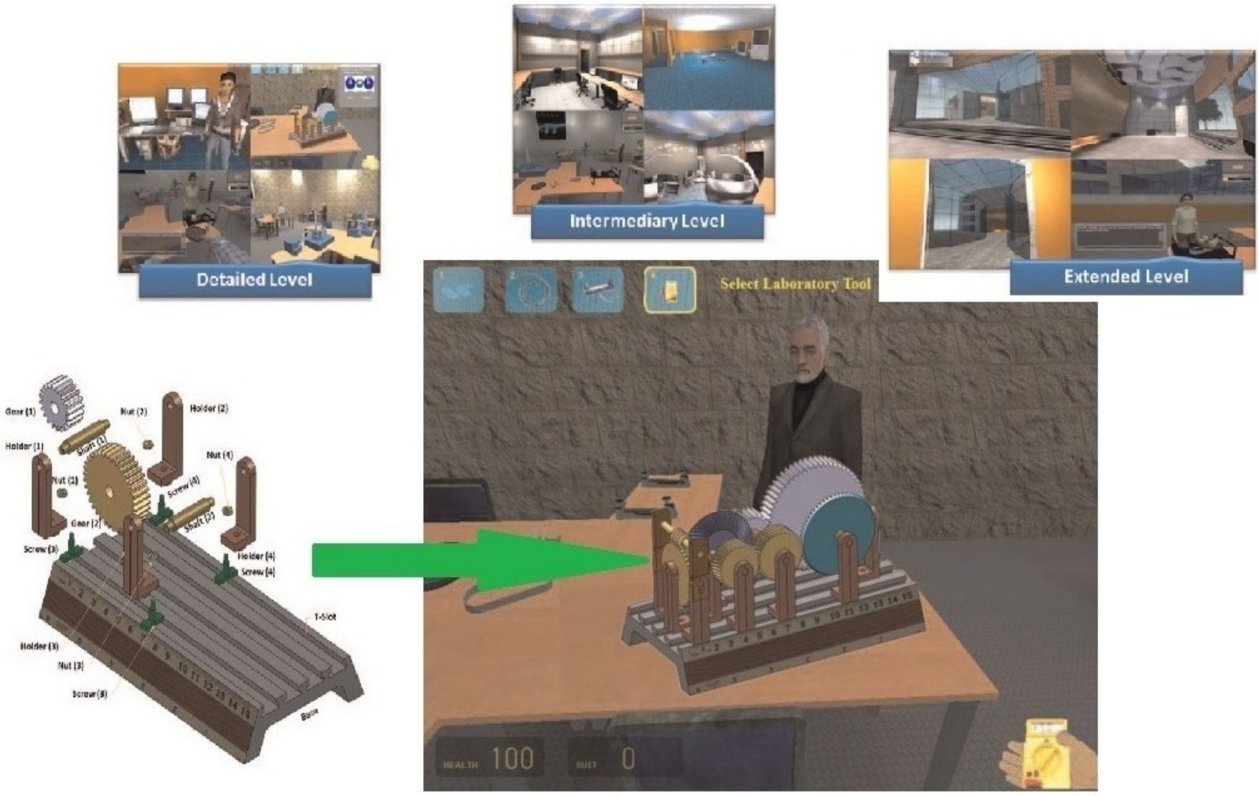


***Figure 4.4***: *Virtual laboratory, developed at Stevens Institute of Technology (figure extracted from Aziz et al., 2014).*

Virtual laboratory for electric machines was elaborated in (Tanyildizi & Orhan, 2009), presenting experimentation on the synchronous motor. In this paper, the authors argue that with the potential increase of users (students), equipping a real laboratory with an adequate number of electric machines becomes highly demanding. Therefore, they presented a virtual counterpart to the physical laboratory, as a solution to this potential problem. The essence of this system was developed with the use of the C++ language. As it was mentioned at the beginning of the paragraph, the focus was on synchronous motor. Therefore, students were enabled to experiment in the virtual laboratory, by changing appropriate motor parameters, and tracking the performance graphically.

Furthermore, the authors tried to check the learning effects of the virtual laboratory. For that purpose, they tested students, after dividing them into two groups: the control group, which used only physical laboratory, and the experimental group, which along with the physical lab, also used its virtual counterpart. The authors concluded that the experimental group showed better scores, which can be observed as a very valuable result when analyzing the overall benefits of the general virtual laboratory concept. Considering our evaluation criteria, and according to the information available from the above-mentioned paper of the authors, this virtual laboratory fulfills the criterion (EC1), and the criterion (EC2). Other criteria are not fulfilled.

### *4.3.3 Virtual Laboratories Related to the Field of Robotics*

We already mentioned earlier in the text, that the primary focus of this chapter will be on robotics. Therefore, this section will be dedicated to virtual laboratory solutions primarily dedicated to this field. Bearing in mind the multidisciplinary nature of robotics, one could say that it represents a perfect testbed for exploring advantages and drawbacks related to the concept of virtual laboratories. Specifications of selected virtual laboratories, along with evaluation criteria, are shown in Table 4.3. While a more thorough description of each laboratory follows in the text.

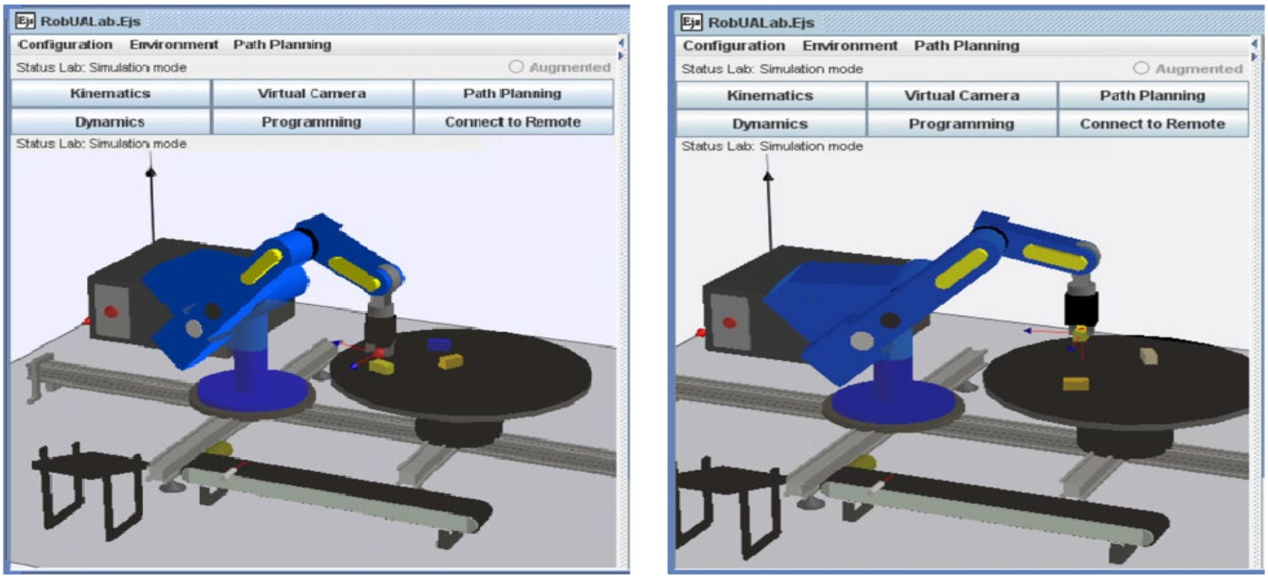


***Figure 4.5:** Simulation environment of the RoboUALab, showing two different stages during the manipulation task (figure extracted from Jara et al., 2011).*

One of the first and most illustrative examples of virtual laboratories dedicated to robotics is certainly RoboUALab (Figure 4.5), developed by a team of researchers from the University of Alicante in Spain (Torres et al., 2006; Jara, Candelas, Puente, & Torres, 2011). The main focus of RoboUALab is put on industrial robotic manipulators. The developed system has in fact a dual nature, enabling students not just virtual laboratory experience, but remote experimentation with robots as well. We have already seen a similar approach with the TriLab project, in the previous section. According to the authors, the developed system offers numerous learning possibilities to potential users (students), enabling them in that way not only to acquire knowledge in robotic fundamentals but also to perform more advanced experimentation. Among others, the system offers an illustrative representation of robot kinematics and dynamics properties (students can move the robot by editing appropriate values of kinematic parameters, they can adjust friction, inertia, link masses, etc.). Furthermore, users can also experiment with path planning, programming of specific routines, or even edit the environment by introducing new objects for pick-and-place tasks. All of these characteristics are accompanied by the appropriate system interface. According to the authors, the RoboUALab system was extensively used in the teaching of robotics-related courses at the University of Alicante, since 2003, with reported positive evaluation from students. Considering our evaluation criteria, and according to the information available from the above-mentioned papers of the authors, RoboUALab fulfills the first three criteria (EC1, EC2, EC3a), while other criteria are not fulfilled.

TABLE 4.3

BASIC INFORMATION AND EVALUATION CRITERIA REGARDING THE SELECTED VIRTUAL LABORATORIES COMING FROM THE FIELD OF ROBOTICS.

| Virtual Laboratory Name, or Acronym | Participating Institutions | Primary Field | EC1 | EC2 | EC3a | EC3b | EC4 | EC5 |
|---|---|---|---|---|---|---|---|---|
| RoboUALab | University of Alicante (Spain) | Industrial manipulators | yes | yes | yes | no | no | no |
| ROBOMOSP | Pontificia Javeriana University (Colombia) | Industrial manipulators | yes | yes | yes | no | no | no |
| VCIMLAB | Eastern Mediterranean University (Cyprus) | CIM systems | yes | partly | yes | yes | no | no |
| Virtual Laboratory for Mobile Robotics | Technologico de Monterrey (Mexico) | Mobile robots | yes | partly | no | no | no | yes |
| sBotics | Universidade Federal do Rio Grande do Norte (Brazil), & Instituto Federal de Educação Tecnolócgica do Rio Grande do Norte (Brazil) | Mobile robots | yes | partly | yes | yes | no | no |
| LABEL | Universidad Miguel Hernández de Elche (Spain) | Parallel robots | yes | partly | no | no | no | no |
| USARSim | University of Pittsburgh (USA) | General robotics | yes | partly | yes | yes | no | no |

Another educational & research platform dedicated to industrial manipulators was presented in (Jaramillo-Botero, Matta-Gomez, Correa-Caicedo, & Perea-Castro, 2006). Namely, the team of researchers coming from Pontificia Javeriana University, in Cali, Colombia, developed the

ROBOMOSP (ROBOtics MOdeling and Simulation Platform). According to the authors, ROBOMOSP is hierarchically organized, consisting of several subsystems (e.g. a subsystem dedicated to 3D simulations). Furthermore, all of the subsystems are hierarchically subordinated. Special attention is put on rich GUI (Graphical User Interface), which offers numerous options for data manipulation, visualization, and above all adjusting of various simulation properties. The subsystem dedicated to robotic simulation and control enables solving of different kinematics (inverse and forward) and dynamics (inverse and forward) related problems. According to the authors, compared with other similar platforms, the ROBOMOSP system contributed by introducing some new features, such as multibody dynamics. It is concluded that the developed system can be potentially used for education & research purposes, or for operators' training purposes. Regarding the potential drawbacks of the system, it should be mentioned that at the time of publication, ROBOMOSP did not incorporate collision detection. Considering our evaluation criteria, and according to the information available from the above-mentioned paper of the authors, ROBOMOSP fulfills the first three criteria (EC1, EC2, EC3a), while other criteria are not fulfilled.

A complex educational environment dedicated not only to a standalone industrial robot, but to an entire CIM (Computer Integrated Manufacturing) process was presented by a research team coming from the Eastern Mediterranean University, Cyprus (Hashemipour, Manesh, & Bal, 2011). According to the authors, the developed system called VCIMLAB (Virtual CIM Laboratory) aimed to help undergraduate students in connecting theoretical and practical knowledge in the field of automated manufacturing systems. Furthermore, the authors aimed to design a safe, and cost-effective alternative to expensive, complex real-world industrial setups. VCIMLAB (Figure 4.6) consists of several working rooms, with different levels of complexity and learning tasks, covering an entire spectrum of the manufacturing processes. Each room consists of different pieces (and different combinations) of emulated equipment, such as industrial manipulators (with virtual teach pendants), CNC (Computer Numerical Control) machines, appropriate computer systems, assembly hardware, etc. Simulation models are realistically emulated, according to the real-world example of laboratory setup in the CIM laboratory, at the Eastern Mediterranean University. Therefore, students are enabled to practice industrial robot control and programming, automation control systems, and FMS (flexible manufacturing systems) fundamentals, in that way gaining experience and training about the entire manufacturing process cycle. The authors concluded that using the VCIMLAB enhanced performance of the students. Considering our evaluation criteria, and according to the information available from the above-mentioned paper of the authors, VCIMLAB fulfills the criteria (EC1), (EC3a), and (EC3b). It also partly fulfills the criteria (EC2). Other criteria are not fulfilled.

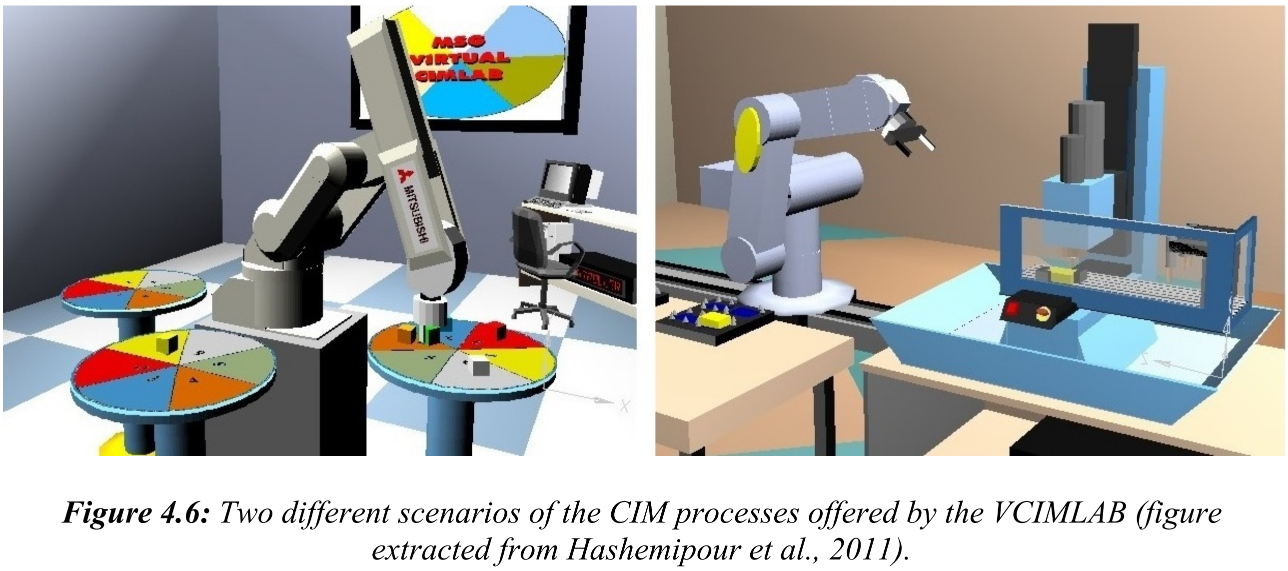


***Figure 4.6:*** *Two different scenarios of the CIM processes offered by the VCIMLAB (figure extracted from Hashemipour et al., 2011).*

Researchers coming from Tecnológico de Monterrey (Mexico), developed a very interesting educational system dedicated to mobile robots (Noguez & Enrique Sucar, 2006). According to the authors, they were motivated by a need for enabling their undergraduate students to learn robotics fundamentals in a more effective manner. This was accomplished by introducing different innovative technical and didactical concepts. One of the main characteristics of this environment is the coupling of the virtual robotics lab with an intelligent tutoring system. A 3-D simulated mobile robot environment (Figure 4.7) enables students to perform different kinds of experimentation, in that way gaining knowledge related to robot mechanical structure, IR sensors, and control system, all of which represent highly important topics not only from the theoretical perspective but as a preparation for hands-on experience as well. On the other hand, a module dedicated to intelligent tutoring, among other things evaluates students according to their performance and makes appropriate pedagogical action according to it. It also employs a sort of a guidance role, in that way helping students while they are using this educational system. According to the authors, who performed an initial evaluation of the system, it can be concluded that the intelligent tutoring system significantly enhanced the knowledge and skills of involved students. Considering our evaluation criteria, and according to the information available from the above-mentioned paper of the authors, this virtual laboratory fulfills the criterion (EC1), and the criterion (EC5). Criterion (EC2) is partly fulfilled, while other criteria are not fulfilled.

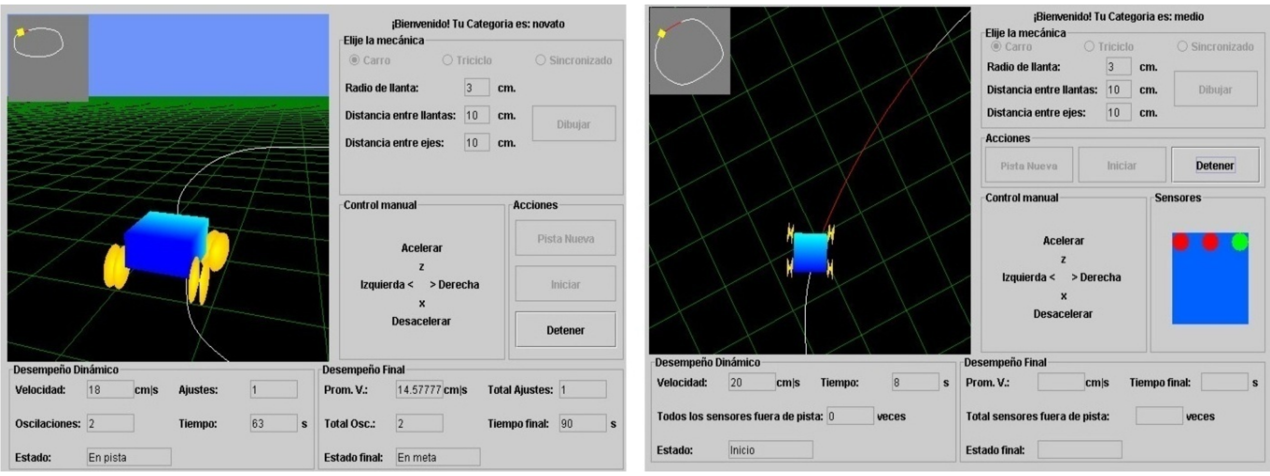


***Figure 4.7:*** *User interface and virtual environment of the mobile robotics laboratory, developed at* Tecnológico de Monterrey *(figure extracted from Noguez & Enrique Sucar, 2006).*

Another interesting example of the educational robotic system is the sBotics, presented in (do Nacimento et al., 2021). The sBotics system (Figure 4.8) represents a gamified learning environment dedicated to mobile robotics, aiming to promote the robotics field in general. A particularly interesting feature of the developed system is the introduction of random errors. Namely, the authors concluded that most of the existing robotic educational systems try to emulate real robots to the highest possible degree, and besides that often insist on the repeatability of experiments (same parameters give same results, upon each simulation). Authors further notice that this kind of behavior is often unviable in real-world conditions, due to the changes (discrete or more influential) of the environment. Therefore, with the introduction of minor errors in the working environment, or robot's sensorial system, sBotics enables each simulation to run slightly differently, which better suits the real-world conditions. The sBotics system offers users (students) to choose among one of the offered testing environments, to choose one of the offered mobile robots, and also to edit certain parts of the system (e.g. change the actuators, etc.). Authors underlined that one of the main goals of the sBotics, was to expand, popularize, and provide higher availability of robotics technology to students in their country. Considering our evaluation criteria, and according to the information available from the above-mentioned paper of the authors, sBotics fulfills the criteria

(EC1), (EC3a), and (EC3b). It also partially fulfills the criterion (EC2). Other criteria are not fulfilled.

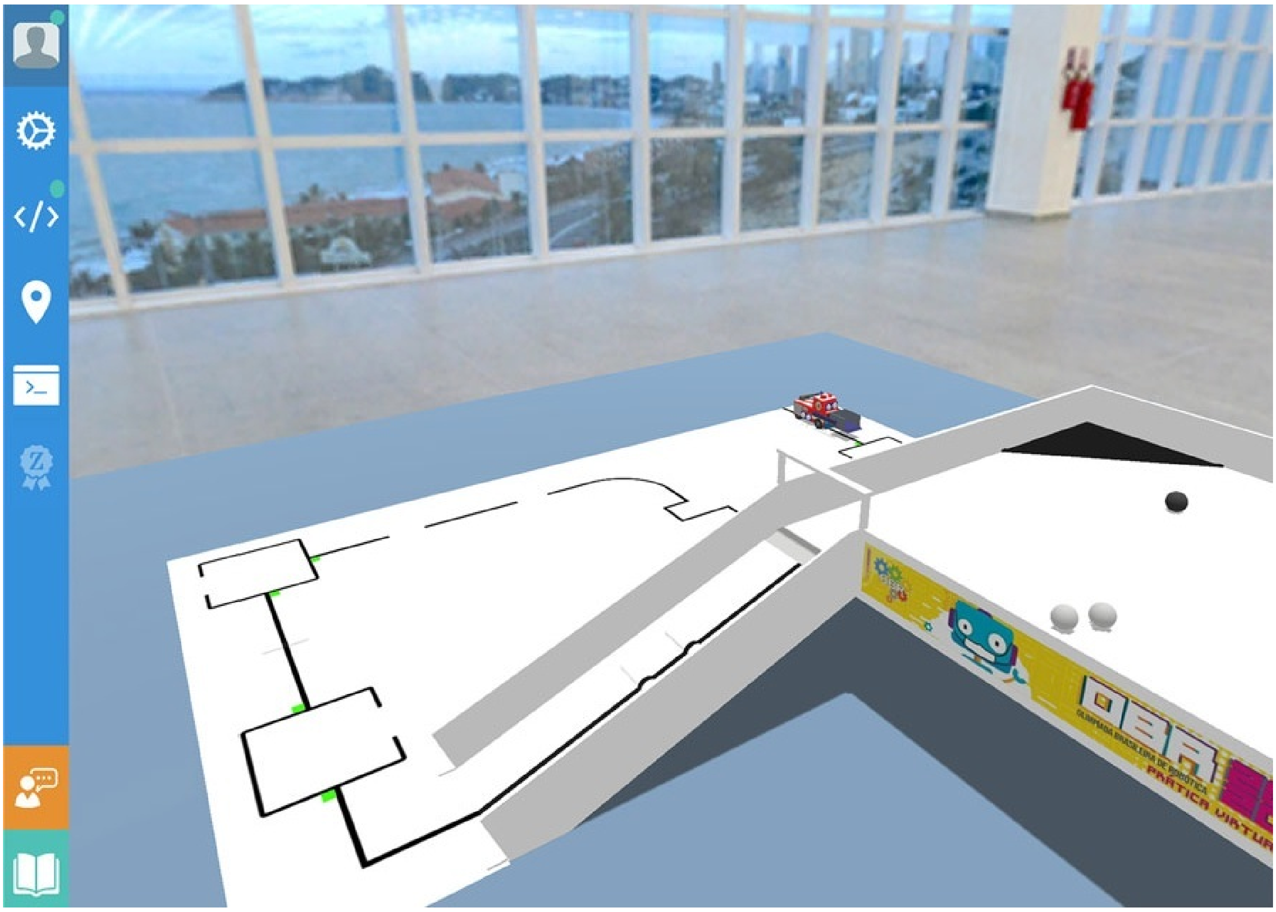

***Figure 4.8:*** *An example of sBotics scenery (figure extracted from do Nacimento et al., 2021).*

An educational platform named LABEL, oriented toward the interesting topic of parallel robots, was presented by a team of researchers (Gil, Peidró, Reinoso, & Marin, 2014). This is one of the rare virtual laboratory examples, if not a unique one, focusing on this complex subject. The LABEL system enabled solving of direct and inverse kinematic problems related to different sorts of parallel robotic configurations, as well as the introduction of students to concepts of singularities. According to the authors, the LABEL system focused on Delta, 5R, and 3RRR robot types. The careful choice of robotic configurations implemented in the LABEL system provided students with the possibility to explore robotic systems with different levels of complexity, which can be very useful to overall learning outcomes. Furthermore, students were enabled to adjust different parameters (such as the coordinates of end-effector, or lengths of the links) through LABEL’s graphical interface, perform a path planning, and consequently start a simulation and watch a graphical representation of the chosen robotic configuration. Authors reported that their LABEL system was implemented in the university courses at Miguel Hernandez University (Elche, Spain) at different levels of study (bachelor, and master programs), and was positively accepted among the students. Considering our evaluation criteria, and according to the information available from the above-mentioned paper of the authors, LABEL fulfills the criterion (EC1), and partly fulfills the criterion (EC2). Other criteria are not fulfilled.

A joint effort of researchers coming from several educational & research institutions from the USA resulted in the development of USARSim (Carpin, Lewis, Wang, Balakirsky, & Scrapper, 2007). Unlike the previous educational platforms which were mainly devoted to specific segments of the robotic field (e.g. industrial manipulators, parallel robots, etc.), the USARSim have a wider character. Namely, although this open-source education & research simulator was initially focused on wheeled mobile robots, it eventually expanded its purpose. According to the authors, it offers an entire spectrum of available robots, including humanoid robots, underwater robotic systems, different kinds of legged and wheeled mobile robots, etc. Authors also reported a certain system limitation at the time, such as the simulator's inability to adjust algorithms related to dynamical gait balance with the humanoids, etc. What is underlined as a feature of high relevance is the extendibility of the USARSim system. Therefore, it is no surprise that the USARSim was reported (by authors) to become a popular choice among researchers (especially within the Robocup community). From the technical point of view, it is also interesting to mention that the system was developed with the use of the widely popular "Unreal Engine". Considering our evaluation criteria, and according to the information available from the above-mentioned paper of the authors, USARSim fulfills the criteria (EC1), (EC3a), and (EC3b). It also partially fulfills the criterion (EC2). Other criteria are not fulfilled.

#### *4.3.4 VLMS - Virtual Laboratory for Mechatronic Systems*

In this sub-section, we will present the VLMS (Virtual Laboratory for Mechatronic Systems). This virtual laboratory is developed at the School of Electrical Engineering (University of Belgrade), as a joint effort of the team of researchers. VLMS development fulfills a lot of the standpoints elaborated in the previous sections of this chapter.

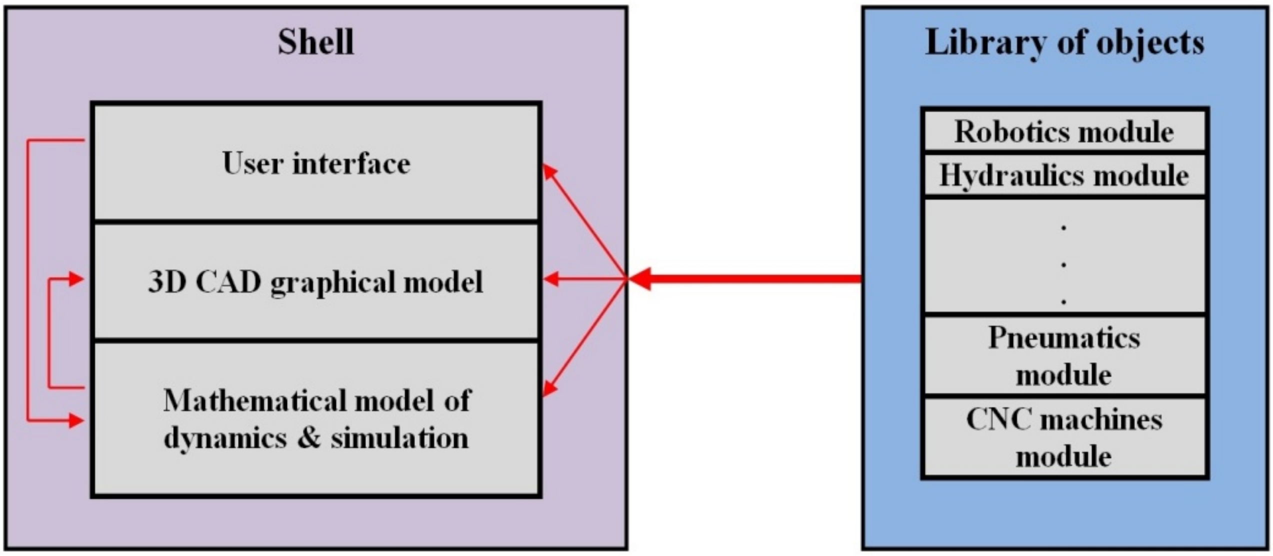


***Figure 4.9:*** *Development concept of the VLMS.*

The general idea of the VLMS concept (Figure 4.9) is to organize a library of objects, in the form of cabinets (further in the text we will call them modules) which consists of shelves with akin objects/devices. The general framework that was built currently consists of two modules (robotics and hydraulics) which will be described further in this sub-section. Other modules, such as Pneumatics, or CNC module are expected to be integrated into the VLMS concept in the future. The idea of the modular concept is to allow for future extensions of the virtual laboratory, by introducing new devices/machinery. In that way (as a final goal), at one point more complex industrial-like production systems could be created. The general logic behind the VLMS is shown in Figure 4.9. The main idea is that every object selected from the library should have a unique user interface, graphical model, and mathematical model of system dynamics. Internal connections between each of them should be predefined and thus could be applied to every object selected from the library.

***VLMS robotics module:***

We will continue the description of VLMS, by introducing a virtual robotic module. Initial development of the robotics module started slightly more than a decade ago, accompanied by the paper on the subject published at the time (Potkonjak, Jovanovic, Vukobratovic, Medenica, 2010). In the meanwhile, several modifications were implemented resulting in the current hereby elaborated upgraded version. In the following text, we will, among other things, repeat some of the observations, made in the already-mentioned initial work on this topic, since they are still applied to the VLMS system in general. The robotic module of VLMS is dedicated to the robotic sub-field of industrial manipulators. In the current version of the system, users (students) can choose between one of the several offered industrial manipulators (Figure 4.10). Expending the virtual laboratory with several more industrial manipulators is in the progress.

Since one of the objectives was to emulate real-world physical devices and their behavior, the notion of dynamics laws is of crucial importance for the VLMS concept. Therefore, mathematical and physical models of the system behavior (based on the theory presented in Vukobratovic et al., 2003; Siciliano, Sciavicco, Villani, & Oriolo, 2009) are at the essence of the VLMS. Manipulator dynamics plays a fundamental role in motion simulation and control algorithm synthesis. Several useful options are provided in the virtual robotics module of the VLMS. Among other things, the user has an option to adjust control variables, as well as to make a choice between appropriate control strategies. Furthermore, users can in a certain sense customize strategy and then perform the appropriate testing of the established controller. Actuators and other parameters can be easily changed too. Thus, users can do the experiments and observe the behavior of the robot in several scenarios, in that way gaining knowledge about the way how the parameters influence the system.

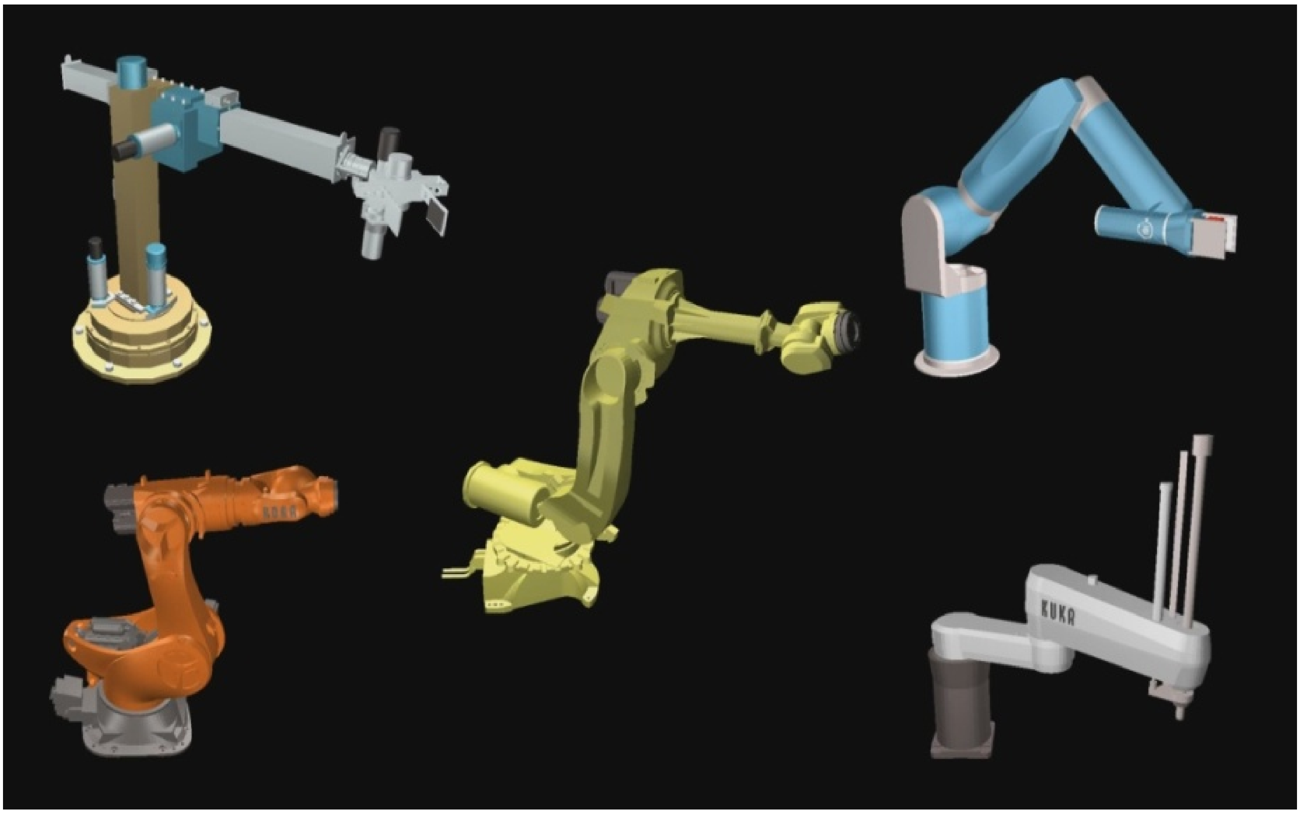


***Figure 4.10:*** *Robotic manipulators currently available in the VLMS.*

Special attention was paid to 3D graphical representation and animation based on virtual reality, in order to make the system more realistic and attractive. Precise and detailed graphical models of robots are provided. Various ambiance effects considering the working space (Figure 4.11) and numerous viewing angles enhance user experience. Further on, graphical representation includes the option for observing the internal components of the device (robotic manipulator), such as the revealed mechanism details of the actuators, etc. One should notice, that the behavior of all of these system components and their internal working principles are following defined kinematics and dynamics laws. Therefore, a user is enabled with a possibility to explore and get a deeper understanding of the particular system component of interest.

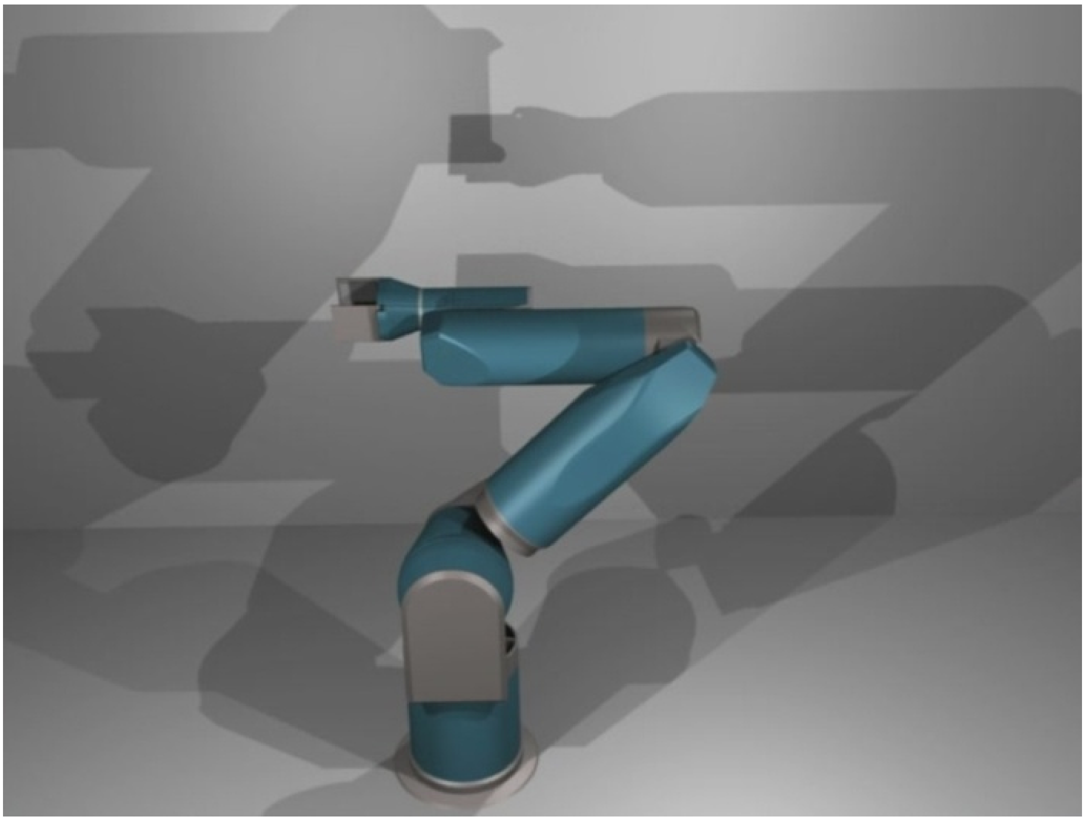

***Figure 4.11:*** *One of the VLMS ambiance scenarios.*

***VLMS hydraulics module:***

Let us now present a virtual hydraulic systems module of the VLMS. The idea behind this module was to thoroughly demonstrate the working principles and control strategy of one complex hydraulic system, which is a good mechatronic example.

The UI of the hydraulics module offers numerous convenient options, in that way enabling a student/trainee to adjust all relevant coefficients, PID parameters, etc. Upon finishing the desired simulation, results can be analyzed by appropriate diagrams (showing time histories of the relevant variables). In addition, 3D graphical animation is also provided, in order to make a more intuitive visualization of the attempted experiment. All features of the UI, highlight the possibility of using the VLMS hydraulic module for various exercises and experiments. Hence, it can be used for the training of future operators, as well as for helping students to learn hydraulics theory.

All system elements move in complete accordance with the system dynamics (Merritt, 1967; Jelali & Kroll, 2003).

Graphical representation of the equipment faithfully resembles an actual real-world system. In the upper right corner of Figure 4.12, one could see an electrical cabinet (consisting of the control unit and low voltage electrical components). On the left side of Figure 4.12, the working surface is placed with all its components (servo valve, hydraulic cylinder, linear position sensor, load, etc.).

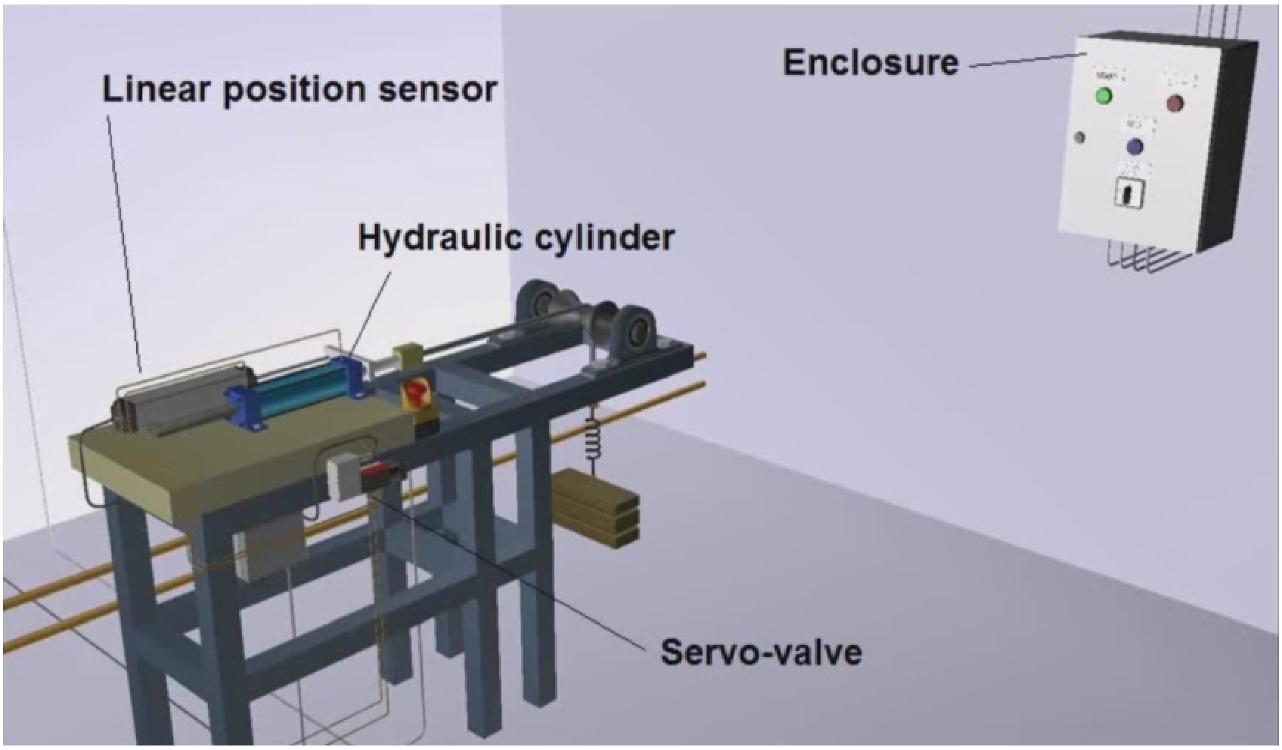


***Figure 4.12:*** *Hydraulic system offered in the VLMS.*

The entire virtual area is covered with a number of cameras, which allows for a user to see any part of the system that he needs. Cameras can move in all four directions (left, right, up, and down), as well as rotate or accelerate.

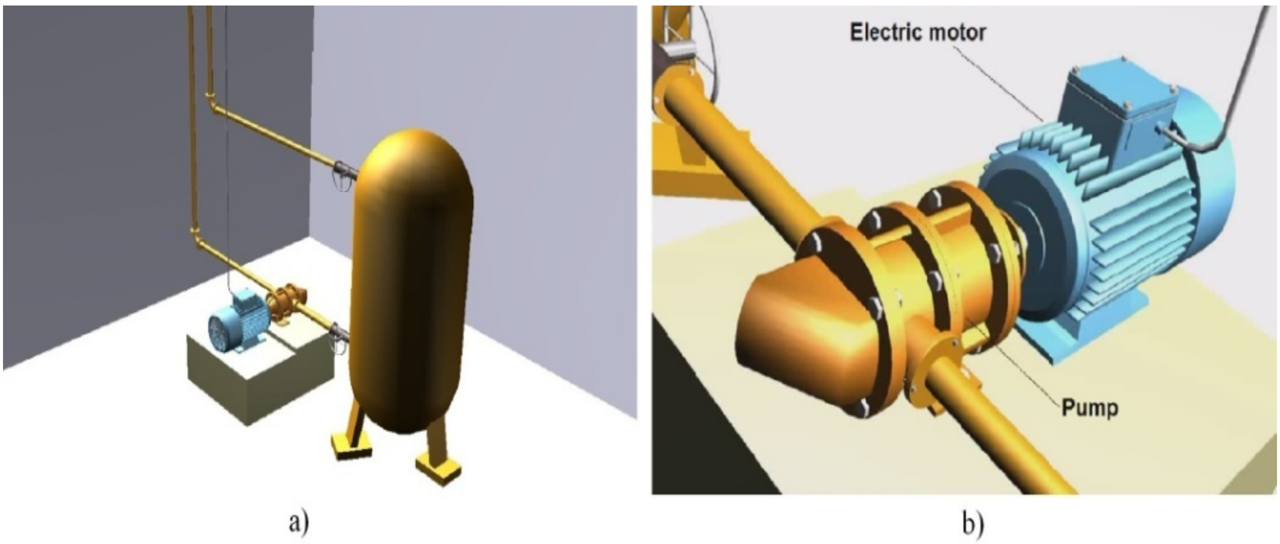


***Figure 4.13:*** *(a) Oil reservoir, motor, and pump (b) Closer look at motor and pump.*

Figure 4.13(a) shows the oil reservoir, electric motor, and butterfly pump. Using the camera options (such as different angles, and zooming) can provide a closer look at the system components that might be of interest (Figure 4.13(b)).

Similarly to the robotic module of VLMS, The user can remove the device housing and have an inside view in internal structures of some system elements (Figure 4.14), in that way having a possibility to gain deeper knowledge about the role and working principles of the particular part of the mechatronic system. Figure 4.14 (right) shows different pressure levels that are highlighted in different colors.

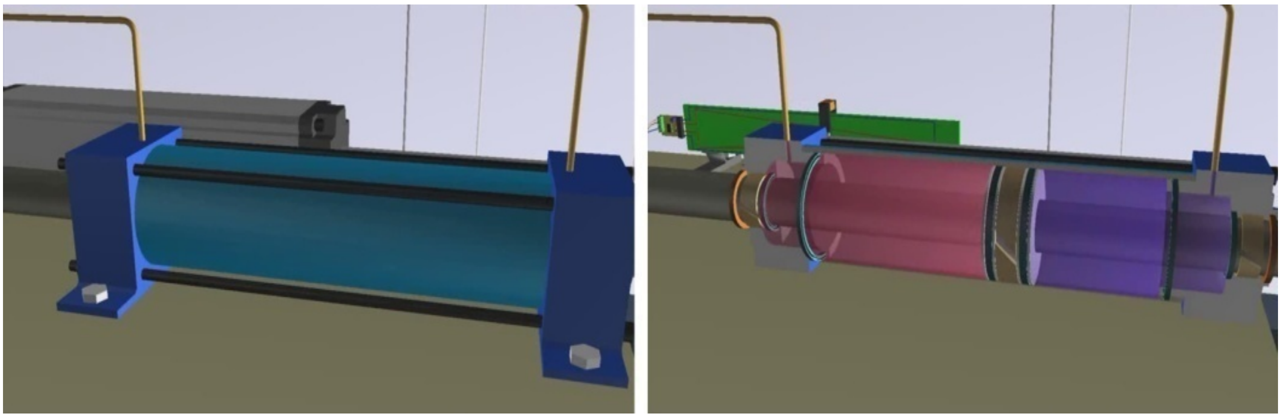

***Figure 4.14:*** *Hydraulic cylinder (left), uncovered cylinder (right).*

The assessment of criteria applied to the VLMS is given in Table 4.4. As it can be seen from the table, VLMS fulfills the first three demands (EC1, EC2, EC3a) but is yet to reach other demands.

TABLE 4.4
BASIC INFORMATION AND EVALUATION CRITERIA REGARDING THE VLMS.

| Virtual Laboratory Name, or Acronym | Participating Institutions | Primary Field | EC1 | EC2 | EC3a | EC3b | EC4 | EC5 |
|---|---|---|---|---|---|---|---|---|
| VLMS | School of Electrical Engineering, University of Belgrade | Mechatronics /Robotics | yes | yes | yes | no | no | no |

## 4.4 Summary, Discussion, and Future Advancements

The main focus of the chapter was to perform and elaborate a deep analysis and evaluation of the current solutions and involved technologies related to the virtual laboratory concept. This aims not only in contributing to filling the gaps related to the current state of knowledge but also aims to serve as a solid knowledge base for future developments. Consequently, this should give us an opportunity to possibly identify some future advancements. Besides many aspects of the virtual laboratories, that are discussed in this chapter, one should also notice the significance and advantage of utilizing such solutions during complex conditions, such as the recent world COVID-19 pandemic. This is already recognized and thoroughly analyzed in the literature (Kapilan, Vidhya, &

Gao, 2021), even predicting the acceleration in the application of the virtual laboratory concept due to such complex conditions (Vergara, Fernández-Arias, Extremera, Dávila, & Rubio, 2022).

Selected virtual laboratories coming from STE disciplines are thoroughly examined. In order to have a methodical analysis, the obtained results are organized into three main classes: physical science (3 virtual laboratories), technology and non-robotic engineering disciplines (6 virtual laboratories), and the field of robotics (7 virtual laboratories). Additionally, the VLMS virtual laboratory developed at the School of Electrical Engineering (University of Belgrade) was presented separately. The primary focus was devoted to the field of robotics, which was already elaborated, and discussed in the previous section. For the purpose of overall assessment (evaluation and comparison) of the selected virtual laboratory solutions, five evaluation criteria were established and elaborated in Section 4.2. Besides comments in the appropriate paragraphs, the obtained assessment results were also arranged in the form of tables, in that way enhancing overall readability.

Established criteria (EC1 – EC5) and requirements elaborated in section 4.2., along with the overall assessment of the virtual laboratories, consequently reflect not just on the current state of technology but also affect certain standpoints for future advancements as well.

Except for one laboratory (which had a rather specific aim), all of the analyzed laboratories fulfilled criterion EC1. Considering the criterion EC2, it was fulfilled in the majority of the cases, either fully or at least to some degree (partly). When we say “partly”, this often refers to the total or partial lack of the precise system dynamics. Criterion (EC3), divided into two sub-conditions (EC3a) and (EC3b) is the first serious point of divergence among the analyzed laboratories. As it can be seen from our analysis, only a limited number of laboratories fulfilled both of the sub-conditions. Another issue was the criterion (EC4), which is fulfilled in only one case. The same could be applied for the criterion (EC5), bearing in mind that only one laboratory fulfilled it. The closest to the integration of all five criteria was one laboratory that integrated criteria (EC1) to (EC4). The criterion (EC4) is especially challenging because it drastically increases the number of interactions in the system, which can be rather problematic in online scenarios, especially when combined with criterion (EC2) and the full criterion (EC3).

From the above-mentioned summary, it can be seen that criterion (EC4) and criterion (EC5) represent the weakest points. While, criterion (EC3), and especially its sub-condition (EC3b) is also often not in the focus of the researchers. Furthermore, it can be seen that integration of all five criteria, clearly represents a complex task, in both development and implementation sense. Namely, besides the obvious objectives of the virtual laboratory development, which can be observed in one simple fact that it should be a worthy replacement of the real laboratory, one should also have in mind the balance between the complexity of the system and its operating speed.

Bearing in mind all the previously said, one may conclude that future developments should be directed toward the integration of the current virtual laboratory solutions on the one hand, and MUVEs/metaverses on the other hand. This is a very challenging task, which among others implies a larger degree of flexibility of both. However, with the progress of related theories and technologies, it could be envisioned that future advancements will enable us to overcome all the obstacles which are currently inhibiting an even broader application of virtual laboratories in STE disciplines.

In the end, we should once more point out, that all analyzed virtual laboratories have a very high level of functionality. However, they are evaluated from the perspective of the features that would be contained in a highly realistic virtual laboratory comparable with (and even in some sense better than) the real physical laboratory.

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# Biography

Vladimir M. Petrović was born on July 16th, 1987., in Belgrade. He finished the prestigious Mathematical Grammar School (Mathematical Gymnasium), a school of special national importance, specialized for gifted and talented students in mathematics, physics, and computer science. He completed bachelor's and master's studies in 2011., and 2012., respectively, at the Department of Signals & Systems, School of Electrical Engineering, University of Belgrade. He enrolled the PhD studies at the same department. He became a member of the MENSA Society in 2007.

He worked as a research assistant at the School of Electrical Engineering, as of November 2012. During that time, he participated in several projects, including:

- "Research and Development of Ambient-Intelligent Service Robots with Anthropomorphic Characteristics" (January 2013. – December 2019.). A project funded by the Serbian Ministry of Education, Science, and Technological Development.
- "Feasibility Study for Serbian Manufacturing Innovation Hub – FS4SMIH" (October 2016. – April 2017.). A project funded by the ReconCell project, as a part of the I4MS initiative and Horizon2020 EU Framework Programme for Research and Innovation.

During his PhD studies, Vladimir M. Petrović had several study visits and professional training:

- University of Zurich, Department of Informatics, Artificial Intelligence Laboratory (September 2013.) Within the study visit, he successfully completed *eSMCs Summer School 2013. "Embodiment and Morphological Computation"*, hosted by professor Rolf Pfeifer.
- TU Dresden (Dresden University of Technology), Faculty of Medicine "Carl Gustav Carus" (September 2016.). Within the study visit, he successfully completed Summer School on Technology Transfer, hosted by professor Stefan R. Bornstein.
- Danube Innovation Partnership Summer School on Knowledge and Technology Transfer (September 2014.). He successfully completed Summer School organized by the European Commission Joint Research Centre, co-organized with WIPO, CTT of the University of Belgrade, and Intellectual Property Office of the Republic of Serbia.

Vladimir M. Petrović is a reviewer of several eminent international journals and conferences. Among others, he served as a reviewer for the Journal of Intelligent and Robotic Systems (Springer), Machine Intelligence Research (Springer), IEEE Symposium Series on Computational Intelligence (SSCI), IEEE International Conference on Industrial Informatics (INDIN), etc. Starting from 2019., he serves as a program committee member for the IEEE Conference on Games - CoG (former IEEE Conference on Computational Intelligence and Games – CIG).

Vladimir M. Petrović authored/co-authored a number of papers at eminent international journals and international conferences. As of 20.02.2022, these papers are cited 734 times according to the Google Scholar database, and 374 times according to the Scopus database. He is a recipient of the ETRAN Best Young Researcher's Award (in the field of Robotics and FMS).

*образац изјаве о ауторству*

# Изјава о ауторству

Име и презиме аутора: Владимир Петровић
Број индекса: 5006/2012

**Изјављујем**

да је докторска дисертација под насловом:

"Application of Virtual Worlds in Agent Theory Research and Engineering Education"

"Примена виртуелних светова у истраживању теорије агената и инжењерском образовању"

• резултат сопственог истраживачког рада;

• да дисертација у целини ни у деловима није била предложена за стицање друге дипломе према студијским програмима других високошколских установа;

• да су резултати коректно наведени и

• да нисам кршио/ла ауторска права и користио/ла интелектуалну својину других лица.

**Потпис аутора**

У Београду, 28.02.2022.

Владимир Петровић

*образац изјаве о истоветности штампане и електронске верзије докторског рада*

## Изјава о истоветности штампане и електронске верзије докторског рада

Име и презиме аутора: Владимир Петровић

Број индекса: 5006/2012

Студијски програм: Електротехника и рачунарство

Наслов рада:

"Application of Virtual Worlds in Agent Theory Research and Engineering Education"

"Примена виртуелних светова у истраживању теорије агената и инжењерском образовању"

Ментор: др Бранко Ковачевић, професор емеритус

и др Коста Јовановић, ванредни професор

Изјављујем да је штампана верзија мог докторског рада истоветна електронској верзији коју сам предао/ла ради похрањивања у **Дигиталном репозиторијуму Универзитета у Београду.**

Дозвољавам да се објаве моји лични подаци везани за добијање академског назива доктора наука, као што су име и презиме, година и место рођења и датум одбране рада.

Ови лични подаци могу се објавити на мрежним страницама дигиталне библиотеке, у електронском каталогу и у публикацијама Универзитета у Београду.

**Потпис аутора**

У Београду, 28.02.2022. ____________________

*образац изјаве о коришћењу*

## Изјава о коришћењу

Овлашћујем Универзитетску библиотеку „Светозар Марковић" да у Дигитални репозиторијум Универзитета у Београду унесе моју докторску дисертацију под насловом:

"Application of Virtual Worlds in Agent Theory Research and Engineering Education"

"Примена виртуелних светова у истраживању теорије агената и инжењерском образовању"

која је моје ауторско дело.

Дисертацију са свим прилозима предао/ла сам у електронском формату погодном за трајно архивирање.

Моју докторску дисертацију похрањену у Дигиталном репозиторијуму Универзитета у Београду и доступну у отвореном приступу могу да користе сви који поштују одредбе садржане у одабраном типу лиценце Креативне заједнице (Creative Commons) за коју сам се одлучио/ла.

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**Потпис аутора**

Владимир Петровић

У Београду, 28.02.2022.

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