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The da Vinci Robot

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ABSTRACT

***Background*: One might assume from the title of this paper that the nuances of a complex mechanical robot will be discussed, and this would be correct. On the other hand, the date of the design and possible construction of this robot was 1495, a little more than five centuries ago. The key point in the title is the lack of a trademarked name, as Leonardo was the designer of this sophisticated system. His notes from the *Codex Altanticus* represent the foundation of this report.**

***Methods*: English translations of da Vinci's notebooks are currently available. Beginning in the 1950s, investigators at the University of California began to ponder the significance of some of da Vinci's markings on what appeared to be technical drawings. Such markings also occur in his *Codex Atlanticus* (the largest single collection of da Vinci's sheets, consisting of 1119 separate pages and 481 folios) along with a large number of other mechanical devices. Continuing research at the Instituto e Museo di Storia della Scienza in Florence has yielded a great deal of information about Leonardo's intentions with regard to his mechanical knight.**

***Results*: It is now known that da Vinci's robot would have had the outer appearance of a Germanic knight. It had a complex core of mechanical devices that probably was human powered. The robot had two independent operating systems. The first had three degree-of-freedom legs, ankles, knees, and hips. The second had four degrees of freedom in the arms with articulated shoulders, elbows, wrists, and hands. A mechanical analog–programmable controller within the chest provided the power and control for the arms. The legs were powered by an external crank arrangement driving the cable, which connected to key locations near each lower extremity's joints. Da Vinci also is known to have devised a programmable front-wheel-drive automobile with rack-and-pinion suspension mechanisms at age 26. He would recall this device again, when, at age 40, he is thought to have built a programmable automated lion, but by then, he had produced his own metal springs as well as drum-containing springs called tambours. He positioned his fusee to a stationary rotating power output shaft that would be used to power his programmable automaton.**

***Conclusions*: Part of the obscurity of da Vinci's robot comes from the difficulties interpreting Leonardo's markings. His designs precede any formal method of blueprint designing. The technical aspects had to be deciphered before anyone could even attempt to reproduce his intended device. This robotic device fits together with other pieces of evidence that link 15th Century automatons to da Vinci's design, namely the automated Tea Servers from Spain. As with many things from da Vinci, looking backward at this master leaves one with a pronounced sense of awe at his prescient view of the world.**

INTRODUCTION

There will appear gigantic figures in human shape,
but the nearer you get to them,
the more their immense stature will diminish.

Leonardo da Vinci

BORN ON SATURDAY, April 15, 1452, in the small town of Vinci, in Tuscany, near Florence was undoubtedly one of the most unusual individuals to represent a master of the Renaissance, Leonardo da Vinci (1452–1519) (Fig. 1).[1] Although best known for his art, he has also contributed significantly to such fields as anatomy, optics, hydraulics, mechanical engineering, mathematics, and others.[2] The intent of this narrative

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FIG. 1. Leonardo (self portrait).

is not to describe the significant advances in our 21st Century understanding of Leonardo as a person but rather to place within those practitioners of robotic surgery the sense of the great debt owed to da Vinci's legacy.

Modern da Vinci scholarship abounds, and interpretation of Leonardo's legacy of writings, drawings, and sketches is proliferating. The current impression of Leonardo probably is more accurate now than ever before, even though only about a fifth of the materials he wrote and drew have been preserved.[3] Understanding the miraculous feats of this Italian *ingegno* and speculate why he did it all becomes possible.[4] Primary sources for Leonardo research are bound collections of his manuscripts, such as the *Codex Atlanticus* in the Biblioteca Ambrosiana in Milan and others (Table 1). His notebooks and single sheets, owned by collectors throughout the world, represent other sources of information. Also, a wealth of modern scholarship and biographical writing has spewn forth over the past decade. This paper represents an attempt to put into perspective the automated mechanisms that so thoroughly intrigued da Vinci and the unique honor bestowed by the naming of our revolutionary computer-guided, master–slave surgical robotic system after him.

YOUNG LEONARDO AND THINGS MECHANICAL

Leonardo was the illegitimate son of a wealthy notary in the Tuscan village of Vinci. His birth date and time were carefully noted by his grandfather (also a notary) in his own meticulous notebooks.1 His childhood was most likely spent with his mother (Catarina) and stepfather in the rural environs surrounding Vinci, and his first known drawing is of this provincial, agrarian countryside. He probably was exposed early to the mills and presses that produced the flour and oils that were the staple of this economy, as he later adapted some of these mechanisms into his own inventions. He also gained a life-long affinity and love for animals during his youth; he later became a strict vegetarian.[3] Leonardo certainly had direct contact with his real father's family, for it was his father who introduced the talented youth to his mentor, Andrea di Cione (better known as Verrochio), in Florence.[1]

Leonardo cultivated an early appreciation of classical knowledge and benefited directly from the flow of newly reintroduced Greek science and philosophy from the fall of Byzantium (1453). Thinkers and writers such as Battista Alberti and Paola da Pozza Toscanelli heavily influenced him with ideas of experiencing knowledge (Aristotelian), fostering a cultivated presence, and ceaseless search for truth and understanding, thus formalizing his pathway of the "Renaissance Man."[1] He also observed and noted technical details of Florence's many festivals and pageants that required Verrocchio's workshops to build the devices that supported such regalia. The final ingredient was the influence of Filippo (or Pippo) Brunelleschi, the master architect. Da Vinci was fascinated by all the details and machines necessary for modern 15th Century building. Leonardo would return to these mechanisms time and time again when speculating about new devices.

DA VINCI AND MATURATION OF THINGS MECHANICAL

Leonardo was absorbed in the experiences surrounding his apprenticeship from 1466 to 1477. He was intensely interested in Florentine spectaculars, mostly religious, that involved celebrations, shows, and performances. In particular, he was intrigued by the mechanical devices that were being contrived to fascinate the crowds. For Medici jousts and carnivals, the workshops of Verrocchio and his pupils would be fully occupied with making standards, banners, costumes, masks, armours, caparisons, and heroic wagons.[1] He was likewise attracted to the theater and the special effects being used innovatively during the performances in this era. Huge revolving discs that were used to change scenery and the wires and pulleys that made actors appear to fly through the air all attracted the attention of his visionary mind. He would take his speculations with him to Milan at the court of Ludovico Sforza.

Before embarking on his Milan period, Leonardo stayed in Florence as an independent artist for 5 years, between 1477 and 1482.[5] It was during this period that he may have designed for Lorenzo Medici his first programmable, mechanical computer-controlled automaton. It is known that he was reading classic Greek texts and had a keen desire to reproduce the science of these masters and perhaps to outdo them. In 1478, his automaton was a three-wheeled mobile cart. It is almost a design to prove that he could create mechanical devices that might rival the Greek god, Haephestus. "... *since he was working on twenty tripods which were to stand against the wall his strong-founded dwelling. And he had set golden wheels underneath the base of each one so that of their own motion they could wheel into the immortal gathering, and return to his house: a wonder to look at*."[6]

The *Codex Atlanticus* f812r[296v-a] shows Leonardo's unique technologic advances in automation from as early as 1478 (about age 26) (Fig. 2). Carlo Pedretti in 1975 first recognized this drawing as an automobile.[7] It so happens that Leonardo's ideas for autonomous mechanization appear to par-

Table 1. Leonardo da Vinci's Original Source References

Codex Atlanticus	Biblioteca Ambrosiana	Milan, Italy	Largest collection of Leonardo's sheets, approx. 1119 originally taken by Pompeo Leoni	This collection has all of Leonardo's range: architecture, town planning, biographical data, personal notes
Codex Forster	Victoria & Albert Museum	London, England	Three manuscripts	Geometry, math, hydraulics, autobiographical, cosmology, horse sculpture, festivals
Manuscripts of the Institute de France	Biblioteque de l'Institut de France	Paris, France	Twelve manuscripts (all in original order)	Geometry, physics, mechanics, autobiographical, "animation of soul." architecture, optics
The Madrid Codices	Biblioteca Nacional Madrid	Madrid, Spain	Five volumes	Hydraulogy, waves, flight, musical instruments, maps, canals
Codex Arundel	British Museum	London	Two volumes (2nd largest collection of papers)	Mathematics, physics, optics, astronomy, submarines, underwater breathing, warfare, music, theater, architecture
Codex Hammer (Gates)	Bill Gates Collection	Seattle, Washington	Probably arranged by Leonardo personally	Hydrodynamics, hydraulics, theories on marine life, lunar phases, fossils (archeology)
Codex Trivulzianus	Biblioteca Trivulziana del Castello Sforzesco	Milan, Italy	Oldest known manuscripts	Linguistics, Latin grammar, caricature drawings, invisible drawings
Codes "On the flight of birds"	Biblioteca Reale	Turin, Italy	Originated in 1506; about 90 pages	Wind, motion studies, anatomy, mechanics, botany, water fountains and gardens
Treatise on Architecture	Biblioteca Medicea Lavrenziana	Florence, Italy	Two volumes	1st volume is work by Martini with extensive annotations by Leonardo
Book on Painting	Vatican Apostolic Library	Vatican City, Vatican	544-page volume	Arranged by Melzi as directed by Leonardo

allel his interest in manned flight, because his first drawings of flying machines occur synchronously (Uffizi c. 1478). Leonardo continued and advanced his fascination with ancient Greek science by developing fully animated automata, and by the age of 56, he designed a water-powered bell ringer using 12 interconnected chambers of actuate float valves. His inspiration here was Pindar's Seventh Olympic Ode (c. 520 B.C.)... "*And their ways teemed with sculptured forms like to beings that live and talk: and high waxed their renown. But in the man who has the craft-lore even the greater skill putteth itself forth without the guide of magic*."[8]

Details of da Vinci's cart have been sought by modern robotic engineer, author, and entrepreneur Mark Rosheim (Fig. 3).[7] Power is generated by a spring drive drum fusee, referred to as the "going barrel" or "tambour." In Folio 4 recto Madrid MS I are Leonardo's series of fusee power supplies. All of his designs have gear ratio increases that would be necessary for propulsion. He developed a T-shaped key for winding the spring fusee power source. Leonardo would study and draw numerous gear systems with variable curved surfaces to produce cams and hybrid drive systems.

Da Vinci's programmable cart had a wooden frame, about 20×20 inches. The frame of his cart was joined by secure fasteners to protect "any mounted" device from the vibrations as the cart moved through its programmed motions. The cart had two large gears and arbalest springs, the source of motive power, each an interdependent subsystem for propulsion and guidance. A rocker arm held in tension by cables connected to the arbalest springs created the escapement to regulate the speed of the gears oscillating back and forth. The unit on the left was felt to be used for propulsion, whereas the right one was for guidance systems and automation of mounted pieces. The front wheel drive is a rack-and-pinion mechanism for steering with the possibility of serving as a trigger for "special effects." The direction and velocity of his cart were controlled by an array of cams attached to the top of the large barrel gears. The left propulsion cams controlled the speed, perhaps even stopping at programmed intervals, turning, or reversing, all of its own volition.[7]

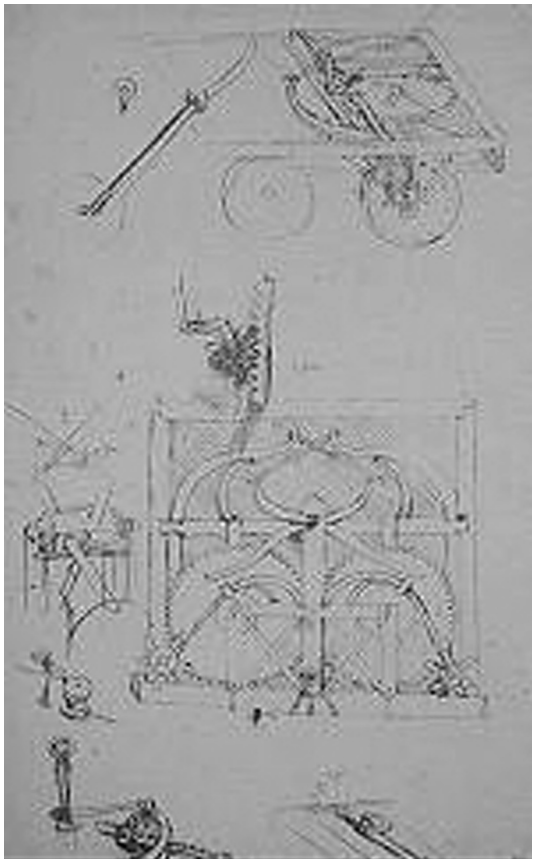

FIG. 2. da Vinci's drawings of automated cart. *Codex Atlanticus*, f812r[296v-a]

THE DA VINCI ROBOT

Da Vinci obviously was interested in recreating and outdoing anything previously reported by the Greek scholars, to become the man who had the "craft-lore." There is evidence from many sources that confirm several of da Vinci's automata and their performances.[9] The first is his automated lion. There exist eyewitness accounts that Leonardo automated a mechanical lion that could move about of its own volition. It could stop, rear up on its hind legs, and open a compartment in its chest. This automaton was publicly displayed on two well-attended occasions: the wedding of Maria de Medici and the arrival of the French King and Leonardo's future royal patron, Francis I, in the city of Lyon in 1515.

FIG. 3. Mark Rosheim's reconstruction of Leonardo's automated cart (base).

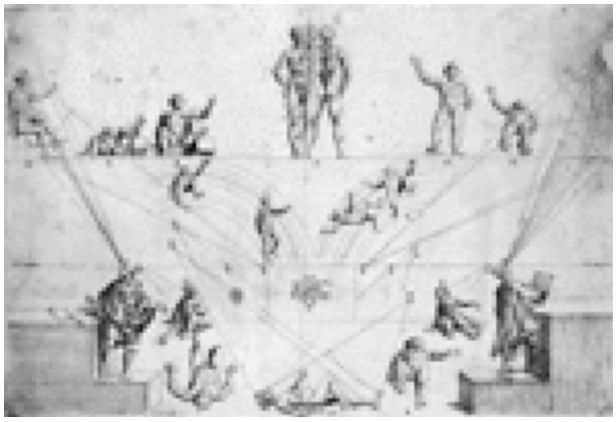

FIG. 4. da Vinci's drawings of his robotic knight (c. 1495).

One of Leonardo's least known designs, which he conceived around 1495, was a humanoid robot (Figs. 4 and 5). It is believed that his earliest studies of anatomy and kinesiology were the natural progression to his desire to animate an automated device just as his investigations of avian flight spurred his imagination to attempt manned flight.[5] In one group of folios that appear to be simply anatomic drawings and are thought to be followed by the Vitruvian canon mechanisms lay the hidden secrets of his humanoid robot.[10] It was not even considered to be a mechanical device until some interest in the drawings followed investigations by a professor at the University of California in the 1950s. This all fits with modern scholarship showing his intense Milan-based interest in things of a war-like

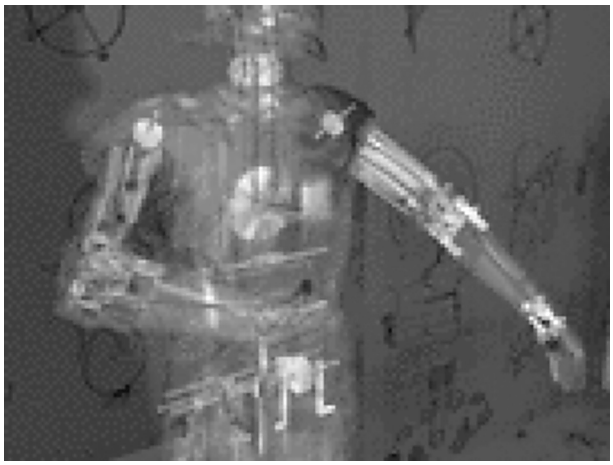

FIG. 5. Artist's rendition of current re-creation of Leonardo's robotic knight (Istituto e Museo di Storia della Scienza in Florence).

nature and Leonardo's attachment to the court of Sforza.[1] In fact, it is highly likely that this automaton knight not only performed independently but produced sounds from drums embedded within the mechanisms.

This humanoid automaton was dressed in a suit of armor, typical of German-Italian 15th Century design, typified by those worn by Milanese militia. This mechanical armored knight could sit up, wave its arms, and move its head via a flexible neck while opening and closing its anatomically correct jaw.[11] It made sounds to the accompaniment of automated drums. Studies ongoing at the Istituto e Museo di Storia della Scienza in Florence suggest that the robot had two independent mechanical systems. The first had three-degrees-of-freedom legs, ankles, knees, and hips and four-degrees-of-freedom arms with articulated shoulders, elbows, wrists, and hands.[11] It appears that the arms were designed for whole-arm grasping and not the fine hand utilization of its human inspirations. A mechanical analog-programmable controller within the chest provided the power and control for the arms. The legs were powered by an external crank arrangement driving the cable, which was connected to key locations in the ankle, knee, and hip.

It is impossible to imagine the shock and awe that would have accompanied the sight of his robotic knight moving about freely in a room of Sforza's castle in 1495. Add to this the mechanical "clack-clack-clack" that might be obscured somewhat by the booming noises of the drums emanating from the robot, and we can almost appreciate what the aging maestro himself experienced.

How did it take us of the "modern era" more than 500 years to appreciate the complexity of da Vinci's devices? There is evidence that others had detailed knowledge of Leonardo's work and that it might have been widely distributed, as has been reviewed by Rosheim's recent book.[10] Certainly, part of the obscurity can be explained by the misinterpretation of his drawings, which predate formal methods of blueprinting and manufacture. Therefore, the technical expertise to recognize complex machines were not focused on what appear as anatomic drawings and motion analysis, all interlaced within the complexity of his widespread and incomplete notebooks. But the luminary brilliance of Leonardo has continuously beckoned to those who seek the foundations of knowledge, and to conclude by quoting da Vinci one last time seems poignant: "*With what words, O Writer, will you describe with like perfection the entire configuration which the drawing here does*?" (1513).

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