Chapter 1
Genealogy of Artificial Beings: From Ancient Automata to Modern Robotics

Nicolas Reeves and David St-Onge

Learning objectives

- To understand the mythological origins of contemporary robots and automata
- To be able to connect current trends in robotics to the history of artificial beings
- To understand the role of crafts, arts and creation in the evolution of contemporary robotics.

Introduction

This chapter is an extensive overview of the history of automata and robotics from the Hellenistic period, which saw the birth of science and technology, and during which lived the founders of modern engineering, to today. Contemporary robotics is actually a very young field. It was preceded by a 2000-years period in which highly sophisticated automata were built for very different purposes—to entertain, to impress or to amaze—at different times. You will see that the methods and techniques that were used to build these automata, and that largely contributed to the development of robotics, were at times imported from unexpected fields—astronomy, music, weaving, jewellery; and that the impulse that drove automata makers to build their artificial beings was far from rational, but rather rooted in the age-old mythical desire to simulate, and even to realize, an entity from inert materials.

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1.1 What is a Robot?

Whereas most of us would think they know what a robot actually is, a closer look at the concept will show that a precise definition of the term is actually not that easy to frame; and that it broadened again in the last decades to encompass a large variety of devices. From the first appearance of the word in the Czech theatre play R.U.R (Capek, 2004), in which it was referring to human beings artificially created to become perfect and servile workers (Fig. 1.1), it is now used for a range of devices as different as robotic arms in factories, battery-operated toys for kids, androids or biomorphic machines. It even came to describe entities that lie at the boundary of technology and biology and that cannot anymore be described as fully artificial.

This evolution is less paradoxical than it seems. As opposed to a common idea, Capek's robots where not strictly speaking artificial machines: they were created with organic materials synthesized by chemical processes. In the scenario, the core of the project was to build teams of workers that were free from everything that was not essential to the implementation of their tasks—feelings, emotions, sensibility. Their role was that of robots, but they were still living biological organisms, which makes them quite different from the highly sophisticated technological devices that come to mind when thinking of contemporary robots. They were in a sense much more related to automata, a word that Capek has actually used in a previous play, but that was completely replaced by "robots" in this one.

This last point is worth noticing. At the time R.U.R. was written, the word "robot" was a neologism forged from slavish roots referring to work, chore, forced labour. Nothing in its original meaning implied that a robot should be a machine: an automaton created to help human beings in the implementation of some task

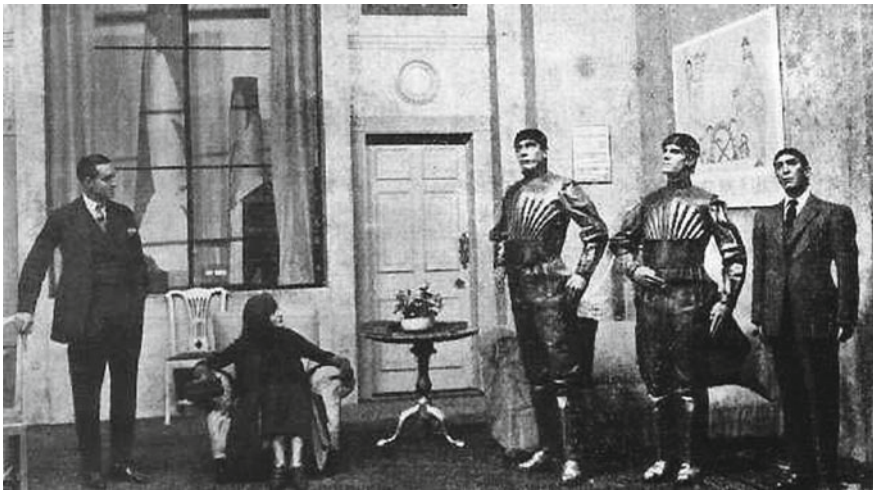

Fig. 1.1 Scene from Capek's play Rossum's universal robots, with three robots on the right; 1920

becomes a robot. In that respect, it actually contradicts the original meaning of the word "automaton", which, etymologically, refers to an animated device which acts *by itself*. The word decomposes in the Greek roots *auto*, which precisely means "by itself", whose origin, strangely enough, is unknown; and *matos*, "thinking" or "endowed with will", from the older proto-Indo-European * *mens*, "to think". It therefore designates an animated artificial being that is able to make decisions and to act autonomously, whereas "robot" is frequently associated with a machine that has been designed for the sole purpose of blindly executing sets of instructions crafted by a human being—the opposite of an autonomous entity. What is hardly disputable however is the fact that every contemporary robot finds its place in the age-old genealogy of automata. It might also be interesting to note that the oldest origins of the root "rob", from which "robot" was created, evokes the fact of being orphan, which corresponds surprisingly well to these artificial beings which, as a matter of fact, never had a biological father or a mother.

Since its first occurrence, the meaning and signification of "robot" have extended well beyond this gloomy etymology. A lot of robots are today created for research, experimentation or entertainment, without any practical use; but current roboticists do not yet agree on a single definition. Two elements however strike out as reaching a broad consensus: first, the device must present some form of *intelligence*; second, it must be embodied. As it is well known, "intelligence" is in itself a tricky notion to define. In this context, it does not indeed refer to human intelligence, less again does it correspond to the common perception of artificial intelligence, better represented by the concept of machine learning. Intelligence for a robot is only about taking decision on its own, based on the limited information it has from its context or from its internal states. Here again, etymology comes to help: the word comes from the Latin *inter ligere*—«to link between». The links can be elementary—a bumper sensing a wall makes the robot wheels stop—or more complex—the robot takes a decision by comparing information coming from multiple sources. The concept of embodiment refers to the physicality of the robot, as opposed to software "bots." On its side, «automaton» today refers indifferently to a hardware or a software device.

For the sake of the present chapter, we will tighten the meaning the word "robot" in order to encompass essentially hardware automata fulfilling two criteria: first, they must be dedicated to the autonomous implementation of DDD (Dangerous, Dull or Dirty) tasks, or to facilitate the implementation of such tasks for human beings; second, they must be able to take decisions through some form of interaction with their context. As we will see below, this definition itself has undergone several variations in the last decades, but we will keep it for the moment.

1.2 A Mythical Origin

The genealogy of robots, as well as the history of robotics, are then intimately linked to that of automata. An extensive recapitulation of this history would be far beyond the scope of this chapter, all the more since several books have already been written on it (among many others: Demson & Clason, 2020; Mayor, 2018; Nocks, 2008; Foulkes, 2017 …). However, an efficient way to understand the fundamentals of human motivation and fascination for robots and robotic systems is to recapitulate some of its main chapters, and to locate in time the bifurcations that progressively separated robots from automata: the evolution of historical trends in robotics is of the greatest help to understand why some aspects of robotic research are better known, and better developed, than others.

The first and likely most important point to consider is that the roots of robotics are not anchored in technology or science, but rather in a mythological ground that extends far beyond these fields, and that can be broadly divided in two layers. The first one is concerned by the myth of a being with supernatural power and unpredictable intentions, an image that still hovers over any robot or automaton. The second involves all the attempts that have been made along history to replicate through artificial mechanisms two natural phenomena that escape human understanding, namely life and cosmological events.

These two layers are intricated at many levels, but they differ by their basic intentions. The first one is most likely at the origin of all humanoid or animal-like automata. It led to the pursuit of creating artificial beings whose power surpass those of human beings: autonomous entities that can be made insensitive to pain, fear, boredom, and to any form of emotion, less again empathy. A lot of examples of inventors who try to build such entities can be found in tales, science-fiction stories, movies and video games, covering all the spectrum of intentions towards mankind—from help, assistance and protection to destruction and domination. However, once it is built, because it should possess, as an automaton, a kind of free will, it can become uncontrollable and behave in unpredictable ways, even for its creator. This is illustrated by Capek's play, but also by the wealth of works that has emanated from the Jewish myth of the Golem, first mentioned in the Talmudic literature. Being an artificial creature made of clay, the Golem was an embryonic form of life created for the sole purpose of helping or protecting his creator. It should be noted that historically speaking, Golem is most likely the first entity that corresponds to the above definition of a robot: an artificial entity built specifically for a implementing a practical task or function.

Despite the highly functional and technological nature of most contemporary robotic systems, the evolution of automata and the emergence of robots cannot be fully understood without realizing that most of them originate from the will to simulate life; that automata makers have been developed highly advanced skills, and have been spending tremendous amounts of time and resources, in order to achieve this goal with the highest possible precision; and last but not least, that in every automaton maker rests the secret and hidden dream of seeing one day his own inanimate creatures come to life—a dream to which, in a previous work, we gave the name «Geppetto syndrome» (Reeves, 1992).

From their very beginnings, automata were created to simulate. Their main—and often only—objective was to dissimulate what that they actually were: assemblages of inanimate matter pretending to act by themselves. It is not a coincidence if the first automata appeared at time during which a first, elementary understanding of physics was slowly emerging. Since only a tiny part of the population had access to it, its mastering was often perceived as magical by common people. Even if one of the main objectives of the new-born Greek science was to explain natural events by natural causes, that is, to get rid of supernatural explanation, its power could easily be confused with that of entities found in myths, tales or religious texts. Several works exploited it in order to create devices whose purpose was either to entertain, or to siderate crowds by simulating the intervention of supernatural forces. Automata built for practical purposes were virtually non-existent.

This was not always obvious. At first glance, the perpetual clepsydra built by Ctesibios from Alexandria (Fig. 1.2), of whom we will talk below, could claim to be a primordial robot, since it has the function of giving the time of the day. An ordinary clepsydra cannot be considered as an automaton: it is akin to that of an hourglass that uses water instead of sand, and as such, it does not feature any autonomous component. But Ctesibios' device, built three centuries BC, was coupled with a mechanism that refilled its tanks every day with water coming from a source, and that reconfigured its internal states in order to indicate the time for each day of the year. Being completely autonomous, it qualifies as an automaton. Since it

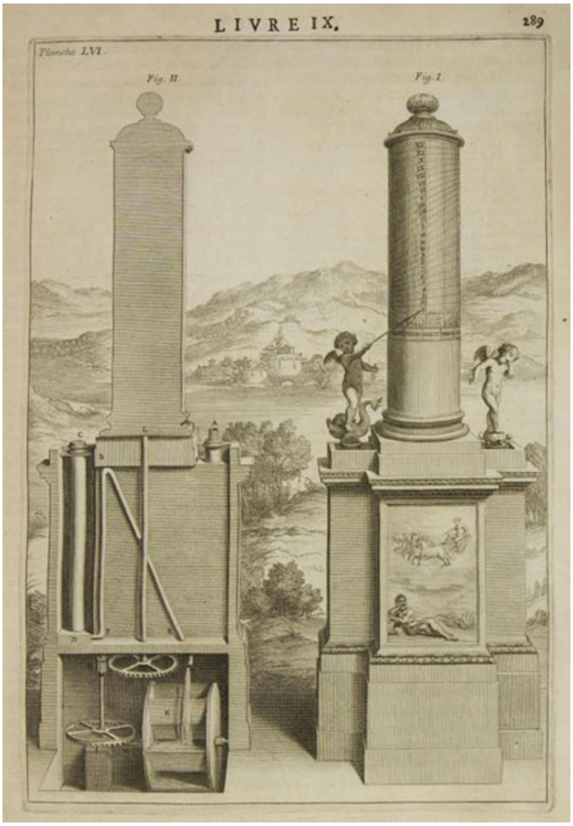

Fig. 1.2 Ctesibio's clepsydra, circa 250 B.C, as represented in the French translation of Vitruvius' treatise "ten books on architecture" by Claude Perrault (1864)

was built for a practical purpose, since it incorporates some kind of *intelligence* by reacting to the amount of water in its tanks, and since it was embodied, it could claim to be a first instantiation of a robot in the modern sense of the term. But this interpretation only holds when considering it with our contemporary eyes. Like most time-measuring devices, Ctesibios' clepsydra was more an astronomical model than a clock: it transposed the movements of the Sun into an autonomous mechanism. Just like humanoid or zoomorphic automata were trying to describe, comprehend and replicate the functions and behaviour of living beings, the first clocks, up to the beginning of the scientific revolution, were mainly planetary or cosmological models built to translate a partial understanding of celestial mechanics.[1] Vitruvius himself, while referring to Ctesibios' clepsydra in the 10th book of its treatise *De Architectura*, does not attribute to it any practical function. The design and building of such instruments usually requested workers and craftsmen that were the best skilled of their generation. The technological challenges implied by such mechanisms triggered the development of fully new technological and theoretical knowledge, and often requested massive amounts of money that could be provided only by the wealthiest members of the society. They became symbols of prestige, and testified for the level of expertise achieved in their country of origin. Even today, building a clock with a very long revolution period is everything but a simple venture. It took more than fifteen years to design and twelve years to build the astronomical clock located at the Copenhagen City Hall, completed in 1955; its slowest gear completes one full revolution in 25,735 years (Mortensen, 1957).[2]

All these examples, as well as many others, show that the impulse for creating automata is not originally driven by practical needs. It comes from the mythical desire to understand some of the deepest mechanisms at the origin of life and cosmological events, a desire that stands at the origin of major developments in mechanical science and in technology, and especially those at the origin of modern robotics. To qualify as an automaton, an artificial being does not need to be useful; it does not even need to move, or to do anything: it just has to be able to provide a convincing enough illusion of life (Reeves & St-Onge, 2016).

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[1] In the first mechanical clocks, such as the one built by Richard of Wellington around 1330, the great astronomical orloj in Prague, or the very rare heliocentric clock at Olomouc, also in Czech Republic, counting the hours was only one of many different functions: the indication of time becomes almost anecdotical. Many other dials indicated the sidereal time, the signs of the Zodiac, the phases and position of the Moon, the movements of the Sun and of the Planets, the solstices and the equinoxes, the hours of the tides … Some needed several decades to accomplish a single revolution.

[2] Later devices, such as the eighteenth century Peacock clock in the Hermitage museum in Saint Petersburg, intimately associates the simulation of life with the measure of time (Zek et al., 2006). In this incredible piece of mechanics, once a week, a large peacock extends its wings, deploys its tail and moves its head; a rooster sings; an owl turns its head, blinks its eyes and rings a chime. A small dial, almost lost in the rest of the device, gives the time of the day: its presence is inconspicuous. The presence of time and the cycle of the days are mainly evoked by the three animals: the owl is a symbol of night, the rooster a symbol for the day, the peacock a symbol of rebirth.

An Industry Perspective

Charles Deguire, President and CEO

Kinova inc.

I like to think that I was born an entrepreneur. Both my parents were entrepreneurs, as some of our family members, and from the day I had to decide what I was going to become, I knew the path I wanted to follow. But as in every business case, you need THE idea. In my case, I was raised with the idea … When I was younger, I had three uncles living with muscular dystrophy, all power wheelchair users, and very limited upper-body mobility. The challenges they faced never stopped them, they even founded a private company dedicated to the transportation of people with special needs. This concept evolved to become the public-adapted transport system of Montreal.

One of my uncles, Jacques Forest, had only one finger that he could move. He was challenged by the idea to develop an arm that could be controlled by his active finger to allow him to become independent in his functionality and able to grasp and manipulate objects in his surroundings without external assistance. He generated various innovative technical ideas for such devices that were based on his own experience and intuition. The gripping device he succeeded to build was made from a desk lamp frame and ended by a hot dog pincer. The manipulator is built by every member of the family. It was put in motion by bicycle cables attached to windshield wipers motors that were assembled on plywood and located at the back of his wheelchair. Motors were activated through 14 electronic switches that he controlled through his unique moving finger.

While I was studying to become an engineer, I came across all kinds of new technologies that were all extraordinary. But I realized how having an astronaut doing remote manipulation with a space robot arm could be an aberration when people in wheelchairs could not even pour themselves a glass of water alone. As I was already aware of the reality of people living with physical disabilities, I decided I would dedicate my life to solving those problems, starting with a robotic assistive device built from the ground up, specifically for wheelchair users.

We move problems through a funnel. We start very wide, sort of chaotic. We look internally and externally, within our own industry and other industries, and ask, What process can I use to solve this? Once we've selected a few approaches that we believe have potential, we drill down and get really focused on executing each of them.

We robotize tasks. We did that for people using wheelchairs, expanding their reach. In surgery, we expand the capabilities of the surgeon. In hazardous material handling, we robotized the manipulation of toxic or nuclear waste. But it's always the same process, providing better tools to humans.

Creativity is one of Canada's greatest resources. This is what supports the growth of Kinova and which propels our Canadian manufacture to the international scope.

1.3 Early Automata

Ctesibios is considered as the founder of the Greek school of mechanics. After him, four characters stood up in the nascent field of automata around the Eastern part of the Mediterranean Sea: Philon of Byzantium; Vitruvius in Rome; Heron of Alexandria; and later, Ismail Al-Jaziri from Anatolia. By looking at a few examples of their work, we will see that working in the field of illusion and simulation did not prevent them to produce a major corpus of knowledge on the behaviour of real physical systems, to contribute with large instalments in their area and to leave technical writings that became major sources of inspiration for generations of engineers and scientists. The machines and automata they conceived are nothing less than technological wonders of their time.

Philon of Byzantium lived around the third century B.C. He left a number of treatises that give a very precise account of the technological level of his country. He invented an automated waitress that was serving wine and water, and that is generally considered as the first real humanoid robot in history. About three centuries later, mathematician and engineer Heron of Alexandria designed a series of about eighty mechanical devices, one of which being considered as the first steam machine, some others being moved by the sole force of the wind. Since his researches were unknown to Western scholars for more than a millennium, and since most his machines were destroyed during the fire of the Alexandria library, the count of his invention can only be estimated; many may never have been realized. None of them were dedicated to the implementation of practical tasks: he fostered his knowledge of physics and mathematics (mostly geometry) in order to impress or to trigger mythological fascination through mechanisms whose description can be find in his treatises *Automata*

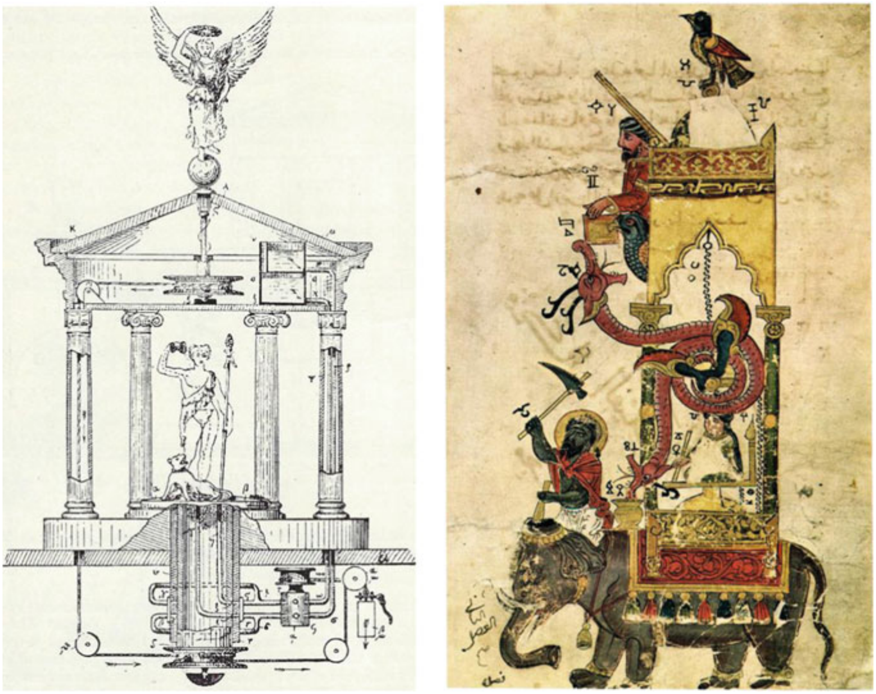

Fig. 1.3 Drawings extracted from Chapuis, 1658 of devices made by Dionysus by Heron of Alexandria, first century A.D (left) and by Ismail Al-Jazari, 1206 (right)

(Murphy, 1995) and *Pneumatica* (Woodcroft, 1851). In what is known as the first example of building automation, the doors of a temple would open after a sacrifice only if the visitors ignited a fire in a receptacle; the fire heated a hidden water reservoir; the accumulated pressure caused a part of the water to be transferred in a second reservoir suspended to a cable and pulleys system attached to the doors; since this reservoir became progressively heavier, it began to go down, which caused the doors to open.[3]

Heron also designed a large animated sculpture of Dionysus (Fig. 1.3, left) in which water flowing from a reservoir to another triggered a sequence of actions: pouring "wine" (red-coloured water) from Dionysus' glass; pouring "milk" (white-coloured water) from his spear; rotating Dionysus central statue; rotating the statue of an angel over that of Dionysus; and finally pouring again wine and milk from opposite outputs. Some versions of the corresponding plans and diagrams include a group of dancers circling around the main statue, as well as a fire that was ignited automatically by a lighting device. Another of his treatise, *Dioptra* (Coulton, 2002), is

[3] This mechanism, as well as a number of the automata designed by Heron, have been reconstructed by the Kotsanas Museum of Ancient Greek Technology. They can be seen in function on a video produced by the Museum at http://kotsanas.com/gb/exh.php?exhibit=0301001 (accessed Dec 30 21).

key to modern roboticists, since it describes several instruments with practical aims, such as the measure of distances and angles. It includes the first odometer, a device that worked by counting the rotations of the wheels of a chariot. It was tailored to the Roman mile unit, which was obtained by adding 400 rotations of a 4-feet wheel; a series of gears slowly opened a hatch to release one pebble for each Roman mile. Such a device obviously does not qualify as a robot nor as an automaton; but the very idea of gathering information from the external world through a measuring device is key to modern robotics. It is worth noticing that such a device actually converts information coming from a continuous phenomenon—the rotation of a wheel—into a discrete one—the number of pebbles. Odometry is nowadays often computed from optical encoders fixed to motor wheels, but the measurement concept is similar to what Heron had imagined two thousand years ago.

Another of Heron's achievements is an automated puppet theatre. It represents an impressive example of the level of skills and technological knowledge that was put to use for the implementation of a device meant only for entertainment. It is also the first known historical example of a programmable mechanism: the movements of the puppets were controlled by wires and wheels whose movements followed a pre-recorded sequence. They were actuated by the movement of a weight suspended to a wire, just like for the German cuckoo clocks that appeared two millenia later. Any computer programs that is used today for about every imaginable task is a remote descendant of this machine that was built only to amuse or to surprise people. It is all the more stunning to realize that for centuries, the efforts put to work to achieve such a goal far exceeded those dedicated to the creation of practically useful robots, a situation that lasted up to the middle of the twentieth century; and that this energy has led to intellectual and technological achievements that sometimes did not find any other application for extended periods of time.

About ten centuries later, Ismail Al-Jazari, an engineer and mathematician living in Anatolia, fulfilled numerous contracts for different monarchs; he was hired to invent apparatuses aiming at impressing crowds during public parades (Fig. 1.3, right). By a clever use of hydraulics, levers and weight transfers, he designed several mechanisms whose parts would move autonomously. In his most famous treatise, *The Book of Knowledge of Ingenious Mechanical Devices* (Al-Jazari, 1974), he details systems ranging from a hydraulic alarm clock that generates a smooth flute sound to awake the owner after a timed nap, to a musical instrument based on cams that bumped into levers to trigger percussions. The cams could be modified in order to generate different percussive sequences, which constituted, ten centuries after Heron, another implementation of a programmable automaton.

It is to be noted that other devices, such as the Antikythera Machine, an astronomical calculator dated second century B.C. and whose inventor is unknown, has sometimes been regarded as an automaton; however, according to historians and scholars, it was operated by a crank, and thus does not meet the autonomy criterion. It remains nonetheless related to the first automata, and in particular to the first mechanical clocks that appeared almost fifteen years later, by the fact that it does represent, somewhat like a mechanical clock, a scaled model of a planetary system, executed with stunning precision and skills for the time.

1.4 Anatomical Analogies: Understanding Through Replication

1.4.1 Leonardo Da Vinci

It is impossible to recapitulate the history of automata without referring to Leonardo da Vinci (1452–1519). Some of the works of this visionary artist and inventor are also heavily grounded into the age-old mythological fascination for the simulation of human beings. In order to implement them, he explored extensively the anatomy and kinematics of the human body; but as it is well known, his work spanned about all the existing disciplines of his time. It would be difficult to say which of his endeavours had the greatest impact on modern-day arts and sciences. His inventions and practical treatises on mechanisms triggered and propelled the first industrial revolution that came more than three centuries later. Some of the pieces and assemblages he managed to manufacture thanks to his unique craftsmanship skills, such as gear heads and pulleys, are now mass-produced by complex industrial equipment, but they remain informed by the same design principles.

For roboticists, the inventions that are most related to contemporary projects are his mechanical knight on one side, and his self-propelled cart, also sometimes referred to as *Leonardo's Fiat*, most likely the first autonomous vehicle, on the other. The cart included a differential drive propulsion system with programmable steering for travel. The whole mechanism was originally seen as powered by wound up springs. In 1997, researchers understood that their real use was not to propel the cart, but to regulate its driving mechanism. In 2006, a first working replica, built at scale 1:3, was successfully made in Florence; all previous attempts have failed because of this misunderstanding (Gorvett, 2016).

The mechanical knight on its side is a complex machine (Fig. 1.4). It involves tens of pulleys and gears which allegedly allow him to sit, stand, move its arm and legs; it was however unable to walk. It is not until 2004 that a first prototype was implemented. It confirmed the possibility of all these actions, as well as several others: jaw actuation, neck rotation, visor movement. Way ahead of his time, while still rooted in the ancient mythology of artificial beings, Da Vinci's mechanical knight is connected to the very essence of the automaton. It stands as an ancestor to several recent humanoids, and its role in the original design of the NASA's Robonaut is said to have been influential.

It is not yet possible to account for all of Da Vinci's robotic endeavours, partly because many of them have been lost to history. Additionally, as previously stated, not all of his surviving designs are complete. In some cases, key components regarding machinery or function are missing; in others, as it was the case with his cart, some of his designs are simply to complex, and are not yet fully understood.

Fig. 1.4 Da Vinci's Humanoid automaton; circa 1495

1.4.2 The Canard Digérateur*, the Writer, the Musician and the Drawer*

As can be seen from these first examples, the will to simulate living beings is everywhere present in the history of automata and robots. All of these entities try to replicate the main characteristics of life, and to produce, deliberately or not, the illusion, that they managed to extricated themselves from the nothingness of inert matter. The efforts and energy invested to generate this illusion implied technologies that not only systematically accounted for the most advanced of its time, but also widely contributed to the evolution of these technologies. Beyond a simple simulation, the automaton was trying to reach the status of an *explanative device* endowed with descriptive virtues, making it possible to unveil the secrets of life. So it is with Vaucanson's duck, called the digesting duck (*canard digérateur*) by its inventor, built at the end of the seventeenth century (Fig. 1.5). As its inventor says (Vaucanson, 1738):

> This whole machine plays without you touching it when you set it up once. I forgot to tell you that the animal drinks, dabbles in water, croaks like the natural duck. Finally, I tried to make him do all the gestures according to those of the living animal, which I considered with attention.

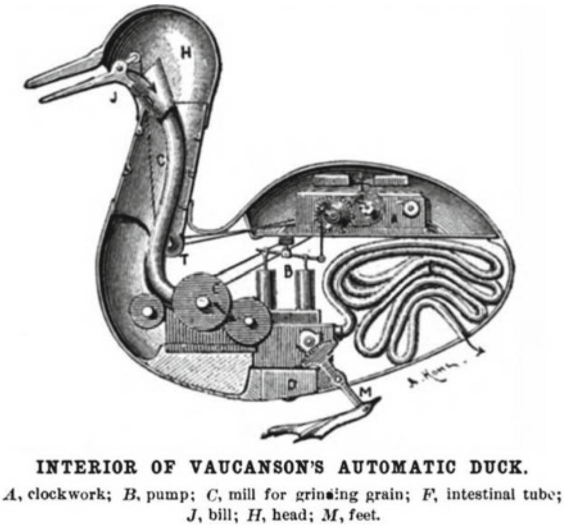

Fig. 1.5 Vaucanson's "canard digérateur" (digesting duck), 1738. This picture is a fantasy reproduction published by the scientific American magazine (1899). Very few original pictures of Vaucanson's duck have been found

Later in the same text, Vaucanson mentions the most unexpected feature of his automaton, namely the fact that it digests and defecates:

> There, in a small space, was built a small chemical laboratory, to break down the main integral parts, and to bring it out at will, by convolutions of pipes, at one end of its body quite opposite.

The simulation of the excretive function is clever: very few people would deliberately implement it for the sake of art or illusion. The very idea seems so unusual that it can only arise, for those who observe it, as a consequence of the will to create an entity that is to the perfect like of a living duck, including all its metabolic processes. One is at times left with the impression that the inventor surrenders to the illusion that the perfect formal simulation of the basic organs of life will fool life itself, so it will appear and animate the entity. The "small chemical laboratory" wants to be the equivalent of a digestive system, by which the food absorbed by the beak would be decomposed into nutritive substances on one side, and on useless substances evacuated through the cloaca on the other.

As can be expected, it was later revealed that Vaucanson's duck was a hoax. Nonetheless, the fact remains that following the Cartesian model, which sees the Universe moved by a great watchmaker, and living beings as nothing more than sophisticated mechanics, such attempts exemplify the tendency to systematically associate living organisms to the most advanced technologies of the time.[4]

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[4] Interestingly enough, the idea of evoking life through its less prestigious functions finds a contemporary instantiation in his installation series «Cloaca» by Wim Delvoye (Regine, 2008), which reproduces all the phases of human digestion, from chewing to excretion, through successive chambers in which the food is processed by some of the enzymes, bacteria and biochemicals found in the digestive system. The installation must be fed twice a day. By observing the device in operation, it is easy to remain under the impression that the artist, helped by a team of biologists, has perfectly

They also mark the beginning of a slow bifurcation by which the evocation and simulation of life left the domain of formal analogy to join, by a long process, that of information flows and transfers. Here again, this separation was initiated by the model of human beings that prevailed at the end of the seventeenth century, a model that distinguished the body—the material component—from the soul—the driving and decision-making force. Descartes himself considered man as made from these two components. It is generally admitted that his model of the animal-machine (Descartes, 1637) was induced to him when he learned about the existence of a simple automaton, an idea later extended by La Mettrie's concept of man–machine (La Mettrie, 1748): this may be a glimpse on the process by which an object, initially built as a *simple formal simulation* of a given phenomenon, can become a model meant to *describe and explain* that phenomenon.

The concept of man and of animals as sophisticated mechanisms has led to the design of more and more sophisticated automata, with a gradual increase in the complexity of their functions. About a century after Descartes, the automata built by the Jacquet-Droz family initiated the separation between matter and information (Fig. 1.6). Not only were they driven by the equivalent of programs that were advanced versions of those created by Ctesibios and Heron of Alexandria, but the program themselves, recorded in rolls, cams or discs, could be changed, thus modifying the internal states of the automaton: they became independent of its material moving components. Changing the program opened spaces of possibilities that remained limited, but nonetheless real (Carrera et al., 1979). One of the given automata, the Musician Player, could play five pieces of music; the second one, the Drawer, could create four different drawings; the last one, the Writer, was the most complex. It can draw forty different characters; the text to be written is encoded on dented wheels, which makes it a fully programmable automaton. By looking at these delicate and impressive technological pieces, on can only regret the almost complete disappearance of automata arts since the nineteenth century. Fortunately, a few passionate artists still maintain this practice today; some of their most recent works, such as François Junod's *Fée Ondine*, are nothing less than jewellery pieces in movement. And as can be expected, Junod's studio is located close the Swiss town of La Chaux de Fond, the first town ever planned around the activities of the watchmakers.

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grasped the mechanism of several vital functions; but here again there is an illusion, at least partial. The use of biological substances and living organisms such as bacteria prevents the device to meet the definition of an automaton, since it does not use only inert materials; it thus cannot claim to testify for a full understanding of the phenomena involved—which was not anyway the explicit intention of its author. However, despite all the explanations provided and in spite of the highly technological appearance of the work, the visitor cannot help feeling the presence of a strange animal plunged into the torpor of a heavy digestion, like a beast after a too copious meal; and to ask himself whether or not it presents a risk once awaken: the mere mention of the digestive function is enough for the visitor to readily accept the image of a living being.

Fig. 1.6 Jacquet-Droz's automata: drawer, musician, writer; 1767–1774

1.4.3 Babbage and the Computer-Robot Schism

The bifurcation that made the automaton and its controlling program two distinct entities cannot be located at a single moment in time. As we have seen, it can be traced back to the devices created by early Greek engineers and to Al-Jazari's percussive automaton; but several other steps intervened since; and the trajectory leading to contemporary computer programming has taken an unexpected detour through music and textiles. Seventy-five years after the Jacquet-Droz's automata, Henri Lecoultre created a musical box in which the melodies were recorded on interchangeable rolls. Barrel organs, which first appeared during the sixteenth century, could play melodies that were pre-recorded on rolls, discs, cards or ribbons perforated with holes that determined the melodies to be played—such instruments were actually called *automatophones.*

This principle was almost immediately transposed to create the first Jacquard loom by Basile Bouchon, the son of an organ maker, and by his assistant Jean-Baptiste Falcon (Fig. 1.7); they adapted musical boxes mechanisms from his manufacture to create the card readers that controlled the patterns to be woven (Eymard, 1863). It is worth noticing that the Jacquard loom also used the cylinder developed by Vaucanson, in another illustration that the technologies required to implement machines with practical uses often originated from the artistic realm, where they were developed with completely different motivations.

The perforated card system lasted for more than two centuries. It was extensively used for the programming of the first generations of computers. It played an essential role in the Manhattan project during which the first atomic bomb was created,

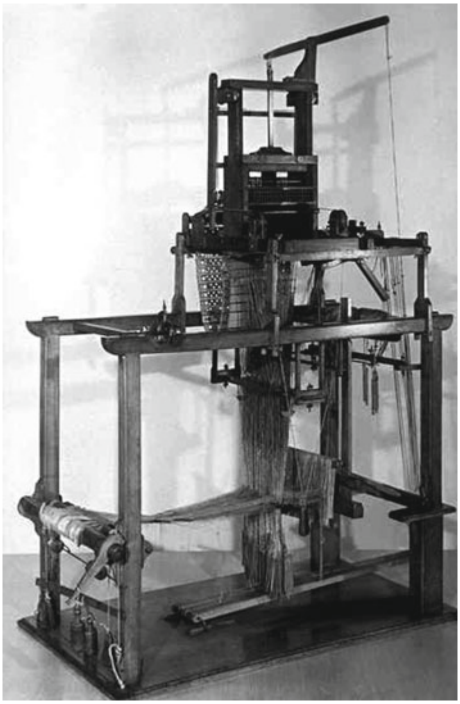

Fig. 1.7 A Jacquard loom, 1801

establishing an odd and peculiar connection between the delicacy of the melody played by a musical box, the patterns on a cotton fabric and the thundering apocalypse of a nuclear explosion. It was also by observing the Jacquard loom that Charles Babbage had the idea to design his *Analytical Engine*, today considered as the first full computer in history (Fig. 1.8). This huge machine included all the main elements of a modern computer: an input device that separated data and instructions, thanks to two punch card readers; a mechanical "driver" that prepared and organized the data for processing; a "mill", made of hundreds of gears that performed the operations—the mechanical equivalent of a CPU; a "memory" which stored intermediate and final results; and an output device in the form of a printer.

The Analytical Engine was never completed, due to problems of financing and manufacturing precision. It however remains, along with the Jacquard loom, the first example of a device that fully and completely separates the flow of information from the material processing unit. It is also remarkable for another reason: Ada Lovelace, the daughter of the poet Byron, was fascinated by mathematics. She wrote for the Babbage's machine the first known mathematical algorithm, a sequence of instructions for computing Bernoulli numbers,[5] which makes her the first programmer in history. Her clairvoyance and insights were actually nothing less than visionary. She

[5] Bernoulli numbers, named from Swiss mathematician Jakob Bernoulli, were identified in 1713 during the study of sums of powers of integers. If $\boldsymbol{S_m(n)}$ represents the sum of the $\boldsymbol{n}$ first integers individually raised to power $\boldsymbol{m}$, then the value of this sum is given by:

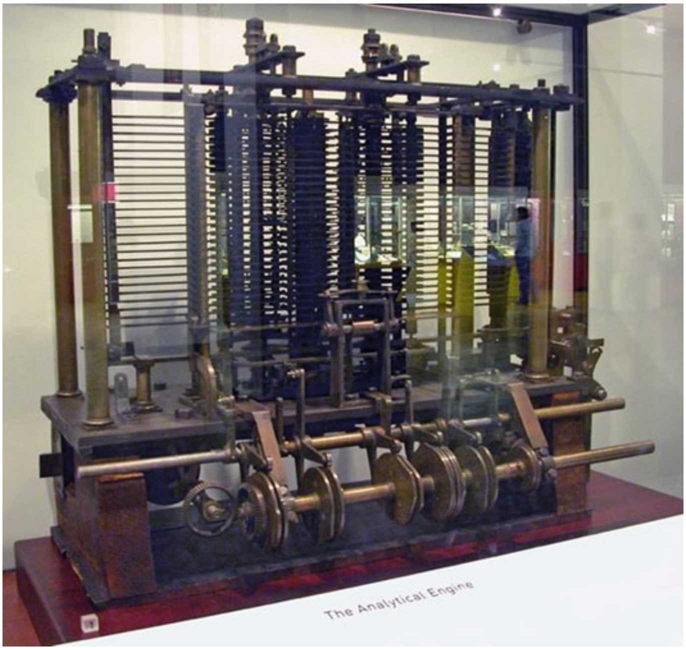

Fig. 1.8 Uncompleted prototype of Babbage's analytical engine, exhibited at the London museum of science; 1871

foresaw the possibility for such devices to perform not only numerical operations, but also symbolic calculations, and to use them to associate letters and signs in order to produce results that had nothing to do with mathematics, such as the composition of musical pieces, in another loop that reconnected the machine with its musical box origins (Lovelace, 1843). This is also probably the first known evocation of a form of artificial creativity, a characteristic which, perhaps more than for many other automata, testifies for the impulse to bring machines closer to human beings: art at that time was seen as the prerogative of the human species, an idea still largely preponderant today. The question of the relations between arts, robots and automata will be discussed more in detail in Sect. 6.2.

$$S_m(n) = \frac{1}{m+1}\sum_{k=0}^{m}\binom{m+1}{k}B_k n^{m-k+1}$$

In which coefficients B^k are Bernoulli number. They can be obtained through the following generating function:

$$\frac{x}{e^x-1} = \sum_{k=0}^{\infty}\frac{B_k x^k}{k!}$$

Ada Lovelace's algorithm was derived from this function.

1.5 Industrial (R)evolutions

Technological progress took a new pace over the course of the last two centuries, as the Western world underwent what we refer to as the "industrial revolutions"; the plural form is used here because at least four revolutions have been identified (Marr, 2016). The first major change intervened as a result of the use of steam and water to generate power. The second corresponded to the emergence of mass production and division of labour, and to the discovery of electricity as a power source. The third took place at the end of the sixties, with automated production and the exponential development of computing and electronics. The fourth can also be called the «digital revolution», and stands as a result of a merging of technologies that broke down the limits between the digital, physical, and biological spheres. The field of application of this last revolution is often referred to as "Industry 4.0."

The first revolution is a direct implementation, at larger scales, of several early contributions that were mentioned above, but it was also grounded on many works by Leonardo Da Vinci. It is only in the third one that the first robotic systems (industrial automata) were widely adopted, though it seems obvious that the second revolution paved the way for it. This third revolution exploited the discoveries and breakthroughs made by several inventors, among which Nikola Tesla is certainly not the least. It is during the third revolution that the lineage of robots branched from the main trunk of the genealogy of automata. For the first time, artificial entities endowed with a degree of autonomy were put to work, becoming nothing less than automated servants or slaves insensitive to fatigue, not vulnerable to health hazards, and hopefully more robust and durable than human workers. The fourth revolution will not be discussed in this book, as history is still being written on the impacts of the changes that it brought, but it will be referred to in the last section of this chapter.

The rise of industrial robots during the twentieth century required several scientific breakthroughs in power (electric, pneumatic, hydraulic), power transport and tele-operation (remote control). Nikola Tesla [1856–1943] was an engineer and inventor who referred to himself as a "discoverer". He solved most of the requirements and constraints needed by the third industrial revolution, and stands out, with about three hundred patents, as of the most proficient inventor of his time. He is widely known for his contributions on electricity transport and alternative current. These works had obviously a major impact on robotics; but we will focus here on his contributions to the use of radio waves.

In November 1898, Tesla demonstrated that a small autonomous boat could be remotely operated, from distances up to several feet (Fig. 1.9). The instructions were sent by coded pulses of electromagnetic waves. On demand of his audience, he instructed the ship to turn left or right, or to stop. This was the first demonstration of a remotely operated vehicle. It was not a robot in the full sense of the term, but it was, according to its inventor, "borrowing the mind" of the human operator so that future, advanced versions could fulfil mission together. A handful of patents, such as the one on advanced "individualized" (protected) multi-band wireless transmission, followed this demonstration; another one concerned the first "AND" circuit, a device that combined two radio frequencies to minimize the risks of interferences.

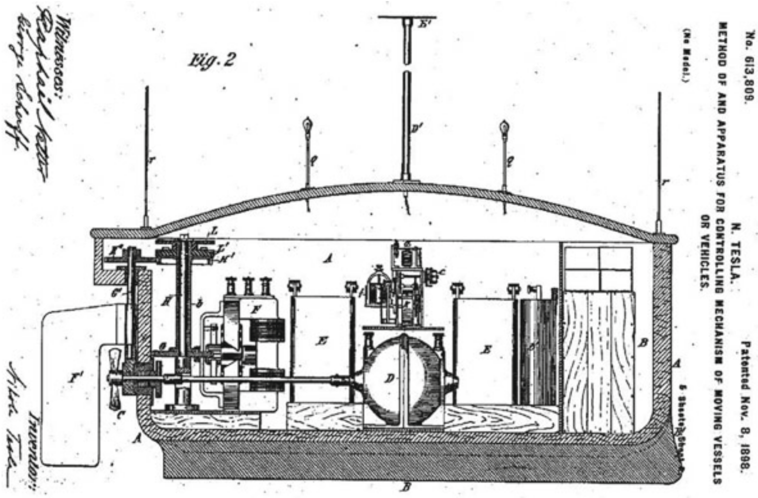

Fig. 1.9 Nikola Tesla radio-operated vessel plan from his US patent 613809Al, 1898

Tesla's boat would be hardly more than a toy today; at the time, he was nothing less than the forerunner of all remotely controlled devices and systems. He tried to write a list all of its potential application. By reading it, one cannot help to find him a little bit optimistic about the consequences of the military ones:

> Vessels or vehicles of any suitable kind may be used, as life, dispatch, or pilot boats or the like, or for carrying letters, packages, provisions, instruments, objects, or materials of any description, for establishing communication with inaccessible regions and exploring the conditions existing in the same, for killing or capturing whales or other animals of the sea, and for many other scientific, engineering, or commercial purposes; but the greatest value of my invention will result from its effect upon warfare and armaments, for by reason of its certain and unlimited destructiveness it will tend to bring about and maintain permanent peace among nations.

As for every new technological breakthrough, the militaries were quick to foresee the uses they could make for this invention. They massively funded the research on related technologies and quickly deployed remotely operated equipment in operation fields—without, as could be expected, helping in any noticeable way the pacification of conflict areas. As he foresaw at the time, the most advanced robotics research ventures and developments are still funded by the military industry, which is still the first to deploy these new technologies. From a mythological and largely poetic origin, robotics became within a few decades a field in which sophisticated war machines were developed.

Still, while most of the works done in this domain are not publicly available, some initiatives do contribute to the general advancement of the field. Nowadays, the United States Defence Advanced Research Projects Agency (DARPA) is hosting several robotics challenges: autonomous vehicle races (2004–2007), humanoid emergency response (2012–2015), heterogenous robotics swarms' tactics (2019–2022)

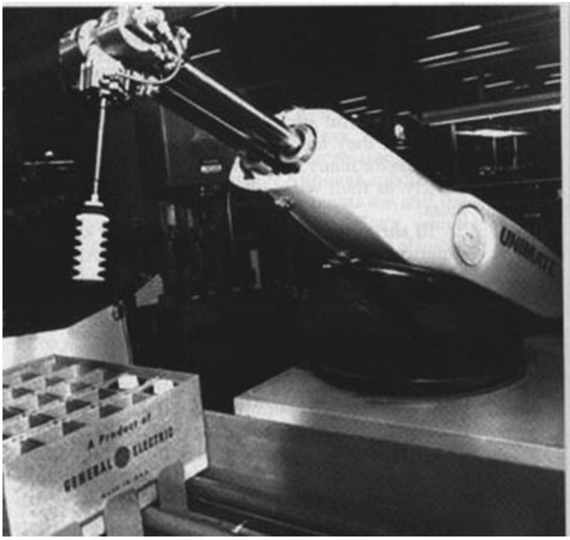

Fig. 1.10 Unimate robotic arm deployed at general electrics facility to handle pick-and-place of heavy parts; 1963

and subterranean exploration (2018–2021). Some of the competitors of these challenges are funded millions of dollars by the DARPA to push the boundaries of their research.

If we go back to the industrial realm, mass production in the third revolution has resulted in a lot of repetitive tasks in manufacturing processes. Most of them were perfectly fit for simple robust automation: the sixties welcomed the first industrial robotic arm, the Unimate (Fig. 1.10), designed by Georges Evol. Even if some early version of digital switches (vacuum tubes) and digital encoders were commercially available at the time, none of the off-the-shelf parts would fit his design, so every single component of the first set of Unimates was specifically manufactured for it. It was deployed at General Motors in 1961, and was the object of the first on-site study for market, integration, ease of use and safety of industrial robots.

Several lessons were learned from it; two of them proved essential. The first one is that robot obsolescence is likely to strike well before utter wear-out. It led to the conclusion that the life of an industrial robot depends on its robustness (ability to hold together) as well as on its versatility (ability to evolve and to adapt to new jobs). The second one relates to the fact that the complexity of a robot is so high that it becomes difficult to guarantee its reliability, a criterium that depends on the owner programming skills, on the production system into which the robot is integrated, and on the quality of its maintenance. It is however important to note that, after the Unimate was used for about a decade, several owners agreed that the financial benefits of replacing human workers with it were not significant, but they still wanted to go along with it because it kept their workers away from industrial accidents and health hazards.

The Unimate featured up to six axes, one of them prismatic (translation), and a payload of 225 kg. The first one was sold at a loss, but after six years, the company, Unimation Inc., started to do profits; it later changed its name for Staubli. Others then joined the market, such as ASEA with its IRB series. The first commercialized IRB, the IRB6, had five axes and a payload of six kilograms. ASEA focused on the ease of integration of its product, whose overall mass was 112 kg, and whose integrated control electronics, including its DC actuators, was fully integrated within the enclosure. It then merged with Brown, Boveri & Cie to become ABB, competing with Staubli to become one of the main robotic arms manufacturers in the world.[6]

1.6 Modern Robotics

During the last decades, while the industry was trying, through several attempts and test sites, to robotize manufacturing processes, tremendous progresses on robotic systems design, kinematics, sensing and control were achieved. The corpus of knowledge on advanced robotic systems resulting from these breakthroughs constitute the fundamentals of modern robotics, a field that explores the possibility to deploy reliable robots in unknown dynamic environments. One of the most important phenomena of this period is certainly the progressive convergence between biological and robotic systems that can be observed since the end the 70's, during which the age-old attempts of simulating life through formal analogies gave place to new experiments that tried to reproduce the dynamic aspects of biological processes.

1.6.1 Coping with the Unknown

Managing complex tasks or missions autonomously in unknown, changing contexts requires a high level of performance in perception, decision-making and agile

[6] It may be worth noticing that Staubli and Brown Boveri are both Swiss enterprises; Swiss is widely recognized as the country where watchmaking was born. It is for more than four centuries the country in which the research and development of mechanical clocks of all scales remains the most active in the world. It can legitimately be assumed that the unique expertise thus developed in the field of micro-mechanisms was essential for the development of robotics, leading to the emergence of a cutting-edge robotic industry. What is less known is that this situation originated, rather paradoxically, from religious concerns: when Swiss became a protestant country after the Reform, in the sixteenth century, Calvin banned the wearing of all ornamental objects. Goldsmiths and jewelers had to find another way to use their skills. They applied them to the realization of watches and clocks, which, because they had a practical function that could be used as an alibi, could become miniature artworks and allow people to wear expensive devices that looked like jewels without incurring the wrath of the church. Watchmakers established themselves in several cities, most of them being located in an area called the «Jurassian Arc», not far from France, in the very area where the Jacquet-Droz family built its famous automata. Here again, by a strange detour, expertise coming from an artistic realm—jewelry—becomes the historical origin of one of the most important developments in robotics and in the robotic industry.

motion control, all elements that can be observed in a wide variety of configurations and biological strategies in nature; this is one of the main reasons why living systems quickly became a source of inspiration for roboticists. Among the first fully autonomous robots are a handful of prototypes realized in 1948 by William Grey Walter, a neurophysiologist fascinated by the complexity of emerging behaviours manifested by simple biological systems. He was convinced of the possibility to transpose such strategies in the field of robotics by using elementary devices. In order to prove his hypothesis, he designed a wheeled robot of the steering tricycle type which was able to detect light directly through a frontal photodiode sensor, without any programming (Fig. 1.11, right). It was then instructed by simple electronic logics to actuate the wheels in order to head towards the strongest light source in its environment. This very simple instruction led to an emerging behaviour—a behaviour that was not planned nor programmed, by which it could autonomously avoid obstacles; emerging behaviours represent one of the essential characteristics of living beings. When the battery level was getting low, the robots behaviour switched in order for it to seek the darkest spot around, as if it was trying to burrow in its lair. The protective shell over Walter's robots, as well as their slow velocity, led people to christen them turtles, or tortoises. The latter name was kept by their creator, most likely because, as mentioned in Alice in Wonderlands, tortoise are wise teachers.

Interestingly enough, the relations of roboticist with turtles extended far beyond Walter's prototypes. In the sixties, a new teaching approach, called Logo, was developed. It was based on recent cognition and learning researches and implemented into programming languages. One implementation made Logo history: it consisted in a method to teach the basics of procedural thinking and programming to children. Kids would learn either by instructing a turtle icon to move on the screen of a computer monitor, or a turtle-like robot to move on the floor. Logo remained one of

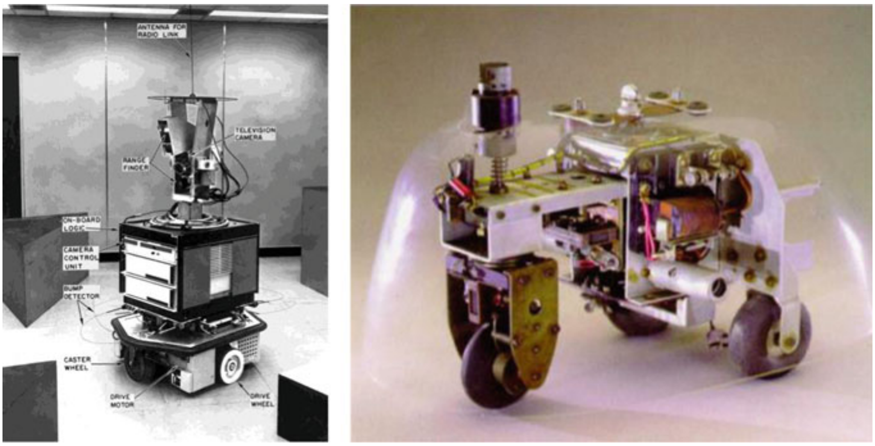

Fig. 1.11 (left) Stanford Shakey robot, circa 1960; (right) Walter Tortoise (1948–1949)

the only toolsets for the teaching of procedural programming and thinking until the late nineties, in primary schools as well as in high schools.

Walter's tortoises inspired a great deal of other robotic works. Twenty years later, in 2010, two employees from Willow Garage, Tully Foote and Melonee Wise, started working on the newly released Microsoft Kinect camera to integrate it with an iRobot Create platform.[7] The result was an affordable, easy to use robot, perfectly fit for teaching and training, to which they gave the name «TurtleBot». Its popularity is closely intertwined with the one of the Robotic Operating System, or ROS (discussed in Chap. 5). One of the most important conclusions of these experiments is that platforms with heavy limitations on sensing abilities and processing power can develop complex behaviours that mimic those of insects (ants, bees, termites, etc.), birds or fishes; and in particular those of animal societies in which groups of individuals can implement complex tasks that are out or reach of a single element. This paved the way for the field of swarm robotics, discussed in Chap. 11.

Since they were using light as their only source of information, the artificial tortoises became very sensitive to the calibration of their sensor, as well as to their context; they required a very controlled environment to perform adequately. A first step in exploring unknown contexts was accomplished by a Stanford-designed robot named Shakey (1966–1972). Shakey (Fig. 1.11, left) was the first robot able to reason about its own actions: it could make decisions based on the combination of inputs from several sensors in order to fulfil a given task (explore, push an object, go to a location …). The platform itself consisted in a differential drive actuated vehicle equipped with cameras, range finders, encoders and bump detectors. Its "brain" computer was a SDS 940 the size of a room, with which it communicated over a radio link. Shakey vision system was able to detect and track baseboards, which allowed it to navigate in its large playground. Working with Shakey allowed the researchers to produce essential contributions, such as the A* path planning algorithm and the visibility graph, both introduced in Chap. 8, as well as the Hough transform in computer vision.

Right after Shakey, Stanford contribution to modern robotics continued with another autonomous vehicle, called the Stanford Cart (1973–1979). Originally designed to mimic a lunar rover operated from Earth, which implies a 2.6 s delay in the transmissions of instructions, it quickly became obvious that such a setup had only two options to choose between: move really slowly, or make the steering and navigation autonomous. To detect obstacles, the Cart was equipped with the first stereovision system (3D imagery). To plan safely its path, it would take a fifteen minutes break and scan its surrounding after each metre travelled. In 1979, using this strategy, it managed to cross autonomously in five hours a twenty-metre room filled with chairs, without any collision.

[7] The iRobot Create comes from the same manufacturer that today sells the Roomba vacuum cleaner robots.

These robots, as well many others that we could have presented here, constitute major milestones in the recent history of technology. As opposed to most of the automata from which they descend, they have the possibility to move by themselves, and to adjust their internal sets and behaviour according to the data coming from their sensors—an elementary form of exteroception. They directly lead to the current state of research and development in self-driving vehicles and drones. Altogether, they pave the way to service robots outside of the industrial realm that are able to cope with challenging dynamic unknown environments.

1.6.2 Robots in Arts and Research–Creation

As anyone may guess, research in robotics is an extremely active field. What is less known is that robotic arts are also very dynamics. As for many technological developments, it didn't take long for artists to take hold of the new knowledge, methods and tools coming from this rapidly expanding field. This should not come as a surprise since, as we have seen, automata of all kinds have always maintained a close relationship with arts. Whereas scientists and engineers were, and still are, concerned on *how* robots should be built, artists, as well as researchers from human sciences, ask the question of *why* they should be developed. Many of their works invite us to evaluate the risks, stakes and potential linked to the emergence of more and more sophisticated machines. As you will see, the border between research and creation in robotics can be very porous, and sometimes completely blurred. Within the recent field of research–creation that lies precisely at the intersection of arts, science and technology, are conceived robotic works that trigger the production of new knowledge and new technological developments in these three domains.

Just like automata arts, robotic arts do not produce robots with practical purposes. They nonetheless managed to trigger a wealth of developments and breakthroughs in mechanics as well as in mechatronics and programming. The impulse that drives them presents no major differences from the one that drove the Jacquet-Droz family to build his Writer or his Musician, or Vaucanson to build his duck, by using some of the most advanced techniques of their time. Furthermore, the often-quoted leitmotiv stating that the first robotic artists were *playing* with their contraptions, instead of *working* to make them useful, should be seen as a positive statement rather than a deprecating one: research in any field is first and foremost a ludic activity, driven by the curiosity and desire for exploration that are inherent to the human nature.

Artists cannot rely, like university researchers, on established research infrastructures; nor do they have access to the same level of human and material resources. But as a counterpart, they have a freedom of research and action that would not be possible in an institutional environment. Not being limited by any calendar constraint, research trend or industrial need, robotic artists are free to explore unexpected research tracks. Not being incited by their peers to work at the edge of technology, they can investigate the potential of low-tech devices with personal sets of motivations, which adds to the specificity and unicity of their work. This has two consequences. First, major results have been obtained by people with limited technological expertise and very limited means and resources, at times verging on *arte povera*, demonstrating, if necessary, that essential breakthroughs can be achieved from elementary devices.[8] Second, the association of artists with university researchers, or with industrial partners, is likely to produce results that could not be possible for artists or researchers alone.

A quick look at artworks from the domain shows that robotic arts are essentially of hybrid nature. From 1920 on, artificial humanoids began to appear in theatre plays and performances. They were most of the time remotely controlled, and thus had no degree of autonomy. It is now commonly accepted that art robots should supprimer be able to interact in some ways with the audience, or with its environment, so that their behaviour can change according to the context in which they are presented.

The very concept of interaction is actually related to a potential dialogue with an artificial being. The occurrence of this dialogue depends on the elements that are used by the robot to communicate, which is why robotic arts have also played an important role in the development of intuitive human–robot interfaces. The first computer-controlled robotic art piece was the Senster (Benthall, 1971). It was equipped with an interface that gave him a pseudo-human behaviour, in the sense that it was attracted towards soft movements and sounds, but repelled by sudden gestures and loud noises. The range and level of technologies that were used to implement it (microphones, Doppler radars, hydraulic rams, plus an 8 K memory P9201 computer from Phillips, whose price at the time exceeded that of a three bedrooms apartment in London) made it impossible to afford by an independent artist; it was actually commissioned by the Philips company.

The Senster, who looked somewhat like a three-legged, four metres giraffe whose movements were derived from that of a lobster's arm, can be seen as pioneering the field of research–creation: its main objective was artistic, but its implementation required a collaboration with experts from several fields and disciplines. Since it was sensitive to the general ambiance of its context, it was able to trigger emotions in the people that interacted with it. It looked like worried when the environment became too agitated or too noisy, which incited people to act so as to make it "feel better" or "more worried". This empathic attitude can be observed in many later works that were designed precisely to trigger it. The Hysterical Machines family by Bill Vorn were octopus-like mechanical robots hanging from the ceiling. When the visitors came too close to them, they become extremely agitated, even showing signs of panics through rapid light effects and frantic movements of their metal tentacles. In front of such reactions, most of the viewers felt sorry for them and were incited to walk back to calm them down (Vorn, 2010). The Aerostabiles project by Reeves and St-Onge consisted in large robotic cubes levitating in wide internal spaces (Reeves & St-Onge, 2016). They could remain still in the air thanks to sensors, actuators and ducted fans (Fig. 1.12). A micro-computer permanently readjusted their position, producing slow oscillations. Despite their high-tech appearance, far remote from

[8] This is obviously not limited to artists, as shown by Walter's tortoises, which are among the simplest robots that can be imagined; or by a software automaton like the Life Game by John Conway, a quasi-elementary system that triggered the birth and evolution nothing less than artificial

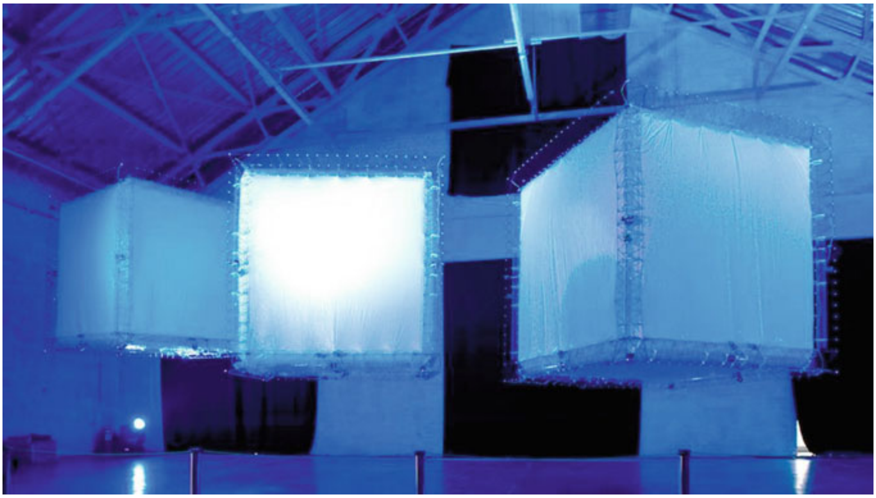

Fig. 1.12 Three Aerostabiles, flying cubic automata by Reeves and Saint-Onge (Moscow, 2010)

that of any living being, they managed to trigger intense emotions, since their very soft movements were interpreted as a form of hesitation, or breathing; they were seen by some visitors as large, floating animals that were prisoners in some way of their technological envelope.

This connexion between the artificial movements of a robot and the emotions felt by the visitor is of outmost importance on three points. First, it demonstrates again, if needed, that the essence and potential of any automaton lie in its simulation abilities. Second, it shows that, even for living beings, powerful impressions and emotions can be communicated even while considering only the formal components of movements, displacements and gestures. Third, as a consequence of the second point, it opens the possibility to develop strictly formal or mechanical vocabularies for triggering and controlling human impressions and emotions, with all the risks and potentialities that such a project implies.

Several other aspects of early automata can be observed in robotic artworks. The puppet theatre built by Heron of Alexandria finds contemporary counterparts in Szajner's "The Owl and the Robot" or "Petit Nicolas", two interactive, theatrical computer-controlled automata scenes; in Vorn and Demers' "No Man's Land", which involved more than fifty robots of nine different *species* detecting the presence of viewers and reacting to it (Demers & Vorn, 1995); or in Rogers' «Ballet Robotique», a movie showing large industrial robots choreographed so as to evoke animals or

life, a new science that has since the 60's produced a wealth of theoretical and technological results in several disciplines.

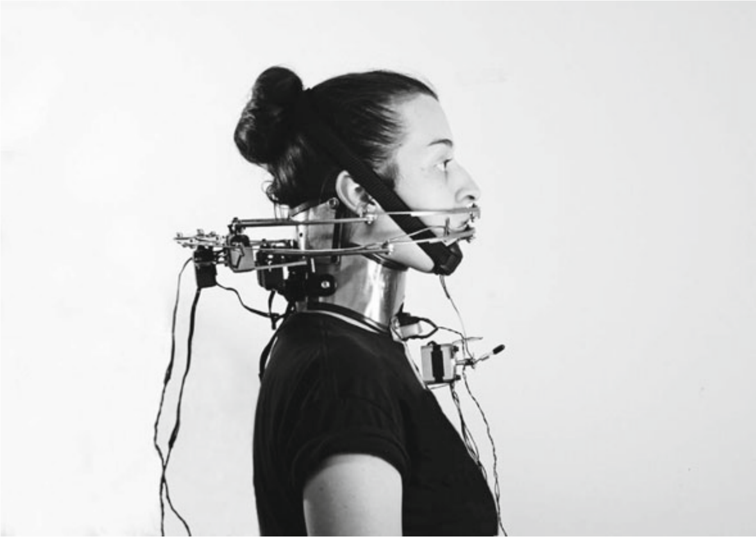

Fig. 1.13 Human speaker experiment by artist Nataliya Petkova, 2017

plants. "The Robotic Church" by Chico McMurphy involves forty different robots that play their individual sound-producing sequence (McMurphie, 1989).[9]

The level of interaction in these pieces is rather elementary, but they still demonstrate the importance for robotic artists of attempting a dialogue between the robots and the viewers; or at least, to trigger a reaction or an emotion from the latter. The next step consisted in conceiving works in which human and robots would act together in installation or performance scenes, trying to maximize the integration and the collaboration between human and robotic performers. Among the pioneers of such projects, Stelarc stands out as the first artist to have experimented robots as advanced prosthesis of his own body. In his seminal piece "The Third Hand", he tried to control a robotic arm affixed to his right forearm through his own muscular impulses, in order to make it write the same thing as his right hand (Stelarc, 1981). He also designed pieces in which he reversed the mutual roles of the human and of the robots: in his "Ping Body" piece, distant viewers located in three different cities could trigger his body movements through a muscular stimulation device (Stelarc, 1995). A less known but maybe more radical piece, "The Human Speaker Experiment" (Fig. 1.13), presents a performer whose tongue, throat, cheeks and lips are actuated by mechanic and electric devices, so as to allow a computer to make her pronounce different words and sounds (St-Onge et al., 2017). Such installations convert the body into passive objects whose only role is to follow the instructions sent by the computer, like human

[9] McMurphie's installation strangely evokes a famous low-tech automated piece from the outsider arts category, "Le manège de Petit Pierre", a life-size mechanical fair created and built by Pierre Avezard, a handicapped farm boy, and which differs from more sophisticated automata theatres only by the precarity of its materials (Piquemal & Merlin, 2005).

interfaces. Just like the self-destructive multi-machine performances in the 80's by the Survival Research Laboratories (Pauline, Heckert and Werner), they convey strikingly powerful messages about the risks linked to the expansion of robotic devices in our daily lives, and the possibility for them to escape all human control (Ballet, 2019).

One cannot evoke robotic arts without mentioning another category of pieces, namely those that deliberately try to give inanimate objects the appearance of life. "Robotic Chair" by Max Dean is an ordinary looking chair that disassemble and reassembles autonomously (Gérin, 2008); Boursier-Mougenot's Grand Pianos slowly move in an exhibition space, sometimes bumping into each other (Bianchini & Quinz, 2016); Mike Phillips Sloth Bot is a white abstract prism, several metres high, which imperceptibly moves in the atrium of a public building, getting closer and closer from groups of people who end up noticing his ominous presence and quickly getting out of its way (Phillips, 2007). Paul Granjon's sexed robots live in an enclosure called the "Robotarium", in which their only concern and objective is to mate with each other. They are also inspired by Walter tortoises in several ways; for instance, when low in battery, they seek the darkest spot as their nest (Pitrus, 2013). Such works are often infused with a dose of humour, which does not prevent them to carry strong statements about the potential futures of robotics, and the necessity for us to carefully evaluate the risks involved in some specific development axis.

Other artists propose works that directly address these notions, by entering active discussions and controversies surrounding the research and development of killer robots. The ethical problems raised by such machines are nothing less than overwhelming. In a 2021 piece called Spot's Rampage, Brooklyn collective MSCHF has purchased one of the famous yellow dog-shaped robots from Boston Dynamics, which used to be displayed playing and jumping on videos that became viral. They equipped it with a paint gun and offered to anyone the possibility to pilot it online, so as to make more concrete the possibility of armed police robots wandering in the street of large cities (MSCHF, 2019).

One common point of the works mentioned in the present section is that they can hardly be relegated to a single domain: all of them are nurtured by data and information coming from the three fields of art, science and technology. They are inherently trans-disciplinary—some authors even qualify them as post-disciplinary, since a robotic artist can navigate between theatre, performance, music, video, installation, sculpture, bio-arts, visual arts, and many others, producing equally valuable works in each of these fields. They can be characterized by the fact that they constantly cross boundaries between all fields and domains, and by the way they manage to thrive on these boundaries. Just like former automata makers, researchers-creators in robotic arts are dedicated to the creation of artworks which constitute their final objective. Just like them, through the process of conceiving and implementing them, they develop advanced new skills, expertise and knowledge that can be then transferred to several other fields; and just like them, the mechanisms they imagine can be seen as models for some hidden or ill-explained aspects of reality, and help understand these aspects. And last but not least, the interactive nature of most robotic artworks directly connects with the age-old impulse to create works that simulate features of living beings.

1.7 Social Robotics

While several challenges still need to be addressed for robots to be able to robustly navigate any cluttered terrain, vacuum robots and robotic pets are getting common in household. Robots in our daily routine can have a significant impact on our lives and no enough study were conducted yet on this topic. However, opening the door to psychology, education and sociology over the past decades of research in robotics also contributed to promote robots as potential good artificial companions (Fig. 1.14). A handful of companies hit that market with innovative products, but very few succeeded, in a surprising contradiction to the success of AI start-ups. The often-quoted refrain in the industry is that "robotics is hard."

If you think engaging Alexa or Siri in a natural conversation is difficult, just try building a robotic humanoid that can function in any capacity similar to a human. Simply put, initiatives in social robots such as Rethink Robotics, Jibo, Nao and Mayfield Robotics helped to grow and spawn an industry only to find that more nimble competitors, in the shape of robotic assistants with no mobile components,

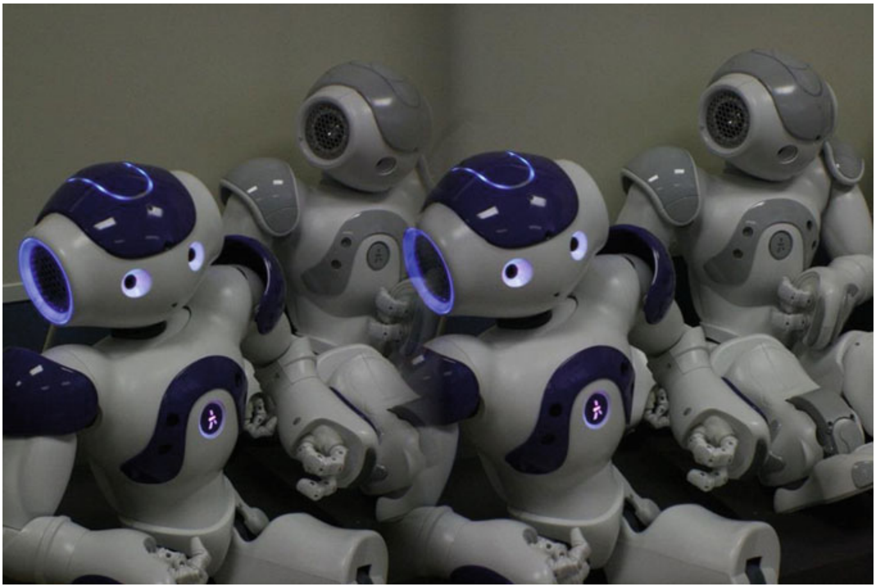

Fig. 1.14 A small pack of Nao's humanoid robots from Jaume I University. Nao is one of the most popular robotic platform for human–robot interaction in psychology and it has made its place in the child education market

outcompeted them. For whatever reasons, the venture investors determined that these market forces were more important than any longer-term vision that the robotics company had and decided not to continue funding it. Anki CEO and co-founder Boris Sofman gives a clue of the reasons behind that state of affair:

> You cannot sell a robot for $800 or $1000 that has capabilities of less than an Alexa.

Roboticist Guy Hoffman adds:

> When designers will start their own social robotics companies and hire engineers, rather than the other way around, we will finally discover what the hidden need for home robots was in the first place.[10]

This does not mean that social robots have no role to play whatsoever. Many things that are not directly connected with robotics as such can be learned from each of these experiments. Jibo, for instance, is a major case study for the first large-scale human grief and mourning for robotic systems, with hundreds of owners sharing their distress and psychological state after its end of life was announced. There is obviously a major field of research, centred around the emotions that can be triggered by an artificial being, to be investigated here. As we have seen, the field of robotic arts has been considering and exploring these phenomena for several decades now. It is not unreasonable to suppose that joint research–creation ventures involving human scientists, psychologists, artists and engineers will be ideally equipped, theoretically and technologically, to address these questions.

1.8 Robotic Futures and Transrobotics

Throughout this chapter, we encountered several examples of a sequence in which an entity that evokes more or less precisely the shape of living beings induces the creation of more sophisticated devices intended to bring this evocation to the level of a similitude, then to an assimilation, then to a model: the representation becomes the paradigm. The same situation reoccurred at the procedural level with computers and computer science, where it stands at the origin of a new model of human beings in which the antique separation between body and soul is transposed, through an immediate formal analogy, into a separation between matter and information.

Before exploring the consequences of this model, it should be noticed that the mechanistic paradigm of the human body readily led to the resurgence of another primordial myth, through the hope that immortality was at reach. The idea of the body as a machine implicitly supposes the independence of its various components and the possibility of remedying the failure of an organ by the transplant of an identical one, or by the implantation of a prosthesis. From there was born the vision of human beings gradually transformed into robots through the progressive replacement

[10] Stalker and stalked: What Killed Off Jibo, Kuri and Kozmo? in Asian Robotics Review 273, https://asianroboticsreview.com/home273-html (accessed January 30, 2022).

of their biological, ephemeral components by artificial ones; and whose longevity becomes considerable thanks to the use of unalterable materials, such as titanium, gold, palladium. Moreover, such hybrid beings would progressively become able to wander in extremely hostile environments, such as deep space or ocean abysses, and even of surviving intergalactic journeys, indefinitely pushing the borders of territories colonizable by mankind.

Today we know that no material is eternal. A stable element such as gold that can remain unchanged for billions of years, but this remains very far from eternity; no robot can last forever. Information however has no prescribed age limit. Since it can be transposed from one material entity to another, it can theoretically last as long as the Universe itself, which is as close to eternity as it is possible to be. Analogies with certain properties of living matter readily come to mind: if we look today at the fossil of a fern in a museum, we know immediately what we are looking at, because we have seen living ferns quite often in our lives. But this fossil is 300 million years old: the fact that we are able to identify it means that the information that controlled its morphology has remain unchanged since it was living—it lasted longer than the highest mountain ranges of the late Paleozoic. We are thus led to the conclusion that life is the optimal process that Nature has found to preserve information, and to allow it to travel towards the future: being immaterial, it can jump from one individual to its offspring when the materiality of the parent degrades. This life-inspired strategy led to the emergence of a particular class of automata, on which will now focus our attention, and which tries to embed three characteristics of living beings: self-building and healing; replication; evolution.

Automata with such abilities are still in their infancy: they are mainly found in university or industrial labs. However, the development of miniaturized mechatronic components and of new materials, as well as the availability of cheap and powerful microcontrollers, allow to foresee their use for practical applications in a not-so-far future.

Several examples of self-building or self-reconfigurable robotic structures have been proposed in the two last decades. One of the first examples consists in basic cubic "bricks" equipped with an arm on each of their faces. Sets of such cubes can built cubic lattices with various topologies: the cubes can carry one another from one node of the lattice to the next (Yoshida et al., 2003). These modular robots were rather heavy and cumbersome, but they prepare the grounds from miniaturized systems in which such "bricks" could become the basic cells of robots with advanced functions; moreover, a robot built this way could theoretically self-disassemble and reconfigure in a completely different one in order to perform different tasks. Such devices may seem very upstream of potential applications; but their potential is so promising that they are the object of intensive researches in several labs. Many designs have been tried, such as the two-hemispheres ATRON robot by Modular (Jorgensen et al., 2004), chain structured systems such as the CEBOT (Fukuda & Kawauchi, 1990) made of three different cells (wheel mobile, rotation joint, bending joint), Yim's Polypod, made of segments and joints (Yim et al., 1995), truss structured systems such as Hamlin's Tetrobots (Hamlin & Sanderson 2012) or Ramchurn's Ortho-Bot (2006), which remains at the state of a concept.

Self-healing robots are also the object of a lot of attention from researchers. They can be broadly divided into two categories. The first one consists in mechanical robots that are able to repair their own components by using tools that are integrated in their structure, such as the PR2 robot configured at Tokyo University (Murooka et al., 2019). Such robots would theoretically be able to fix themselves after a failure, like a surgeon that performs surgery on himself. The second one includes robots that are made of soft materials («softbots») that self-reconstruct after having accidentally been damaged or ripped by a collision, like a biological skin (Guo et al., 2020).

Replication and evolution on their side are not independent processes. In both cases, the robot must carry the information that represents itself, in order to transmit it to a device that could built an identical copy of itself. This device could be a separated piece of equipment; but in order to stay closer to the analogy with living processes, which can be deemed optimal since they have been elaborating and fine-tuning through billions of years of evolution, the robot itself should be able to produce its own replicas. Directly evolving a physical robot is out of reach of current technologies; it should however be mentioned that the first evolution of digital organisms has been observed in 1984 on a cellular automaton (Langton, 2000; Salzberg & Sayama, 2004), where it appeared, surprisingly enough, as an emergent feature of the system. A cellular automaton is not a robot; but the fact that an evolution process can take place in the memories of a computer means that generations of physical robots, progressively more adapted to a given task, can be successively built along its course.

Lipson and Pollack's Golem project[11] was specifically aimed to create robots with specific performance specifications, without any human input at the level of design (Lipson & Pollack 2000). Their morphology resulted from a digital evolution process whose results were evaluated and selected through computer analysis, simulation and optimization, before reaching a final shape. The only human intervention consisted in affixing the actuators on the various components. The final product was an articulated worm equipped with a triangular arm; it was able to crawl on different surfaces. Such a result may seem disappointing as compared to the sophistication of the process; but this opinion can be relativized when considering that it took hundreds of millions of years to biological life to reach the same result on Earth. Moreover, a close look at the evolution diagrams reveals striking analogies with biological evolution: both underwent stable phases, where they seemed not to be able to produce new proposals or *species*, followed by phases where the number of such proposals literally exploded. Knowing that a computer can evolve robots much faster, and maybe more efficiently, than biological evolution, reminds us that the field of robotics faces us with unlimited possibilities, but also with risks that must be carefully considered for each of its new development axis and trends.

We will end up this chapter with a small tale that will briefly take us back to the first age of automata. Thousand years ago, a craftsman created a human-like automaton for the Chinese emperor. It was so realistic, and behaving so humanly, that it almost became a star in the emperor's court. Everyone wanted to be seen with him. He behaved very elegantly, and with exquisite politeness towards everyone,

[11] Note the mythological reference!

especially young women, with whom it even happened to engage in some form of flirt. Unfortunately for him, he made the error of flirting with the emperor's favourite spouse. The wrath of the emperor was terrible; he feared that the automaton and his wife could become lovers; he ordered the automaton to be executed, which was done immediately. The automaton has made the error of entering a territory which was exclusively reserved to the emperor, namely that of its succession, threatening the perpetuation of his life and heritage.

Today, the situation is completely reversed. Despite all the mythical worries associated with such as project, building an automaton or a robot that could reproduce itself and evolve by following lifelike processes is an objective that is looked for rather than feared; the first team to accomplish such a feat would be immediately acclaimed at the international level. This is illustrated by a very recent project by Kriegman and Bongard (Kriegman et al., 2021), in which small entities made of skin cells of frogs are dubbed «biological robots» in the media, a name that looks like a contradiction in itself, but that translates the perplexity of contemporary commentators in front of such researches.[12] These microscopic entities are able to replicate themselves, not by regular cellular division (mitosis), but by assembling other cells freely floating in their environment—the new ones are biological constructions, rather than offspring of biological «parents».

Most of the robots we know today are dedicated to practical tasks. In that respect, one can wonder to which extensive research about bio-inspired robots, lifelike robots or biorobots so remote from our daily concerns can be relevant. The answer lies in two points. The first one is the observation of the optimal efficiency of living processes for about all imaginable tasks, and the hope that this efficiency can be one day transposed in artificial entities. The second one is linked to the fact that after thousands of years of evolution, the most advanced researches on automata and robots remain deeply connected with the myths and fears that led to the creation of the very first ones, thousands of years ago. As shown by Kriegman and Bongard's experiments, the convergence with living beings, once seen as an illusory attempt, is now stronger than ever; and the meaning of the term «robot», as well of that of the suffix «bot», has expanded far beyond its original significance. New knowledge about biological and genetic processes led to the emergence of life-inspired automata and robots, which in turn ended up bringing new knowledge and models for some of these processes.

It is still too early to know which of these attempts will become successful, and which ones will remain as milestones in the ongoing genealogy of automata; but we can legitimately suppose that the future of robotics lies in a more and more pronounced convergence between artificial and biological entities at all scales, from a whole organism to cells and molecules; and that we will soon see hybrid robots involving more and more biological or life-inspired components going out of the lab to enter industrial and domestic environments.

[12] The authors gave the name «Xenobots» to their creatures.

Chapter Summary

After examining the difficulties linked to the precise definition of the word “robot”, the mythical origin of all robots and automata was exposed; it was regularly reminded in the following sections. Early automata built by the Greek founders of mechanics, namely Ctesibios, Philon of Tarentum, Heron of Alexandria, were described. They were followed by the presentation of works from the Renaissance to the Classical Age, in which automata that tried to simulate life and life processes by replicating as precisely as possible the form and/or anatomy of living beings. From there, the genealogy of robotics bifurcated. A new branch appeared, in which the machine and the information controlling it became fully separated. It can be seen as the origin of modern computers and robots. Some early automata from Antiquity could be programmed to modify their behaviour, through different mechanisms; but surprisingly enough, the ancestors of modern programming are to be found in musical boxes and in the Jacquard loom. They also led to Babbage’s Analytical Engine (1843), the first device that featured all the components of a modern computer, for which was written the very first algorithm. The industrial era saw an almost complete loss of interest for automata. The expressed needs of large-scale manufacturing paved the way to the implementation of the first industrial robots. It was simultaneously realized that mobile robots, able to cope with unknown, changing environments, could find a wealth of potential applications in several fields. Robots became more and more autonomous; their sensors became more and more efficient; computer and mechatronics equipment became smaller and smaller. Robots could begin to take decisions on their own by comparing information from different sources and by using processes inspired from biological organisms. From there, a marked convergence was established, and is still going on, between artificial and natural beings. Some of the latest robots developed in research labs use materials and strategies coming both from biology and technology. Their potential, as well as the interest they raise, allows to see them as harbingers of the next phases of robotics. The possible applications of such machines are impressive, and we can legitimately be fascinated by such technological achievements. But we must also consider the risks raised by the introduction, in our daily life as in industry, of autonomous artificial entities increasingly close to living beings, and whose abilities and power expand almost exponentially with time.

Revisions Questions

1. *How do the arts contribute to the development of robotics?*
   There may be one or more correct answers, please choose them all:

   A. *By allowing studies to be carried out free from the laboratory environment and the constraints of research*
   B. *By prioritizing aesthetic considerations*
   C. *By making researchers popular*
   D. *By questioning the present and future emotional implications of technologies*

2. Which of the following historical figures is recognized for having produced the first programmable automaton?
3. Who is known to have written the first machine algorithm?
4. Can you identify the main impulse(s) that drove the first automata makers to build their works

   There may be one or more correct answers, please choose them all:

   A. *To demonstrate their knowledge and skills*
   B. *To simulate and/or replicate living organisms*
   C. *To help understand phenomena such as life or celestial mechanics through explicative models*
   D. *To impress, entertain or amaze crowds*

Further Reading

Demson M, Clason C R (2020)

Romantic Automata: Exhibitions, Figures, Organisms. Bucknell University Press

A brilliant collection of essays, most of them based on the eighteenth century literature about robots and automata, which describe the contradictory feelings that emerged in the Romantic times, when it was realized that the construction of life-like artificial entities, once seen as a technological achievement, could actually lead to the emergence of mechanical beings deprived of the qualities that are inherent to humanity such as empathy and compassion. A source of fascination and entertainment for centuries, automata began, in a short period of time, to trigger less positive emotions such as dread and fear, in a pivotal moment that is cleverly apprehended by the authors.

Herath D, Kroos C, Stelarc (2016)

Robots and Arts: Exploring an Unlikely Symbiosis. Springer, Berlin

A pioneer book about robotic arts of all kinds, Robots and Arts presents, through some of the most emblematic projects of the field, a thorough and in-depth reflexion about the role, status and future of robots in a world where these artificial beings are progressively becoming daily companions and partners. It constitutes an eloquent demonstration of the essential contribution of artists to the general discourse on the evolution of technologies. The argument is elaborated through a trans-disciplinary compendium of texts by artists, scientists and engineers. Though this is not the main objective of the book, the different contributions also make the case for the importance of research–creation, by showing the wide number of disciplines, expertises and skills that are required to produce even simple robotic art pieces, and the necessity to promote such fruitful collaborations in university labs as well as in artists' studios and technological research centres.

Foulkes N (2017)

Automata. Xavier Barral, Paris

The epic history of automata, from the oldest to the most recent, in a book profusely illustrated with documents from all periods. The intimate links of automata with clocks watchmaking, their parallel evolution with that of technologies, their links with magic and myths, are clearly exposed, as well as the different roles they have occupied throughout history, in several regions of the world. A well-argumented book that can be used as an introduction as well as a reference.

Mayor A (2018)

Gods and Robots: Myths, Machines and Ancient Dreams of Technology. Princeton University Press

A historical account of the links between the fantastic characters of the earliest myths in history, recorded in Crete, the Roman Empire, Greece, India and China, and the first instantiations of these artificial beings and mechanisms that are the ancestors of all robots and automata that have been designed since. Perhaps one of the clearest evocations of the origin of automata, all born from this obsession to breathe life into inanimate beings, and an irrefutable demonstration of the fundamental role of art, imagination and legends for the greatest scientific and technical developments.

Nocks L (2008)

The Robot: The Life Story of a Technology. John Hopkins, Baltimore

A history of robots mainly centred on the technological aspects of the field. The argument remains generally more factual than for the previous ones and gives less prominence to the non-technological roots of automata; but it takes on its full importance in the light of several elements which will serve as a useful reference: a glossary, a timeline, an abundant bibliography, as well as information on the state of research and development of contemporary robotics through statistics on currently operating laboratories, firms and companies.

Wilson S (2003)

Information Arts : Intersections of Art, Science, and Technology. MIT Press, Cambridge

A reference book in the field, Information Arts presents itself as the first international survey of these artists who prefigured the development of research–creation by exploiting data and concepts from all scientific fields, as well as the results of a large number of technological advances. Soundly argumented from a theoretical point of view, this essential work, based among other things on the visual and bibliographical analysis of major artistic approaches, shows here again that the artist does not limit himself to staging these concepts and their developments: through the positions it takes in front of their social and cultural consequences, it participates in the discourse on their evolution and becomes a full player in the determination of future research programs.

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