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Master Thesis

The "Piano"-Arithmomètre of Thomas de Colmar - The 19th Century's Largest Mechanical Calculator

a historical investigation, 3D Modelling and an animation video

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Preface

1.1 Introduction

This work examines various aspects of the largest calculating machine of the 19th century, the so-called "Piano" Arithmometer. The machine is part of IBM's historical collection of calculating machines and was loaned to the Arithmeum for 10 years in 2019. As a result, it was restored, allowing for a profound insight into its mechanics. The precise documentation of the parts enabled the didactic analysis and historical comparison of the calculating machine, which is extensively discussed in this work.

In addition to the main section on its functionality, this work focuses on the comparison and developmental history of Thomas' calculating machines. This is also illustrated and methodically elaborated through the use of the free 3D graphics suite Blender and the creation of an animated film.

The goal of this work is to create the most accurate and faithful reproduction of the machine using a 3D model. The components of the calculating machine were accurately recreated in Blender based on the meticulous preparatory work done during the restoration. A particular challenge was the modeling of the numerous ornaments, for which a photoscanning technique was applied.

After an introduction to the topic and a brief historical contextualization, the second chapter presents the builder of the Piano Arithmometer, Charles-Xavier Thomas de Colmar, and explains his motivation for constructing a calculating machine. The following chapter encompasses the main part of this work, the Piano Arithmometer, where the used components and their functions are explained. Furthermore, an investigation is conducted into how the construction of this particular exemplar came about.

Chapter four delves into the mechanics of all known Arithmomètre calculating machines up until 1855, providing a detailed comparison.

The fifth chapter focuses on the use of the graphic programs Blender and Metashape, which were employed to create the 3D model and produce an educational animation film.

In the conclusion, the results of this work are summarized, and an outlook on further research is provided.

1.2 Temporal context

Even before Charles-Xavier Thomas de Colmar filed his first patent, various inventors had conceived and realized computational aids and calculating machines. This, coupled with the close connection to clockmaking, explains why certain specific components and mechanisms can be found in many calculating machines. Undoubtedly, Thomas was already aware of the principle of the stepped drum invented by Leibniz in the late 17th century. In his first patent, Thomas used stepped drums for the mechanical storage of numbers. Building upon this principle, he designed his subsequent calculating machines, which, after a long period of development, made serial production possible.

Until this invention, calculating machines were mostly built as unique pieces or luxury items. The following machines, which also utilized the stepped drum as their mechanical number storage, are worth mentioning in this context:

- The first four-species calculating machine with stepped drums, created by the philosopher, mathematician, and polymath Gottfried Wilhelm Leibniz in 1671.
- The first four-species calculating machine to be fully functional over all decimal places, invented by the pastor, astronomer, and inventor Philipp Matthäus Hahn in 1774.
- The first four-species calculating machine with an interchangeable positional numeral system, developed by Johann Helfrich Müller in 1783.

Only 76 years after Hahn's fully functional calculating machine, Thomas introduced the calculating machine that initiated serial production. Driven by the industrialization in the 19th century, the demand for solutions to computational problems increased significantly. It was precisely during this time that Charles-Xavier Thomas provided a remedy with his design, achieving high production and sales figures. For the first time in history, calculating machines were commercially marketed. This trend continued even after Thomas's death, with many other inventors joining the sales by either copying or further developing the machines. One of the most renowned centers of the calculating machine industry in this context is the Saxon town of Glashütte.

With the increasing distribution through serial production, numerous adaptations and new designs for calculating machines were introduced to the market. Furthermore, over time, there was a need for calculators to be portable, enabling calculations to be performed anywhere. As a result, increasingly smaller calculating machines were designed. One exemplary case is the Curta, invented by Curt Herzstark in the 1940s. Similar to Thomas, Müller, Hahn, Leibniz, and many other calculating machine inventors, the Curta employed the principle of the stepped drum and compressed over 200 years of calculating machine history into a small, portable device before the era of machine electrification began historically.

FIGURE 2.1: Portrait of Charles-Xavier Thomas de Colmar, 1820 [BSEIN, 1920]

Chapter 2

Historical Investigation

2.1 Biography

Charles-Xavier Thomas originates from a Burgundian family originally from Auxerre, dating back to 1281 with a person called "Messire Thomas". During the Thirty Years' War around 1634, the family relocated over 300 kilometers eastward to Alsace and settled there. [Arnold, 2006]

After the war ended in 1648, the Treaty of Westphalia granted most of Alsace to France. Yet, the region remained outside France's customs border. This allowed for a cultural and economical flourishing during the following 140 years. [Britannica, 2017]

FIGURE 2.2: Colmar, Petite Venise ("Little Venice"), Drawing by Charles Pinet (1867-1932) [Pinet, 1867–1932]

Charles-Xaviers parents, Joseph Antoine (⋆ 08.02.1758, † 11.04.1831) and Francoise Xaviere Thomas (⋆ 1759, † 01.05.1817) married on the 12th of November 1781 and moved to their new home in Colmar, the heart of the alsacian wine region. The city was characterized by charming half-timbered houses, cobblestone streets, and picturesque canals running through the town (see Figure 2.2). Joseph Antione studied medicine and was working as a doctor in Colmar. Later, in 1793, he went to the nearby city Rouffach to work as a municipal councillor. In his new function, he was committed to reorganize the city's hospice, introducing soup kitchens for the poor, fighting against beggary, relocating the cemetery outside the city walls and improving the roads and sewers. Francoise and Joseph had three children. Charles-Xavier was born on the 5th of May 1785.

After finishing his studies, he briefly worked for the French government. Subsequently, Charles-Xavier Thomas had commenced his career in the Napoleonic army, like most personalities of his time, who later made a name for themselves. He was appointed as a "Garde Magasin des Vivres" (storekeeper of supplies) for the French army in 1809 when he was 24 years old. He served under Marshal Soult in Spain and was entrusted with the management of the supplies and provisions for the army's headquarters in Seville.

In Seville, Charles-Xavier met a young girl from a noble and wealthy family, Francisca de Paula, also known as Frasquita, Garcia de Ampudia Alvarès y Valdès, Countess of Ampudia (⋆ 25.11.1795, † 1874). Charles-Xavier and Frasquita likely got married in Seville around 1810. By marrying into a noble family, Charles-Xavier sought to acquire a title of nobility for himself. He would later be known as Thomas de Colmar. Their first son is born in December 1811 in Seville.

Charles-Xavier rejoined the army in Madrid, and was then appointed as the storekeeper for all the combined armies in Vitoria in the Basque country of Spain. He later moved to Bayonne with the army, and was even appointed as the inspector of supplies.

Thomas did exceptionally good work in his military positions and received a lot of recognition. In documents related to him kept in the archives of the Historical Service of the Army, at the Château de Vincennes, Charles-Xavier Thomas is praised for his services to the administration. In a biography, "La Vie en Alsace" by J. Joly, published in 1932, it is written that *"Mr. Thomas displayed intelligent and tireless activity in his various functions, thanks to which the provisioning of the armies was always largely ensured, even at the most critical times."* (translated from [Joly, 1932, p. 130]) [Arnold, 2006]

Alongside his work for the french army he realized the future potential of the insurance industry. Insurance companies had been operating in England since 1765, so Thomas went there to study them and quit his military career. Upon his return to France, he was one of the first to introduce the principles of insurance and proclaim its benefits. In May 1819 he became the General Director of the Insurance Company "Le Phénix," (french for: "The Phoenix") in Paris. [Soleil, 1929, p. 4][Arnold, 2006]

Although Thomas significantly influenced the development of the French insurance industry throughout his life, the majority of historical reports about him is due to his mechanical inventions. The first ideas for the invention of a calculating machine probably arose in him due to the complex calculations required for supplying the troops in Spain. This incentive was now further reinforced by the increasing computational workload for managing his insurance company. This resulted in the submission of his first patent in 1820. [Thomas, 1820]

Nonetheless, he could not freely apply his personal concepts at "Le Phénix", which quickly lead to his exit from the company. It took a full ten years before he was finally able to put his plan into action. He established his own company in 1829: The Fire Insurance Company "Le Soleil" (french for "The Sun"), whose headquarters would be located at 13 Rue du Helder. With his company, Thomas de Colmar laid focus on fire insurance and assumed the position of Director General until his death. [Soleil, 1929, p. 4]

FIGURE 2.3: Portrait of Charles-Xavier Thomas de Colmar in:
Centenary of "Le Soleil" 1829-1929 [Soleil, 1929, p. 5]

Thomas de Colmar had a genuine philanthropic concern and considered insurance as a blessing for humanity. He introduced numerous innovations that often became standard in the insurance industry, for example: Contracts with unlimited terms and automatic renewal clause and fire coverage maintained even in case of riots or wars. High-performing employees were rewarded with bonuses. He even offered his new customers to handle all the formalities for the termination of their previous contracts with other insurance companies free of charge. [Arnold, 2006]

The first years after the foundation of "Le Soleil" were successful and delivered encouraging results. Thomas expressed himself very positively at the first shareholder meeting in 1831. However, several disturbances arose during the 1830s, which caused trouble for the company.

In 1832, the cholera outbreak completely paralyzed business in Paris for several months, with several employees of the company falling victim to the disease and the date for the shareholders' meeting being postponed. [Soleil, 1929, p. 11-12]

In the year 1834, there were riots in Lyon. The conflict was a significant uprising of silk workers against their employers and the government, resulting in violent clashes and ultimately suppression by military forces. This became known as the "bloody week", with a number of buildings and city districts heavily damaged or completely destroyed. The riots claimed over 600 victims. [Gadagne, 2020]

The economic crisis, which was caused by these riots, affected the company's business and in 1834 an appeal for 200 francs per share had to be made. The number and extent of the claims made 1836 a catastrophic year for all insurance companies and it was only in 1839, ten years after its foundation, that Soleil was able to pay a dividend to its shareholders after repaying the 200 francs raised on each share in 1834. [Soleil, 1929, p. 11-12]

Thomas had put his work on the Arithmomètre on hold since the introduction of its first model in 1821, most likely due to the turbulent times he was facing. It wasn't until the crisis of the 1830s had been overcome that Thomas was able to fully unleash his potential once again.

In 1843, he founded a second insurance company, "Compagnie de l'Aigle" and continued working on his invention after 1846. His machine's sales appeared to be off to a slow start, but he had enough financial backing from his insurance companies to move forward with his passion project. The Arithmomètre seems to be truly functional and marketable since 1850. Thomas de Colmar offered specially decorated copies of his machine to several crowned heads, including Napoleon III., Pope Pius IX and Czar Nicholas I. among many others. In return, he received congratulations, gifts, or honorary distinctions. This served primarily to increase the publicity of his invention and was a great success. In 1851, Thomas de Colmar received the gold medal of the Society for the Encouragement of National Industry, as well as a silver medal at the London Exhibition. In 1857, Thomas de Colmar was appointed Officer of the Legion of Honor by an imperial decree. According to the "Moniteur Universel" of August 15, 1857, he received this honor in recognition of his invention of the arithmometer. [Arnold, 2006]

FIGURE 2.4: Château De Maisons [Rouargue, 1838]

In 1850, Thomas de Colmar, who had gained a lot of wealth by the time, acquired the "Chateau de Maisons" (Maisons Castle, see Figure 2.4) and the 33 hectares that make up what is called the Petit Parc. Thomas de Colmar's wealth allowed him to carry out numerous renovation works on the property. He restored the entire property, lived there with his family, and hosted sumptuous parties. In 1860, Emperor Napoleon III. and Empress Eugenie were his guests. [Arnold, 2006]

FIGURE 2.5: Thomas de Colmar in 1868 [Soleil, 1929, p. 47]

Thomas de Colmar had every reason to be proud of his work. He passed away in March 1870 at the age of 84, still holding the title and responsibilities of general manager until his last day. At that point, approximately 800 of his Arithmometers had been sold. [Sebert, 1879, p. 406] [Soleil, 1929, p. 14]

After Thomas' death, his fourth son Louis Nicolas Andre Thomas took over the business of the insurance company "Le Soleil". He also continued the production of the Arithmometer. [Arnold, 2006]

The Société d'Encouragement awarded Mr. Thomas de Colmar their grand gold medal. A hundred years later, the society commemorated the significant day when "the first industrial calculator" was presented for their consideration, as mentioned in their bulletin. During the celebration held for this occasion, Maurice d'Ocagne, professor at the École Polytechnique, conveyed his thoughts as follows: [Soleil, 1929, p. 46-47]

"Indeed, we know that throughout his long career and regardless of his multiple occupations, Mr. Thomas de Colmar never ceased to work on improving his invention. He had the satisfaction of seeing it applied not only in the majority of insurance companies but also by the artillery services at the Ministry of War and the Ministry of the Navy, by railway companies, and soon by most financial companies." (translated from [Soleil, 1929, p. 46-47])

2.2 Motivation for inventing, building and selling calculation machines

Wie vorher schon gesagt: Durch seine Zeit beim Militär kamen die ersten Ideen. Mit der hinzukommenden Arbeit in seiner Versicherungsgesellschaft wurde das Bedürfnis nach einer zuverlässigen Rechenhilfe noch stärker. 1820 dann erstes Patent und 1-2 Jahre Vorantreiben der Arbeiten in diesem Bereich. Bisherige Maschinen waren nur Kuriositäten.

Die 1830er waren schwer zu überwinden, Arbeiten an der Erfindung eingestellt.

Parallel dazu: Die Arbeiten von Prony an seinem Logarithmus-"Mammut-Projekt" begeisterten Babbage, der hiervon in seiner Veröffentlichung von 1832 schreibt (On the Economy of Machinery and Manufacture). Babbage returned to the Prony logarithm project as his primary proof that the principles of the division of labor could be applied “both in mechanical and mental operations.” Indeed, Babbage argued, the calculations of Prony’s third class of workers “may almost be termed mechanical,” even if they hadn’t been done by actual machines. [Daston, 2018]

Vielleicht sah Thomas auch hierin seine Chance diese Prinzipien auf sein Lebenswerk im Bereich des Versicherungswesens anzuwenden, wo schon seither viele Berechnungen getätigt werden mussten. Villeicht wollte er Prony’s Pyramidensystem in seine Branche übertragen, wozu die Weiterentwicklung des Rechengerätes noch einmal an Wichtigkeit gewinnen würde.

Außerdem auch in anderen Berichen (Referenz zu Einleitung mit Ingenieursschulen): With the Industrial Revolution of the 18th century came a widespread need to perform repetitive operations efficiently. With other activities being mechanized, why not calculation?

Über den ganuen Grund der Wiederaufnahme der Entwicklungsarbeit des Arithmometers lässt sich nur spekulieren. Jedoch steht fest, dass die Arbeiten nun in deutlich erhöhtem Maße fortgesetzt wurden. Immer weiter Verbesserungen und neue Modelle. Ab 1850 dann Serienproduktion mit viel Marketing. 1865 letztes Patent von Thomas, danach reichten seine Kapazitäten wahrscheinlich nicht mehr aus, u.A. durch seine Krankheit und sein hohes Alter. [Arnold, 2006][Thomas, 1865]

Chapter 3

The Piano Arithmomètre

FIGURE 3.1: The Piano Arithmomètre (rendered 3D model) [Nöhre, 2023]

The Piano Arithmomètre (see Figure 3.1) played a special role in the public appearance of the whole Arithmomètre series and was a milestone in their history of development. This chapter explores how Thomas' calculating machines were presented in the media in their time and what led to the construction of the Piano in particular. Afterwards, the mechanics are explained in detail. This work is based on the sources collected by Valéry Monnier and made available on his Website [Monnier, 2023]. With this online library he provides an excellent overview, as well as most of the primary source texts themselves. Many of the original texts are also available at "Gallica", the digital library of the Bibliothèque nationale de France [BnF, 2023].

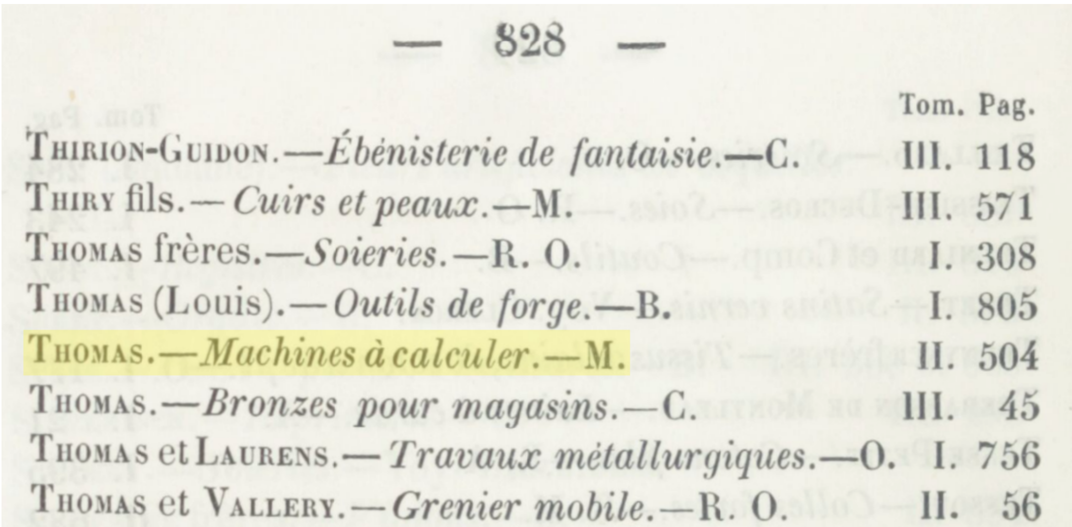
3.1 Public appearance

Charles-Xavier Thomas first made the Arithmomètre public by patenting its design in 1820. Shortly afterwards, in 1821, Thomas presented a functioning machine to the Société d'Encouragement pour l'Industrie Nationale (SEIN), resulting in two scientific reports. In its early years, the Arithmomètre did not leave the scientific realm. It only appeared in patent specifications and journal reports, thus remaining unknown to the general public. [Francoeur, 1822][Hoyau, 1822][Thomas, 1820] These reports are very technical and seem objective and descriptive. The SEIN was founded in

1801 and consists of different committees, dividing the scientists according to their specialization. The commitees award annual prizes to encourage the France's national inventors and entrepreneurs of France. [SEIN, 2023, Secions: History & Mission] The SEIN's reputation makes the reports trustable sources.

Thomas shrouded his invention in silence for the following 20 years. He was most likely busy with his business ideas and family planning. During this time he founded two insurance companies. The reports about his insurance companies were already cited in chapter 2. [Soleil, 1929, p. x]

After the long period of quietness, Thomas continued working on the Arithmomètre in the 1840s. He presented it on an exhibition in 1844, placing it into competition with other mechanical devices for the first time. But the jury rated the machine inferior to many other presented devices. One silver medal and four bronze medals were awarded to inventors in the sub-category "Mesures Diverses. Compteurs et Machines a Calculer" *(translated: Various measurements. Counters and calculating machines)*. One of the bronze medals is granted to Didier Roth, presenting multiple of his calculating machines. Thomas only ended up in the honourable mentions section (see Figure 3.2) among eleven other inventors. This is documented in the jury report of the 1844 "Exposition des produits de l'industrie francaise en 1844", reported by M. Pouillet in the second section "Instruments de Précision" *(translated: precision instruments)* [Pouillet, 1844, pp. 500–505]. The devastating jury rating was certainly not the appreciation he was seeking, leaving the invention with no more public recognition than before.



— 828 —

	Tom.	Pag.
THIRION-GUIDON.—*Ébénisterie de fantaisie.*—C.	III.	118
THIRY fils.—*Cuirs et peaux.*—M.	III.	571
THOMAS frères.—*Soieries.*—R. O.	I.	308
THOMAS (Louis).—*Outils de forge.*—B.	I.	805
THOMAS.—*Machines à calculer.*—M.	II.	504
THOMAS.—*Bronzes pour magasins.*—C.	III.	45
THOMAS et LAURENS.—*Travaux métallurgiques.*—O.	I.	756
THOMAS et VALLERY.—*Grenier mobile.*—R. O.	II.	56

FIGURE 3.2: Thomas' Mention on page 828 in the alphabetic table of all Exposition participants. The letter "M." after his name indicates the "honourable mention" he received (as stated on page 709) [Commission, 1844]

Thomas however, did not stop trying to get good publicity for his project. Being outrivaled by another constructor of calculating machines sparked his ambition even more. The setback of the 1844 exhibition lead to the most labor-intensive years in the history of the Arithmomètre. Thomas had luck finding a new, talented watchmaker named Piolaine from Neuilly, who was further refining the design of the Arithmomètre from now on. This is stated by Maurice d'Ocagne in a scientific review of 1935 about Thomas' inventions. [d'Ocagne, 1935, pp. 783–785]

Thomas presented Piolaine's updated version of the Arithmomètre with many improvements at the next big exhibition in France in 1849. The machine was patented in the same year [Thomas, 1849]. Once again, the original reports (written by M. Mathieu) of the exhibition jury are available as primary source of information. This ensures the reliability of the source and resembles the unaltered opinion of the jurors [Mathieu, 1849]. Thomas is again matched with competitors in the sub-category "Mesures Diverses. Compteurs et Machines a Calculer" in the second section of the "Machines" chapter. At first glance, his efforts seem to be successful. Thomas was awarded one of the five silver medals in the sub-category and three pages in the jury report were dedicated to his machine. [Mathieu, 1849, pp. 549–551]

But this time, in contrast to the previous exhibition in 1844, there was also a gold medal awarded among the devices Thomas was competing with. The winner of the prize was another calculating machine, the "Arithmaurel", devaluating Thomas success [Mathieu, 1849, pp. 542–548]. The machine was built by the watchmakers Jean Jayet and Timoléon Maurel. With the Arithmaurel, they realized a calculating machine capable of automatic multiplication. The machine's mechanical design was judged far superior to the Arithmomètre, using planetary gear units and a large number of filigree components.

Nevertheless, the Arithmomètre appeared in an illustrated french magazine for one of the first times: The "L'illustration: Journal Universel" devoted a large page and a drawn picture (see Figure 3.3) to the new calculating machine by Thomas. The reporter writes about the ingenious design, long time of development and how easy it is to use the machine. It is not clear if the idea for writing the article was conceived by one of the reporters themselves or if Thomas also took initiative to get public attention this way. The following except from the article states that the reporters had a copy of the Arithmomètre at their office, which raises the question if it was brought there on behalf of Thomas himself:

[...] la machine à calculer que quelques-uns de nos lecteurs ont pu voir à l'exposition de l'industrie et dont nous avons eu dans notre cabinet un exemplaire réduit pouvant donner instantanément des produits de cinq chiffres par cinq chiffres.[L'Illustration, 1849, p. 128]
(translated: [...] the calculating machine that some of our readers were able to see at the industrial exhibition and of which we had in our office a reduced copy capable of giving instantaneous products of five digits by five digits.)

At the end of the article it is also stated that Thomas will begin the fabrication of his machines and that they can be bought for 100 or 125 francs. This further hardens the suspicion that Thomas took action to start promoting the Arithmomètre to the public in different types of media. However, this cannot be verified with certainty, since there is no concrete evidence of his intervention. His action becomes much clearer in later texts.

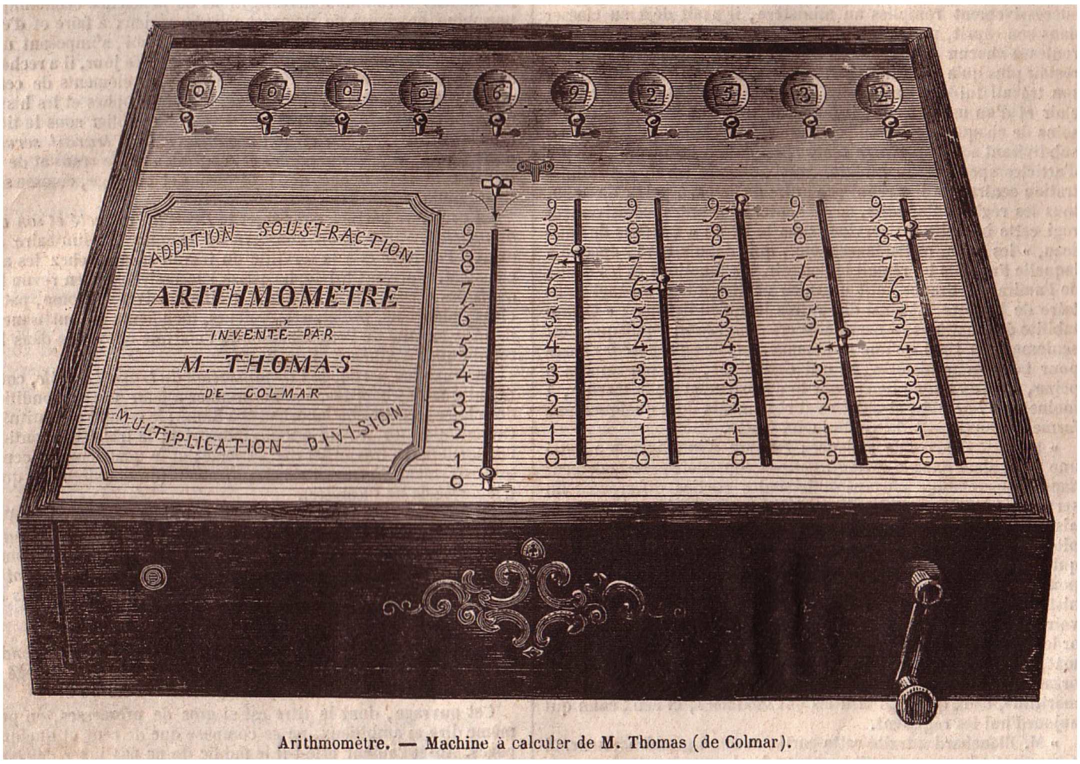


FIGURE 3.3: Drawing of the 1848 Arithmomètre in the "L'illustration: Journal Universel" [L'Illustration, 1849, p. 128], Source: Valéry Monnier [Monnier, 2023]

Thomas also sought to bring attention to the Arithmomètre outside of France. After making further improvements to the design and obtaining a French patent in 1850, he also also filed and received a patent in the United Kingdom and Belgium in 1851. He then presented the new version of his machine at the 1851 "Great Exhibition of the Industry of all Nations" in London. In return, he was awarded with a prize medal by the jury and a report of one page in the official catalogue. [IllustratedExhibitor, 1851, p. 505] This time, he was competing with another calculating machine by Isarael Abraham Staffel from Warsaw. His competitor also received a prize medal and was featured in the exhibition supplement of the Illustrated London News, a weekly released newspaper. [IllustratedNews, 1851, p.354]

In the early 1850s, Thomas raised his efforts to promote his invention across Europe by gifting special machines to a number of crowned and titled personalities. An overview of the surviving machines is maintained also by Valéry Monier [Monnier, 2023, Section: Des cadeaux "royaux"]. These dedication machines were individually ornamented to each of the presentees. In return Thomas received numerous honors and medals between 1851 and 1854. These can be found in Charles-Xavier Thomas' biographic notes, written by E. Dutilleul in 1855. With Thomas being member of the "Légion d'honneur", the biography was published in the "Histoire et fastes de tous les ordres français et étrangers" *(translated: History and splendour of all French and foreign orders)*. However, the document has to be taken with a grain of salt, as it contains many allusions to Thomas' supposed genius and states that he has not yet received the French recognition he deserves. The document reflects Thomas' setbacks regarding the exhibitions in France and raises once again the suspicion of Thomas' influence on the author. [Dutilleul, 1855]

With Thomas' demand for more recognition in his own country, as stated previously, he next aimed for the great 1855 "Expositon Universelle" (world exhibition) in Paris. To surpass his opponents Maurel and Jayet, he was involved in some preparations beyond constructing his next machine. The scientific review "Cosmos" released an article written by F. Moigno, in which he clearly sides with Thomas and devaluates the Arithmaurel's former triumph. He says that:

1. *[...] parce qu'en raison des immenses difficultés de sa construction, leur machine même usuelle coûtera toujours trop cher pour qu'elle puisse se répandre et s'imposer comme nécessaire ou grandement utile.* [Moigno, 1854, p. 3] *(translated: [...] because, due to the immense difficulties of its construction, their machine, even the usual one, will always cost too much for it to spread and impose itself as necessary or very useful.)*

2. *[...] toujours est-il que l'Arithmomètre se perdit complètement dans l'auréole étincelante qui entoura l'Arithmaurel [...]* [Moigno, 1854, p. 5] *(translated: [...] but the Arithmomètre was completely lost in the sparkling halo that surrounded the Arithmaurel [...])*

3. *Lequel l'emportera? On sera peut-être grandement surpris de nous voir annoncer que le vainqueur pourra très-bien être M. Thomas de Colmar.* [Moigno, 1854, p. 8] *(translated: Who will win? It may come as a great surprise to see us announce that the winner could very well be Mr. Thomas de Colmar.)*

Furthermore, Thomas is celebrated splendidly in a 100-page long booklet by Jacomy Régnier. The author writes about the history of mechanical calculating and even the arithmetic itself. But with Thomas' name being mentioned over 80 times throughout the text, it quickly turns out purely as promotional material in Thomas' favor. [Régnier, 1855]

Thomas wanted to emphasize that his mechanism was superior to the Arithmaurel's and that he had no trouble extending the machine's capacity. Therefore, the Piano Arithmomètre was created: 2 metres wide, with a capacity of 30 digits in its result register and 15 setting sliders. A formidable piano-shaped enclosure covered in golden ornamentation ensured to catch the attention of many visitors. The Piano Arithmomètre marked a milestone in the history of the Arithmomètre's promotion, as well as a mechanical milesone that Thomas reached. For the first time it was possible to create a machine of this size.

3.2 External Structure

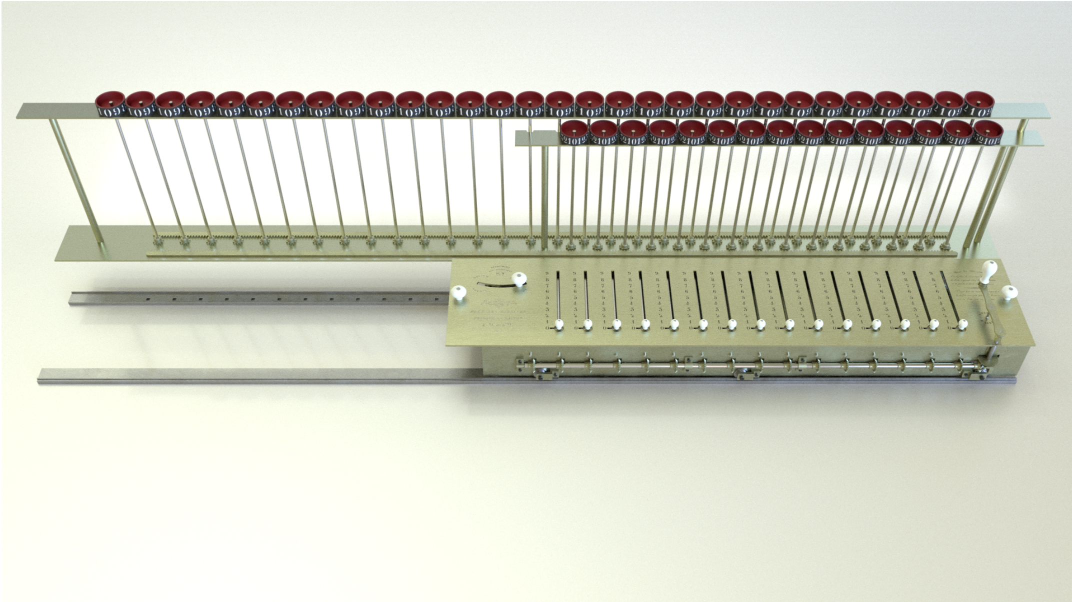


FIGURE 3.4: The Piano Arithmomètre with its enclosure removed (rendered 3D model) [Nöhre, 2023]

In this chapter, the mechanical components of the 1855 Piano Arithmomètre and their interaction are explained in detail. To get a better look inside, the 3D model allows to omit the machine's enclosure (see Figure 3.4).

The Arithmomètre is composed of two assembly groups. The lower group consists of the calculating mechanism and the 15 setting sliders. The unit is nearly 1 m wide has a depth of 310 mm while being 90 mm high. Including the top cover plate and the input sliders the height increases to 120 mm. Each one of the sliders can be set to a position from 0 to 9, according to the engraved numbers in the top cover plate. The main crank to drive the mechanism is located on the right side of the calculating mechanism; the operation control lever is located on the left side. The lever is used to switch the machine between the modes "Addition and Multiplication" and "Subtraction and Division". The lever can also be brought to the middle position to disengage the two assembly groups from each other.

The upper group contains the 30 accumulator cylinders and 15 revolution counter cylinders, together forming the result mechanism. It is 1.75 m wide, with a height of 330 mm. With this machine, Thomas made use of cylinders, because the numbers are supposed to be read from almost eye level. Since the traditional Arithmomètre is usually placed on the desk to be operated from bird's-eye view, every other model uses flat dials to display the numbers. Here, he result mechanism is mostly hollow, with long drive shafts to elevate the cylinders.

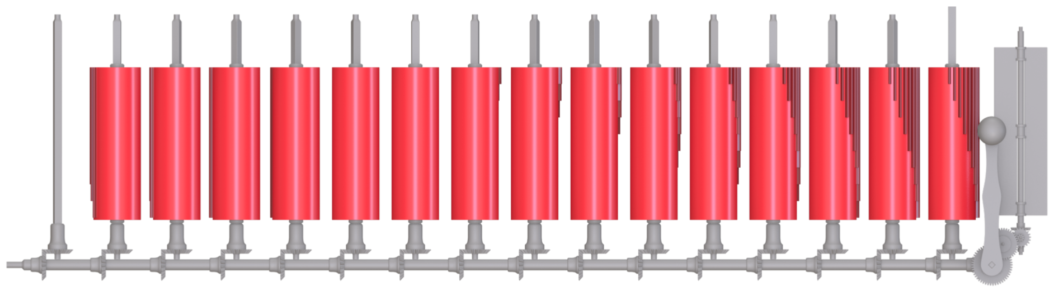


FIGURE 3.5: The main drive system [Nöhre, 2023]

3.3 Internal Mechanics

3.3.1 Drive System

The main drive system (see Figure 3.5) consists of a crank and the main horizontal drive shaft. Each of the 16 vertical square shafts is linked to the main shaft by a pair of bevel gears. The crank is also linked to a wind collector, a brass plate on a shaft. Fast rotational motion of the wind collector creates air resistance and thus smooths and slows down the user's input movement. For every rotation of the crank, the wind collector rotates 31.25 times.

3.3.2 Stepped Drum

Of the 16 square shafts, 15 are populated with a stepped drum (see Figure 3.5, colored in red). It is the main component to store numbers mechanically and differentiates machines for all four arithmetic operations from simple adding machines.

Function

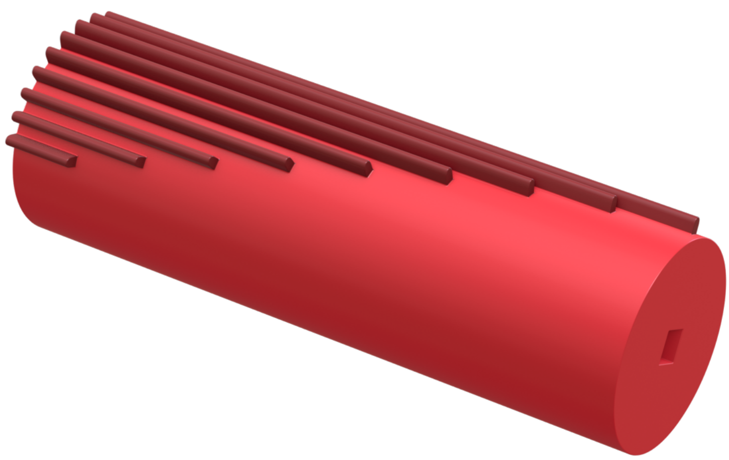


FIGURE 3.6: The stepped drum of the Piano Arithmomètre [Nöhre, 2023]

The stepped drum is a cylinder with nine cogs of decreasing length. For most stepped drums, the total length of the cylinder is divided into nine parts of equal length. The first cog extends to a length of all of the nine parts. For each of the following cogs the length decreases by one part, resulting in a sequence of $9/9$, $8/9$, $7/9$, ..., down to $1/9$ of the cylinder's length. For the Piano's stepped drums (see Figure

3.6), this mostly holds true, except for a minimal offset of the first cog, which serves no particular purpose.

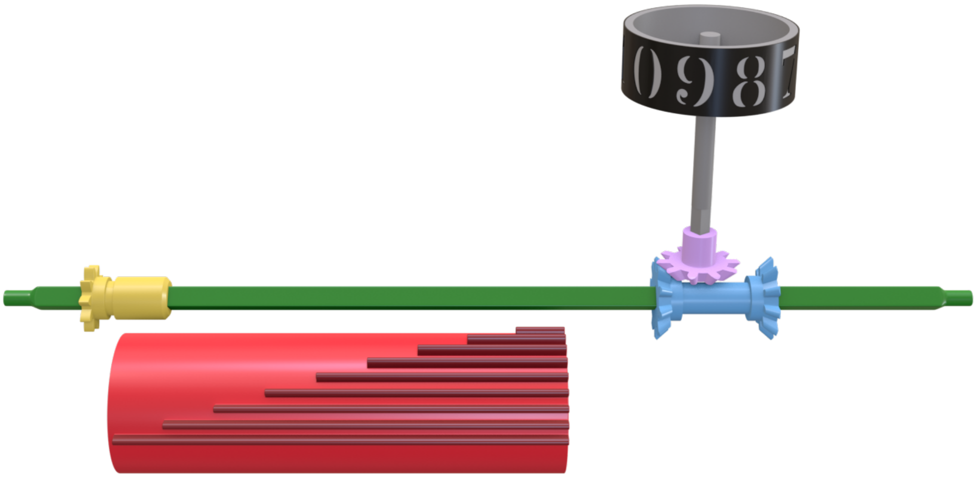


FIGURE 3.7: Stepped drum mechanism for one digit, viewed from the right side [Nöhre, 2023]

The setting gear (see Figure 3.7, colored in yellow) can be slid along a square shaft (colored in green), which is linked to the result mechanism. The sliding motion is originating from the setting sliders on the top cover plate. By setting the slider to a specific number, the setting gear is moved accordingly. This enables the setting gear to engage with a different number of teeth on the stepped drum. Setting gears have ten teeth, which correspond to the ten digits one of the cylinders of the result mechanism. When the crank is turned, all stepped drums are turned simultaneously. Each cog of the stepped drum, which meshes with the setting gear, rotates it by 36 degrees. The motion is transmitted to the result mechanism and advances it by one digit.
For example: The input slider on the top cover plate is moved to the number 4. The setting gear underneath the top cover plate is thus moved by the same distance. At this section, the stepped drum has four cogs, which mesh with the setting gear when the crank is turned, and rotate it by 4×36 degrees to a total of 144 degrees. The result mechanism is advanced by the same 144 degrees and shows the number 4.

Historic Background

The stepped drum originates back to the famous mathematician and philosopher Gottfried Wilhelm Leibniz. He was the first to explore how to store numbers mechanically. He invested a lot of time in inventing and constructing his calculating machine and submitted the plans in 1673 to the Royal Society of London. [Tweedale, 1993, pp. 38–42] The original form of his stepped drums is visible in Figure 3.8.

3.3.3 Exapmle: Simple Addition without Ten's Carry

As an example, a simple addition without a ten's carry is performed: 48+20. First the number 48 is entered by sliding the input slider of the rightmost column to number 8 and the slider left of it to the number 4. The crank is turned one time and the

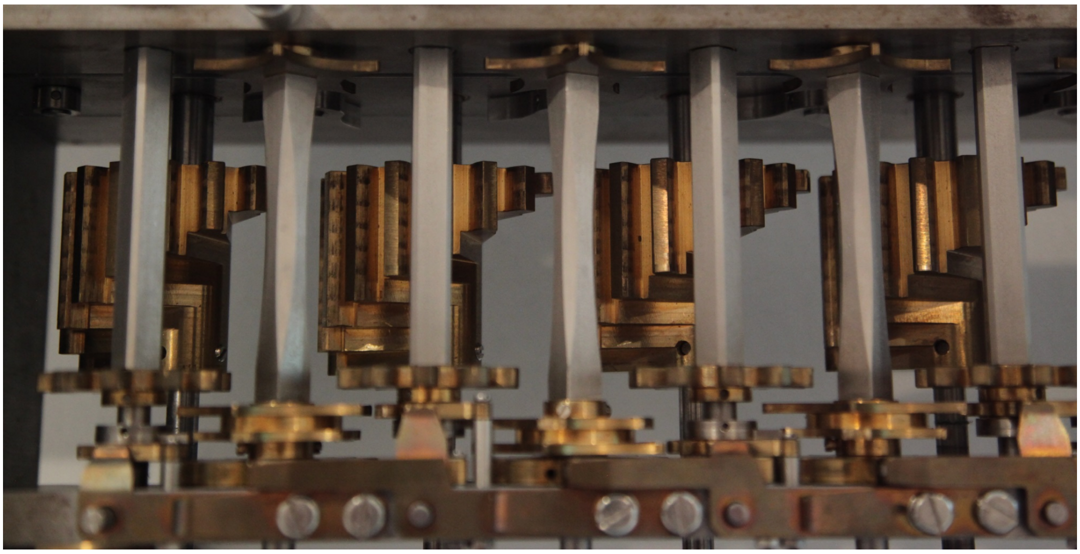
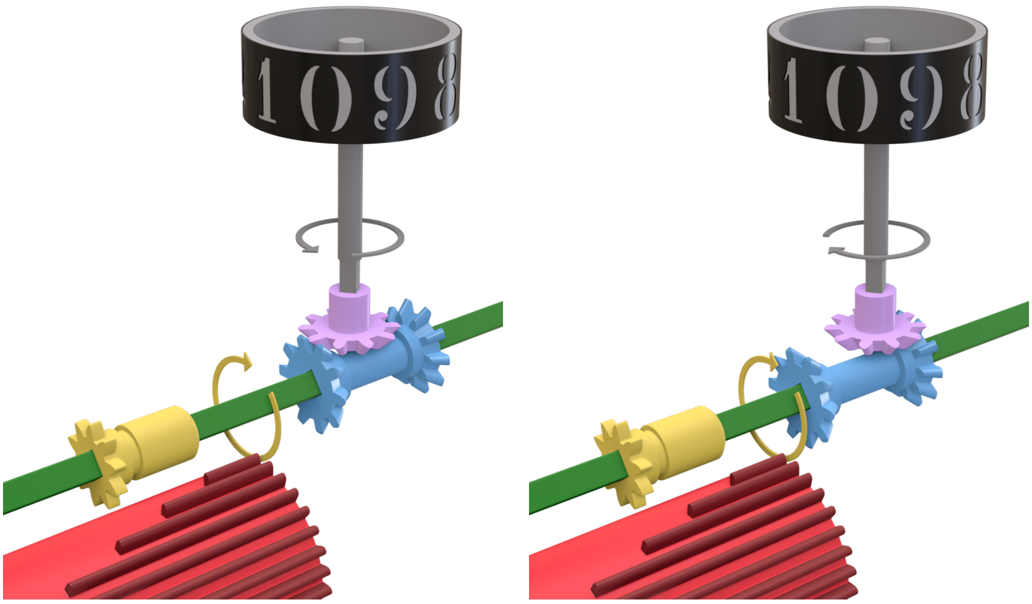


FIGURE 3.8: Leibniz' stepped drums in the replica of his Machina Arithmetica in the Arithmeum Bonn[Nöhre, 2023]

number appears in the result mechanism's display. To input the number 20, the rightmost slider is set to 0 and the slider left of it to the number 2. By turning the crank, the two cogs of the stepped drum now advance the setting gear and thus the result cylinder by two digits. Because it was already positioned to show number 4, the numbers are added. The result 68 is now visible in the result mechanism.

3.3.4 Operation control



(A) Additive position (double-bevel gear moved to back)

(B) Subtractive position (double-bevel gear moved to front)

FIGURE 3.9: The double-bevel gear mechanism [Nöhre, 2023]

The bevel gears in Figure 3.7 (colored light blue and lilac) are responsible for linking the calculating and result mechanism together. Upon closer inspection, the special form of the lower (light blue colored) bevel gear becomes noticeable. The component consists of two bevel gears, opposed to each other and connected together. Thus, it is named the double-bevel gear. Up until now, the double-bevel gear was only used in its back position (when viewing the machine from the front, corresponding to the position in Figure 3.7). In this position only the front part meshes with the result mechanism, turning it in additive direction. The double-bevel gear can also be moved axially along its shaft (green) to the front. In this position the second bevel gear on the back meshes with the result mechanism, turning it in the other, subtractive direction. Figure 3.9 illustrates the two different positions side-by-side.

The setting gear is rotated by the stepped drum's cogs. This motion has always the same direction. Thus, the setting gear's green shaft is always rotating clockwise (indicated by the yellow arrow in Figure 3.9). If the double-bevel gear is in its back position (see Figure 3.9a), the additive, front part meshes with the result mechanism. The result mechanism is rotated counter-clockwise, counting up. If the double-bevel gear is in its front position (see Figure 3.9b), the subtractive, back part meshes with the result mechanism. The result mechanism is rotated clockwise, counting down.

All double-bevel gears are positioned onto a guide rail (see Figure 3.10, which is moved back and forth by the operation control lever on the left side of the calculating mechanism. The right position of the lever moves the guide rail together with the double-bevel gears to the back. The machine is in "Addition/Multiplication" mode. Moving the lever to the left, the guide rail is moved to the front, engaging the other side of the double-bevel gears with the result mechanism. The machine is in "Subtraction/Division" mode.

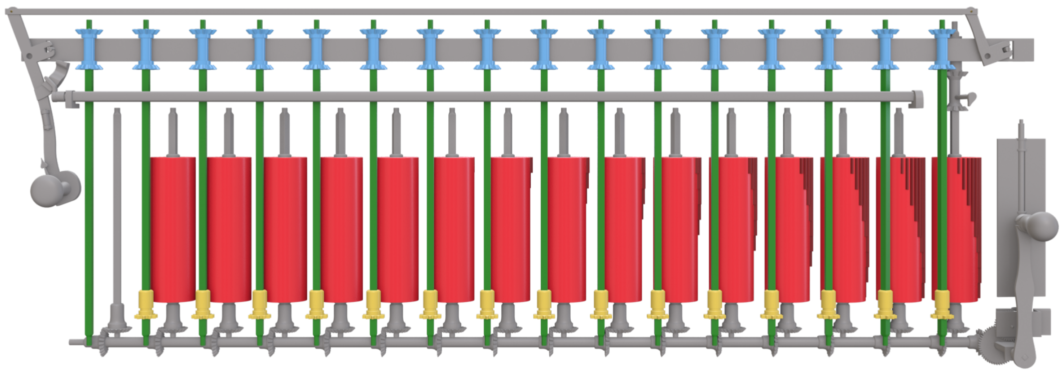


FIGURE 3.10: The main drive system and the operation control [Nöhre, 2023]

3.3.5 Revolution Counter

The Piano is the first Arithmomètre with a multi-digit revolution counting mechanism. As stated in section 3.2, it has 15 display cylinders and is located below the result display. For every rotation of the crank, the revolution counter cylinder above the rightmost setting slider is advanced by one digit. The direction of the rotation is also reversed by the operation control mechanism. Because the revolution counter has to count upwards in both directions (in "Addition/Multiplication" mode and in "Subtraction/Division" mode alike), the layout of the cylinders has to be different from the result display. Unlike the result display cylinders with ten numbers (0-9), the revolution counter cylinders have two sets of numbers. One set advances in clockwise direction, the other set advances in counter-clockwise direction. The two sets meet at the numbers 0 and 9, resulting in 18 numbers on a cylinder in total. Because of the ability to perform carriage shifts, it is never necessary to rotate the crank more than nine times for any decimal place. That is why there is no need for a carry mechanism in the revolution counter.

3.3.6 Ten's Carry

The centerpiece, defining a calculating machine and distinguishing it from mere calculating aids, is the ten's carry mechanism. A ten's carry occurs either when a decimal place in the result mechanism counts in additive direction beyond the number 9, or when it counts in subtractive direction below the number 0. As a result, the adjacent decimal place (to the right) needs to be increased or decreased by one digit accordingly. In contrast to Thomas' earlier machines, the Piano Arithmomètre was equipped with a ten's carry mechanism working almost entirely without springs.

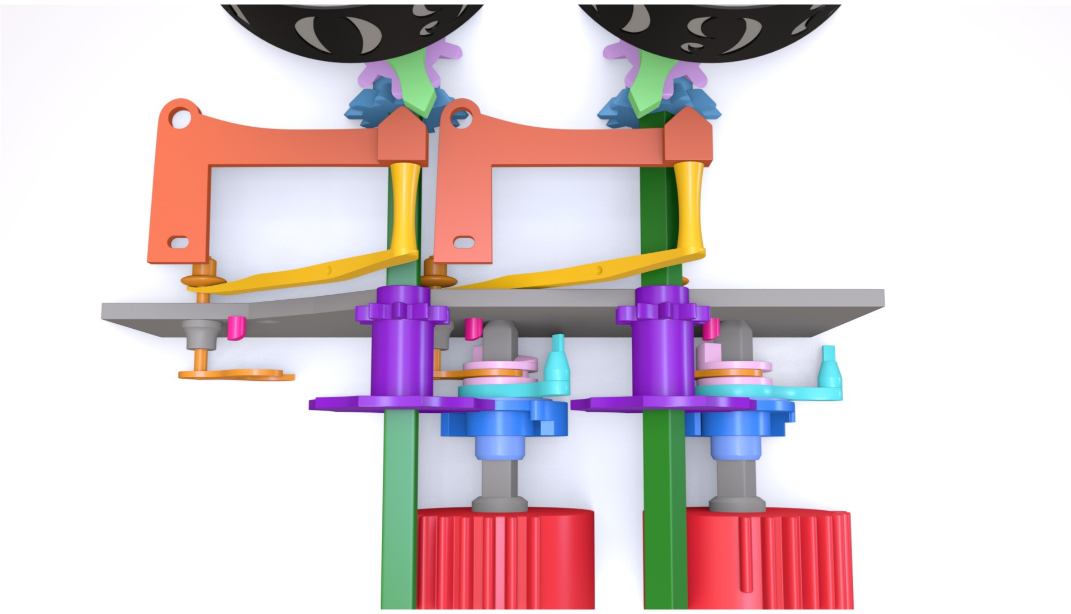


FIGURE 3.11: The Piano Arithmomètre's ten's carry mechanism [Nöhre, 2023]

In the Piano Arithmomètre, Thomas implements a mechanism that first prepares and then executes a ten's carry when it occurs. Both parts of the mechanism are divided by the middle plate of the frame. Both steps are performed within one rotation of the crank.

Every decimal place of the result mechanism is equipped with a carry finger (Figure 3.11, colored mint green). When a transition from 0 to 9 or 9 to 0 occurs, the carry finger pushes against a horizontal lever (Figure 3.11, colored dark orange). In sequence, the horizontal lever pushes against a vertical lever (Figure 3.11, colored yellow), which pulls a retaining claw (Figure 3.11, colored orange). The retaining claw is located on the other side of the frame plate and has a rod, reaching through the plate, connecting the preparation to the execution mechanism. When the vertical lever pulls on the end of the rod of the retaining claw, it is moved towards the frame plate on the other side. The claw is engaged with the execution mechanism by a notch in a cylinder (Figure 3.11, colored pink), which allows the assembly to rotate while the claw stays in place.

The execution mechanism is located on the square shaft of the stepped drum of the next column. Thus, it also rotates with its corresponding stepped drum. The assembly never changes its angular offset relative to the stepped drum. It is only moved axially on the shaft. It consists of the aforementioned cylinder, a carry finger (Figure 3.11, colored turquoise) and a segmented moderating cylinder (Figure 3.11, colored azure). All of these components are bonded together and cannot move independently.

Due to the fact that earlier machines had a tendency to over-rotate when the crank is turned to quickly by the user, Thomas designed an interlocking system. He equipped the setting wheel shafts with a Maltese cross-shaped wheel. The moderating cylinder on the stepped drum's shaft is segmented in such a way, that it only allows the Maltese wheel to rotate as long as the setting gear engages with the stepped drum. The Maltese wheel has ten indentations to interlock with the moderating cylinder, again corresponding to the ten numbers on a display cylinder of the result mechanism. The Maltese wheel is connected to a carry gear, together forming a single component (Figure 3.11, colored violet)

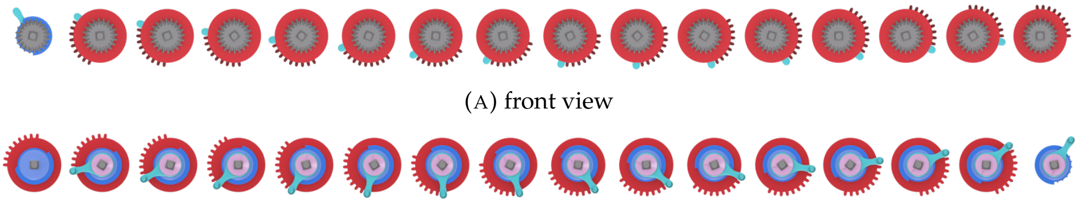
In its normal position, the carry finger passes through the gap between the Maltese cross and the carry gear. When a ten's carry is prepared, the carry finger lines up with the carry gear and engages with it during the rotation of the crank. The finger advances it by 36 degrees, which again equals one digit on a result mechanism display cylinder. The ten's carry has been performed. To return the finger to its normal position, there is a stud mounted on the frame plate near the stepped drum's shaft (Figure 3.11, colored magenta). The notched cylinder (pink) has a helical form towards the frame plate. The interaction of these components results in the whole assembly being pushed back to its normal position. On the other side of the frame plate, both levers are also returned to their resting position. Thus, all parts have returned to their initial positions after the carry has been executed.

Secondary ten's carry

A ten's carry resulting from another ten's carry is called a secondary ten's carry. For example, when adding $99 + 1$, the carry in the lowest order column is performed first, adding 1 to the second column. This results in a second ten's carry, originating from the second column, adding 1 to the third column, ultimately yielding 100 as the result.

To build a machine, which is capable of executing secondary ten's carries across all of its columns is a challenge many calculating machine designers struggled with. Thomas introduced a simple solution to this problem. He installed the stepped drums into the Arithmomètre with an angular offset to each other. From the rightmost column onward, every stepped drum and its corresponding carry finger is rotated by 18 degrees clockwise in the Piano Arithmomètre (see Figure 3.12).

This leads to the carry fingers passing the carry gears one after another and thus the ability for a ten's carry to ripple up the columns. The first two stepped drums do not need to have an offset, because there can never be an incoming ten's carry



(A) front view

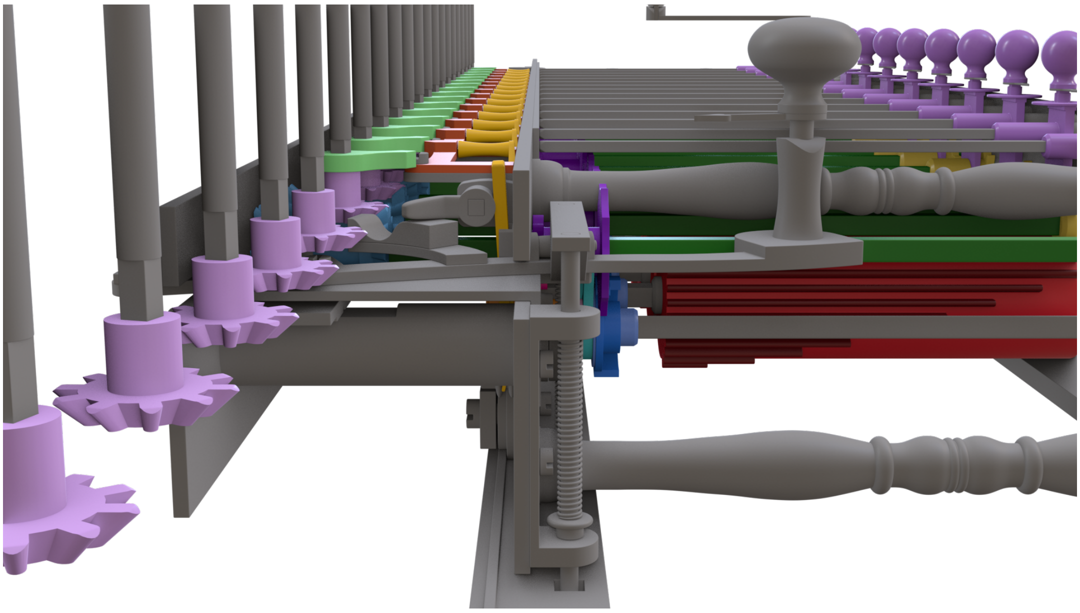
(B) back view

FIGURE 3.12: The angular offset of the Piano Arithmomètre's stepped drums [Nöhre, 2023]

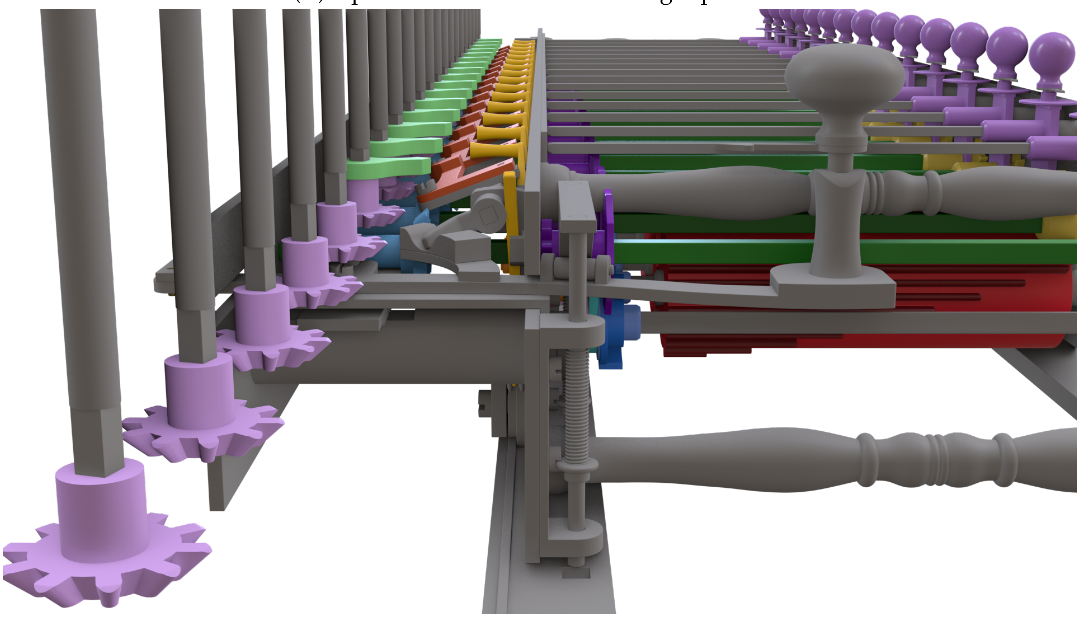
on the first, rightmost column. There is also no carry finger in the first column. In the last column there is just a carry finger without a stepped drum, which increases the range in which correct calculations are possible by one decimal place and thus a factor of 10.

3.3.7 Carriage Shift

To perform rapid multiplication and division, the calculating mechanism's position can be altered relative to the result mechanism. On the base of the wooden casing of the Piano Arithmomètre, there are two rails on which the calculating mechanism is placed using six wheels (see Figure 3.4 and 3.13). The top rail has one cutout for each decimal place the mechanism can be shifted to the left. A retaining pin near the operation control lever is placed into one of the cutouts to hold the calculating mechanism in place (see Figure 3.13, bottom middle). The retaining pin is be moved up or down based on the position of the operation control lever. When the lever is in the right or left position, the pin is in its low position, preventing the mechanism from movement during operation (see Figure 3.13a). If the operation control lever is put in between both positions, the retaining pin is lifted up and the calculating mechanism can slide freely on top of the rails (see Figure 3.13b). Because the result mechanism is not movable, the ten's carry mechanism would interfere with the sliding movement of the calculating mechanism. To circumvent these problems, Thomas implemented a folding mechanism (see Figure 3.13, top left). The horizontal levers of the ten's carry are mounted onto a horizontal shaft, which is able to rotate. The shaft has a finger on the left end, engaged with a curved segment on the operation control lever. The segment is curved in a U-shape, so that the finger of the shaft is pushed up when the operation control lever is in its right or left position (see Figure 3.13a). When the operation contol lever is in its middle position, the finger falls into the low spot of the U-shape, rotating the shaft and folding the horizontal levers downwards (see Figure 3.13b). The levers do not engage with the carry fingers in this position and can slide underneath them. With the operation control lever placed in the middle position, the retaining pin unlocked and the horizontal levers of the ten's carry mechanism folded downwards, the calculating mechanism can slide sidewards inside the enclosure.



(A) Operation control lever in its right position



(B) Operation control lever in its middle position

FIGURE 3.13: The carriage shift mechanism [Nöhre, 2023]

Chapter 4

The Arithmomètre's Evolution

This chapter aims to shed light on the transformative journey undertaken by Charles-Xavier Thomas in the development of his calculating machines. By conducting a comparative analysis of the successive machine models, the progress achieved through iterative improvements can be discerned. This work is again largely based on Valèry Monnier's knowledge, who provides a detailed explanation for all components of the Arithmomètre [Monnier, 2023, section: "Anatomie"], as well as all of the patents filed by Thomas. A timeline of all discussed models is given in the tables 4.1 and 4.2

4.1 Model 1820

Thomas filed and received his first patent on 18th november 1820 [Thomas, 1820]. To this date, no surviving example of this model is discovered. The machine consists of a calculating mechanism with four stepped drums and a setting mechanism with four input sliders and a multiplier wheel (see Figure 4.1). For the following explanation, refer to Figure 4.2.

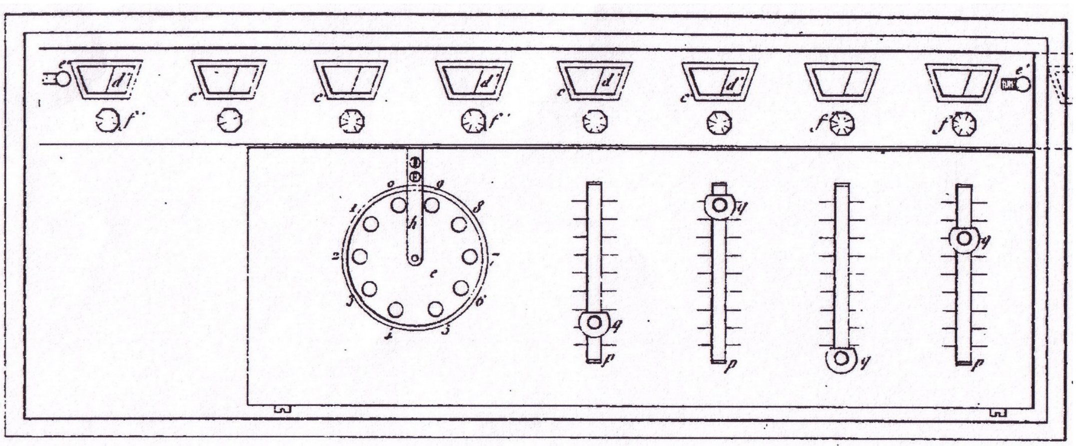


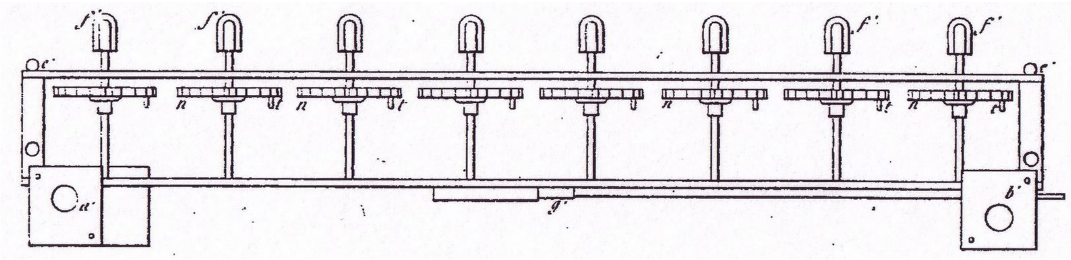
FIGURE 4.1: Drawing of the Arithmomètre in the 1820 patent [Thomas, 1820]

Drive mechanism: The machine is driven by a ribbon, wrapped around a drum *d* (4.2c, p. 29). To execute calculations, the ribbon is pulled out of the machine by the user. The ribbon drum is linked to the stepped drums by a set of spur gears. By pulling the ribbon, all stepped drums are rotated simultaneously. The ribbon drum also incorporates a spring and ratchet mechanism, which pulls back the ribbon into the machine as soon as the user releases it. As it can be seen in following machines, the uniformity of the driving force can be crucial for the machine to produce correct results. The immediate drive mechanism could lead to calculation errors, if not operated carefully.

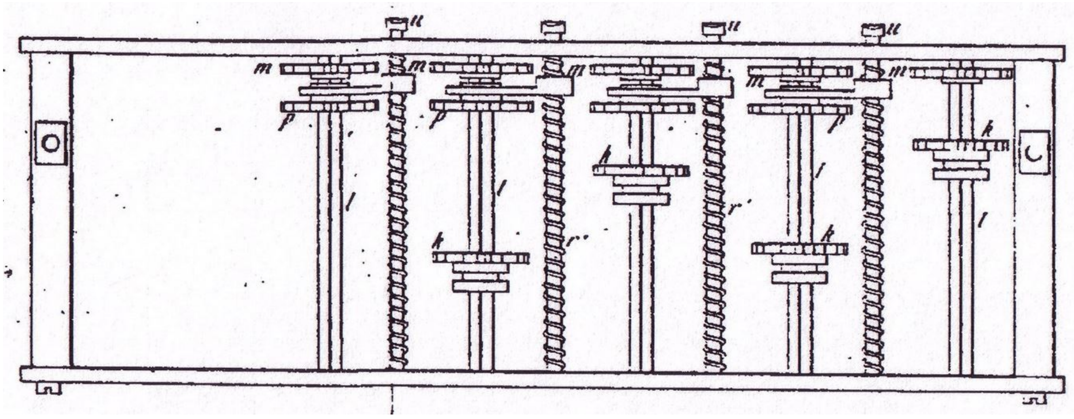
Multiplier: The multiplier is a revolution counting mechanism. The mechanism advances a wheel on the top cover plate by one digit per revolution of the stepped drums. For each of the ten digits (0-9) the wheel has a hole, in which a setting pin can be inserted. A stop ridge connects the center of the wheel to the top cover plate, allowing the wheel to spin underneath. The mechanism is used to stop the machine after a certain number of revolutions of the stepped drums. For example, 123 is input via the setting sliders and should be multiplied with 3. The setting pin is placed into the hole of the multiplier wheel corresponding to the number 3. When the user pulls the ribbon, the wheel's motion is stopped by the pin hitting the stop ridge after three full revolutions of the stepped drums. Therefore the calculation 123+123+123 was executed.

Complementary numbers: The calculating mechanism is operating unidirectionally. This way, the ten's carry mechanism can be greatly simplified. To also be able to subtract and divide with the machine, Thomas implemented the complementary number system in the result mechanism. Each dial of the result display has two sets of numbers, mapped onto the dials in the form of two rings. The set of numbers in the outer ring is increasing in clockwise direction, the other set in the inner ring is decreasing in clockwise direction. Only one set of numbers can be viewed at a time through a masking slider to prevent errors. This enables the machine to perform all four basic arithmetic operations with the same direction of rotation. A downside however is, that it is not possible to switch the mode of operation on the fly. When the slider is put from "Addition/Multiplication" mode to "Subtraction/Division" mode or vice versa, the current number in the result display is lost. The each digit now shows the nine's complement of the previous result. To continue with the calculation, the number has to be re-entered into the result mechanism.

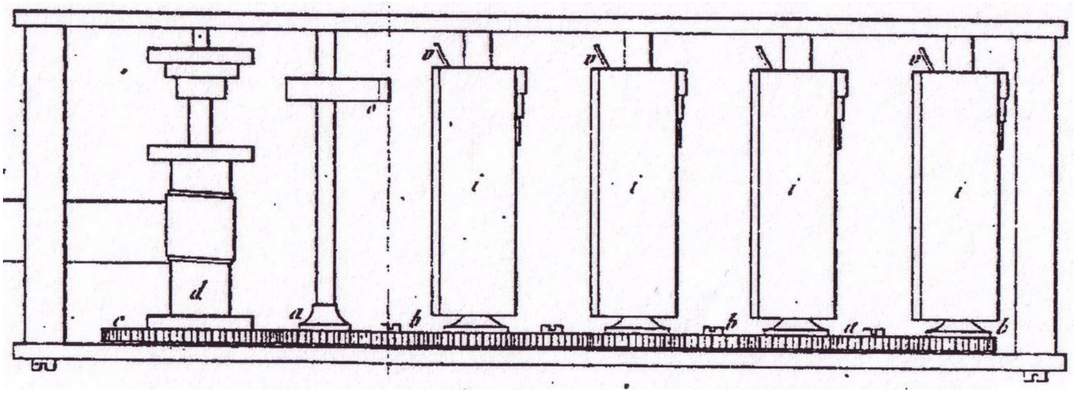
Ten's carry: Thomas 1820 model machine already had a ten's carry mechanism roughly comparable to Thomas' later machines. Since this first iteration, the ten's carry mechanism consists of a preparation and an execution stage. This principle does not change across all Thomas' models. The preparation is performed by a stud in the result mechanism, which is marked with the letter t (4.2a). It pushes horizontally against the top u of a a shaft r (4.2b) and moves the carry gear p out of its resting position. The position is locked by a pawl s (4.2d). The carry gear can now mesh with the carry finger located on the stepped drum. After execution, the pawl is released by a stud D on the back of the stepped drum i (4.2c). The mechanism is heavily reliant on springs, which can be mechanically unreliable.



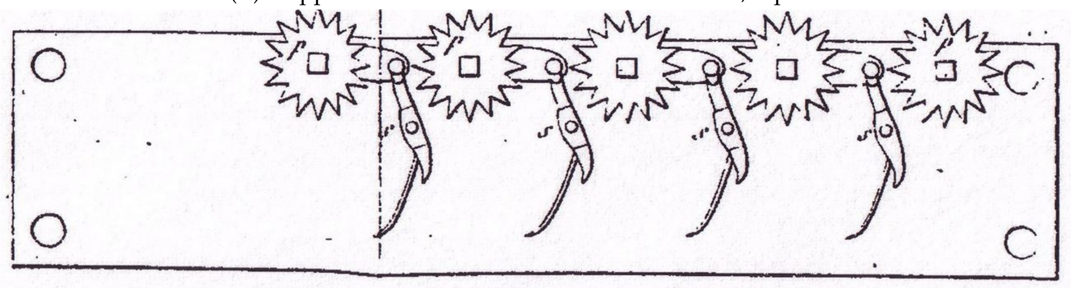
(A) Result mechanism, side view



(B) Setting sliders and ten's carry mechanism, top view



(C) Stepped drums and ribbon drive mechanism, top view



(D) Ten's carry mechanism, back view

FIGURE 4.2: Drawings in the 1820 patent [Thomas, 1820]

4.2 Model 1822

The oldest surviving Thomas Arithmomètre is the model 1822, which was covered in the reports of the SEIN [Francoeur, 1822; Hoyau, 1822]. The design already implements many improvements, compared to the patented model of 1820.

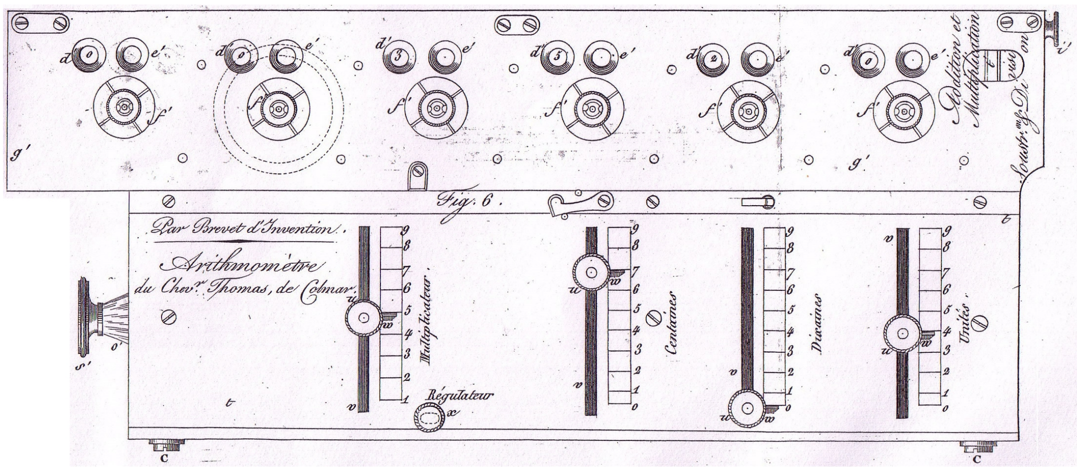


FIGURE 4.3: Drawing of the Arithmomètre in the 1822 SEIN report [Francoeur, 1822; Hoyau, 1822]

Drive mechanism: The drive mechanism is now implemented using a ribbon wrapped around a drum. However, the user's movement is not directly transferred into the machine. By pulling the ribbon, the user now tensions a spiral spring. To start a calculation, a button named "Régulateur" is pressed. This releases the spring, driving the mechanism. To make teh movement of the spring slower and smoother, Thomas included a wind collector in the design. The working principle was already discussed in chapter 3.3.

Multiplier: The multiplier wheel was replaced with a slider. Underneath the slider, a stepped cylinder can be found. Unlike the stepped drums, the cylinder is stepped in horizontal direction, rather than in vertical direction, acting as a revolution counter. The slider moves downwards as the cylinder rotates and stops the mechanism when it reaches the bottom. For example, when the slider is set to the number 3, the machine can perform three full revolutions of the stepped drums, before the slider touches the bottom of the slid.

Complementary numbers: The complementary numbers are implemented in the same way as in the 1820 model.

Ten's carry: The ten's carry mechanism was severely modified. Figure 4.4 shows the underside of the 1822 model's result mechanism together with the improved preparation stage of the ten's carry mechanism. The ten's carry is still initiated by the result mechanism's display dials. However, the studs have been replaced by slanted fingers (marked red). Unlike the horizontal pushing motion in the 1820 model, the new slanted fingers apply vertical force, pushing the tip of a pawl lever (marked green) downwards. This causes the other side of the lever to move up and allow the tip of a shaft (marked blue) to pass through the frame plate. The shaft is moved by a spiral spring wrapped around it. On the left side of the picture the shaft is in its normal position, on the right side the shaft passed through the plate and the ten's carry is prepared. The movement of the shaft leads to the carry gear on the other side of the frame plate being pushed towards the plate. The carry finger meshes with the carry gear, since they are now lined up. Afterwards, the carry gear is pushed back into its resting position by two slanted planes.

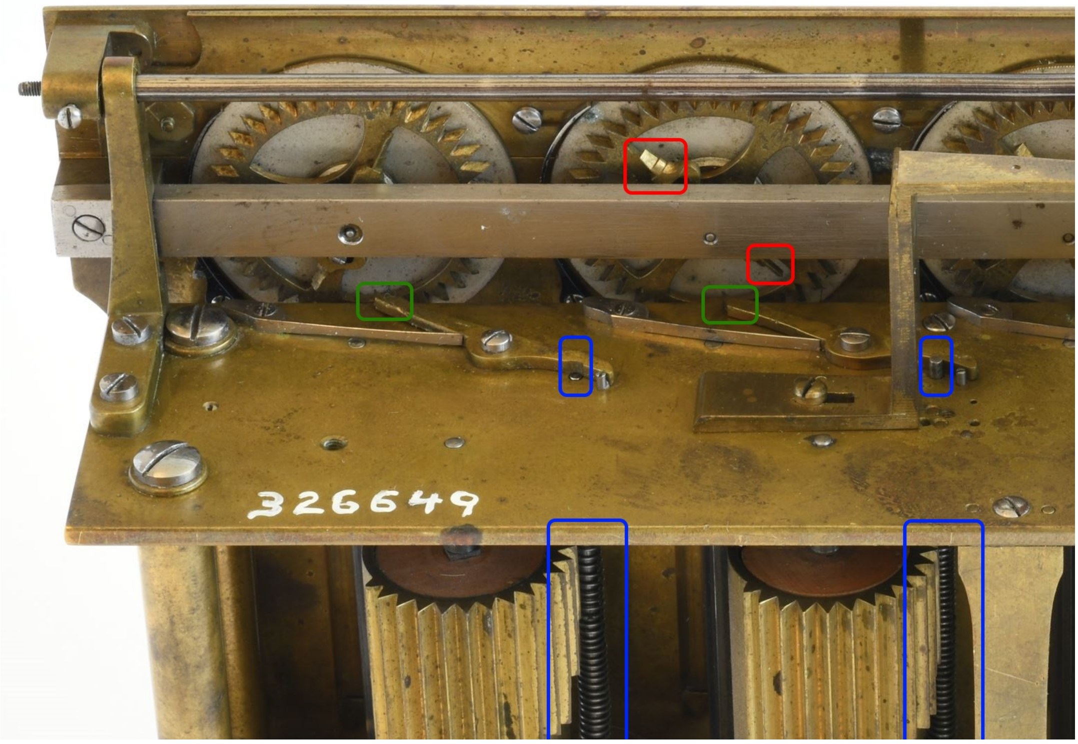


FIGURE 4.4: Photo of the underside of the 1822 model's result mechanism [Rocca,]

4.3 Model 1849

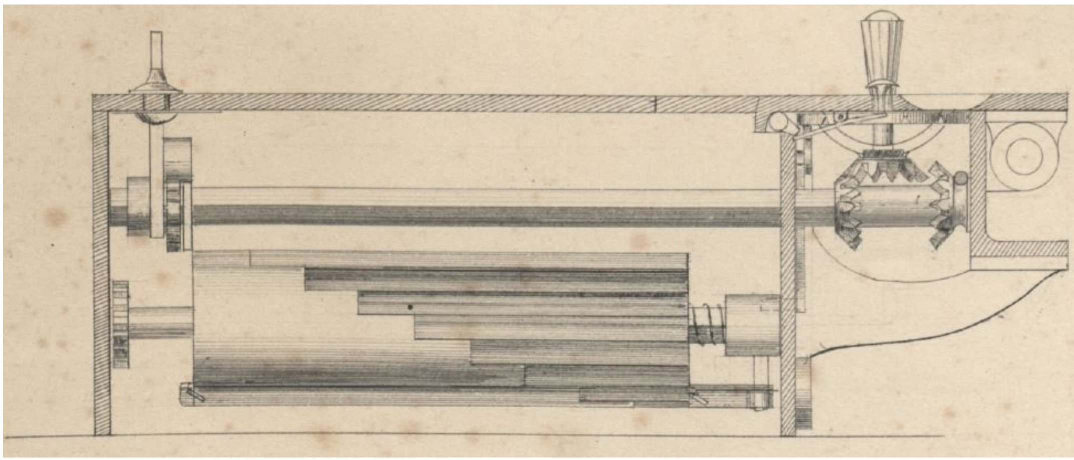
After a long time has passed, Thomas returned to his work on the Arithmomètre and filed a new patent in 1849. The new design had five setting sliders and ten result display dials [Thomas, 1849].

Drive mechanism: The spring mechanism was replaced by a crank on the front side of the machine. This was Thomas' first stepped in removing springs from the design of his machine and making it more reliable. The crank system was also the standard among many other calculating machines. The rotational motion is still distributed to all stepped drums by spur gears in the front of the machine.

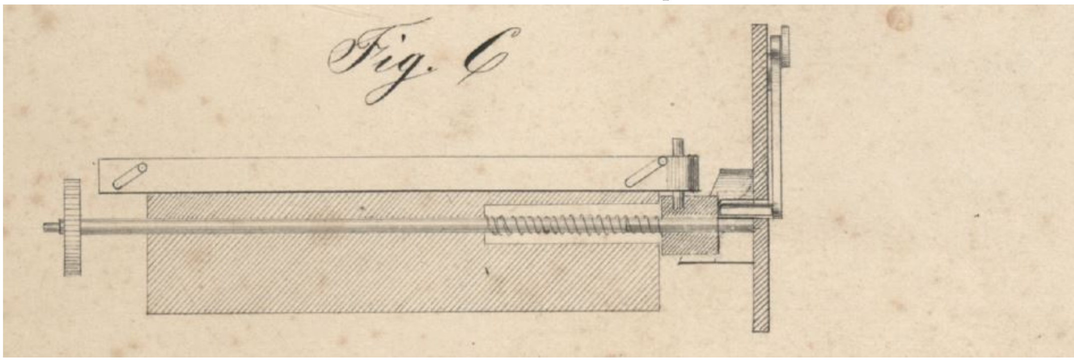
Multiplier: The cylinder underneath the multiplier slider now had a spiral surface instead of a stepped one. When the multiplier is set to a certain number and the crank is turned, the slider is moved down by the spiral cylinder. Once it reaches zero, the calculation is completed.

Result mechanism: The complementary numbers were removed from the result mechanism. With the design patented in 1849, Thomas, together with the clockmaker Piolaine, first introduced the double-bevel gear mechanism. The function of the mechanism was already discussed in chapter 3.3.4. In this early stage, the operation control switch was implemented as a small switch above the multiplier slider.

Ten's carry: While the preparation stage of the ten's carry mechanism wasn't altered significantly, the execution stage was again drastically modified (see Figure 4.5).



(A) Machine side view, normal position



(B) Machine side view, carry finger extended

FIGURE 4.5: Drawings in the 1849 patent [Thomas, 1849]

The long shafts and their accompanying springs to move the carry gear were removed. The carry gears now have fixed positions in the front of the machine. In addition, he carry finger is incorporated into the stepped drums. In its normal position, the finger is retracted into the stepped drum (4.5a). As soon as a ten's carry is prepared, the finger is pushed outward by a spring inside the stepped drum (4.5b) and meshes with the carry gear. Afterwards, the finger is pushed back by a slanted planed and locked into its resting position.

4.4 Model 1850

Only one year later Thomas filed his next patent [Thomas, 1850a] (see Figure 4.6), increasing the pace of development rapidly. Thomas starts to prepare for the series production of his machines.

Drive mechanism: In his new design the crank is moved onto the top cover plate. To still be able to close the lid of the machine's enclosure, the handle of the crank is

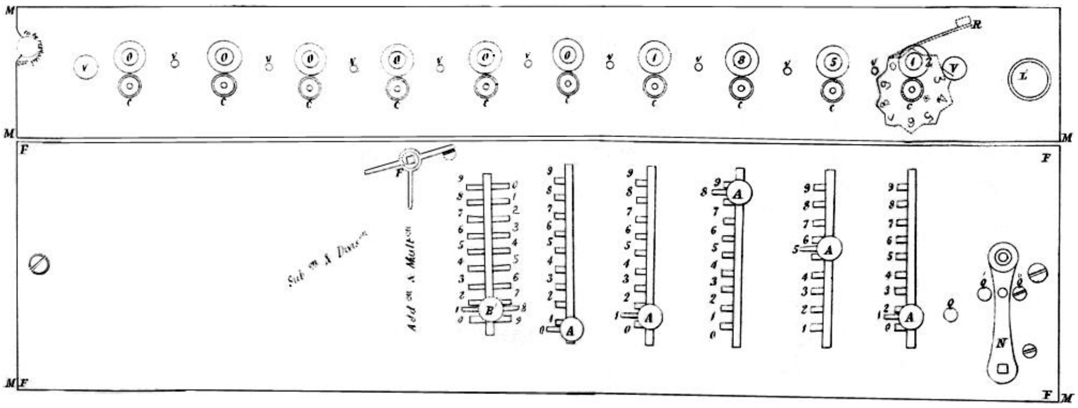


FIGURE 4.6: Drawing of the Arithmomètre in the 1850 patent [Thomas, 1850a]

foldable. With the new position of the crank, the transmission to the stepped drums is also improved. The spur gears in the front of the machine are replaced with a horizontal main drive shaft. Every stepped drum is linked to the shaft by a pair of bevel gears, reaching through the front cover plate (see Figure 4.7, bottom).

FIGURE 4.7: Photo of the underside of the 1850 model [Rocca,]

Multiplier: There were no changes to the multiplier system including the multiplier setting slider on the top cover plate and the helical cylinder.

Result mechanism: There were no changes to the result display dials, however, a zeroing mechanism was added. That way, all result display dials could be set to zero simultaneously. The new mechanism, which can be seen in the patent drawing in Figure 4.8, included a toothed rack *E* and a special zeroing gear *C* for every dial of the result mechanism. The zeroing gear originally has ten teeth, each corresponding to one number on the result display dials (0-9). The tooth corresponding to the number 0 has been removed. By pulling the slider *E*, the toothed rack engages with the zeroing gears and rotates them until the missing tooth is encountered. This sets the dials to zero. The rack is returned by a spring. Later machines implement the design with a turning knob, which has already been accounted for in this patent by the gearwheel *X*. To perform the zeroing, the result mechanism has to be lifted first, disengaging it from the calculating mechanism.

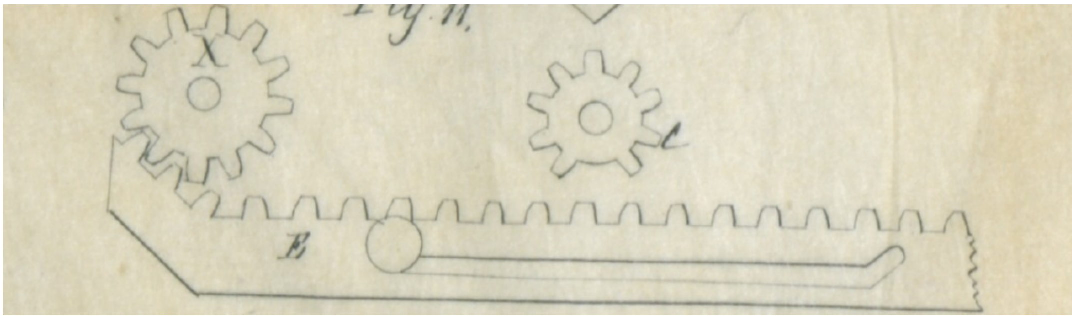


FIGURE 4.8: Drawing of the zeroing mechanism in the 1850 patent [Thomas, 1850a]

Additionally, the operation mode of the double-bevel gears is now switched with a wing nut, which can be seen in Figure 4.9. This implements the idea that was already formulated in the 1849 patent. By rotating the wing nut counter-clockwise into its right position the guide rail with the bevel gears is moved towards the back of the machine. The machine is in "Addition/Multiplication" mode. By rotating it clockwise, the mode is switched to "Subtraction/Division".

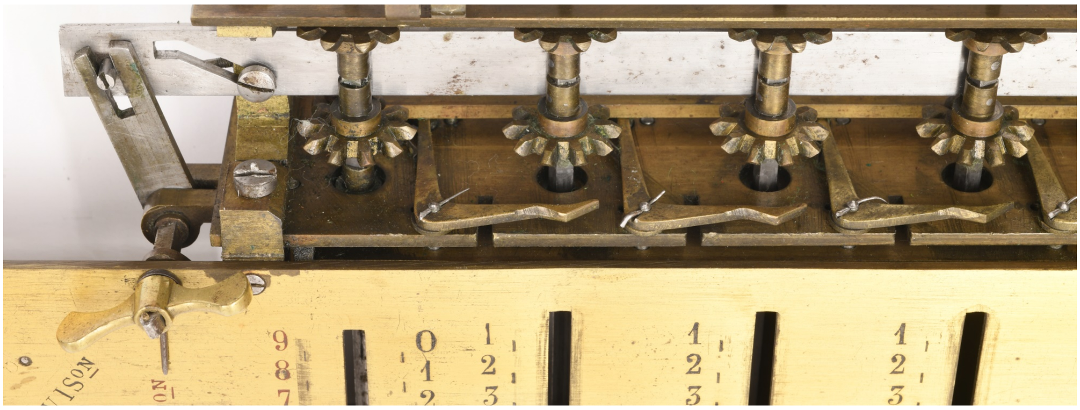


FIGURE 4.9: Wing nut of an 1850 Arithmomètre [Rocca,]

Ten's carry: In this patent, the executing stage of the ten's carry mechanism is improved once again. Thomas abandons the idea of the carry finger retracting into the stepped drum and returns to traditional carry fingers. What remains is the spring mechanism between the carry finger's assembly and the stepped drum.

4.4.1 1850 dedication models

Since the 1850 patent, Thomas' preparation for his calculating machine series production becomes more evident than ever before. For the first time, Thomas is building and gifting special dedication examples of his machine to titled and crowned heads across Europe. The wing nut is characteristic for machines built using the design in the 1850 patent. Examples are given in Figure 4.10. With the model dedicated to Nicholas I of Russia, it can also be seen that Thomas is experimenting with the construction of larger machines with a higher capacity in both, the setting and result mechanism. The normal 1850 type has five setting sliders and ten result dials. The larger model has eight setting sliders and sixteen result dials.

(A) 1850 type Machine dedicated to François de Paule de Bourbon-Siciles [Monnier, 2023, section: Des cadeaux "royaux"]

(B) 1850 type Machine dedicated to Nicholas I of Russia [Rocca,]

FIGURE 4.10: Examples for dedication models of the 1850 type Arithmomètre

4.5 Model 1852

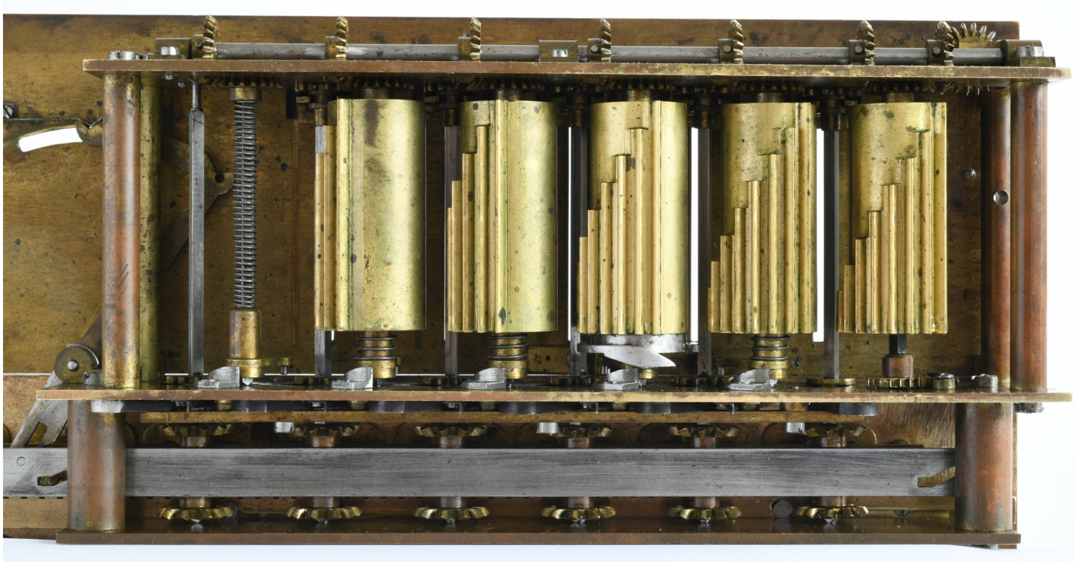
Two years later, the next iteration of Thomas' machine emerges. But it is not until 1865 that new legal rights are obtained [Thomas, 1865]. Yet, the new design can be found in an 1852 instruction manual [Thomas, 1852]. Firstly, the wing nut was replaced by an operation control lever, which can be shifted from right to left and vice versa. The pivot point of the mechanism stayed the same, but the elongated lever resulted in a higher leverage force. This reduced the resistance and smoothed the motion of switching between modes.
Secondly, the multiplier system was discarded completely. This reduced the amount of parts and cost of every machine.

4.5.1 1852 dedication models

Thomas continued to produce dedication models with this new design. The machines can be identified by the aforementioned characteristics: A horizontal operation control lever, no multiplier slider, but still using the ten's carry mechanism with a spring between the stepped drums and the carry fingers. For example, this design was used constructing the machine gifted to the Pope Pius IX (see Figure 4.11).

(A) top view

FIGURE 4.11: 1852 type Machine dedicated to Pope Pius IX, gifted in 1853 [Rocca,]

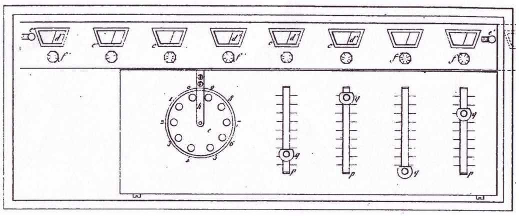


(B) bottom view

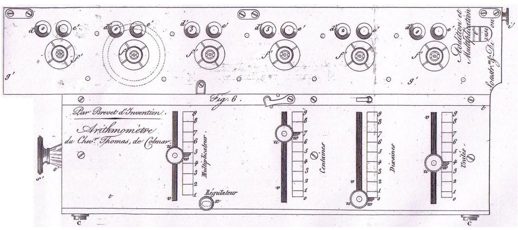
FIGURE 4.11: 1852 type Machine dedicated to Pope Pius IX, gifted in 1853 [Rocca,]

4.6 The Machine No.4

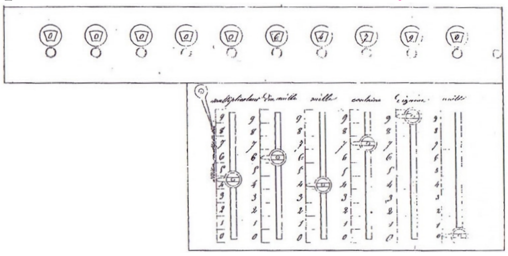
For the first time, Thomas was able to build a machine without the need for springs. Even though the new mechanism enabled Thomas to construct the Piano Arithmomètre, the design was not patented. The surviving machine with the model number 4 is special, because the design is exactly similar to the Piano Arithmomètre. Only the revolution counter is different, implemented by a rotating pointer underneath the crank. It is likely that the machine was created as a prototype before initiating the Piano construction. During closer inspection, the same anomaly of the return of the ten's carry mechanism incorporated in the Piano can be found in this machine. Rather than returning the carry finger immediately after it engaged with the carry gear (as in Thomas' other machines), the helical gear is delayed by a certain angle. This can sometimes leave carry fingers halfway disengaged after a full rotation of the crank while performing a ten's carry. This has however no effect, since the mechanism is returned on the next crank revolution before disrupting other components.



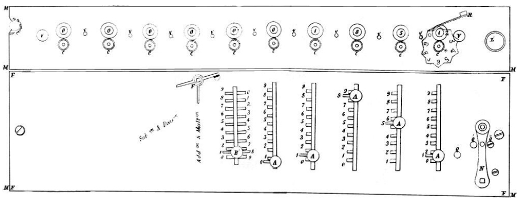
Patent 1820 [Thomas, 1820]



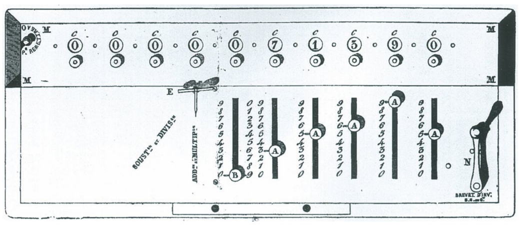
Report 1822 [Francoeur, 1822; Hoyau, 1822]



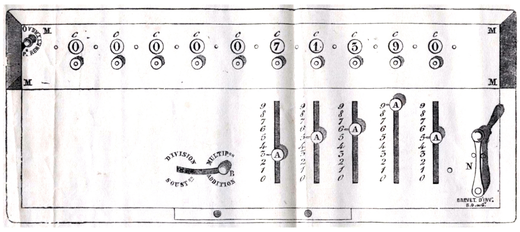
Patent 1849 [Thomas, 1849]



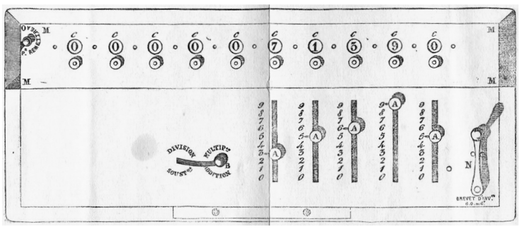
Patent 1850 [Thomas, 1850a]



Instruction Manual 1850 [Thomas, 1850b]

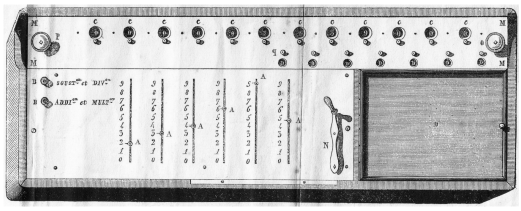


Instruction Manual 1852 [Thomas, 1852]

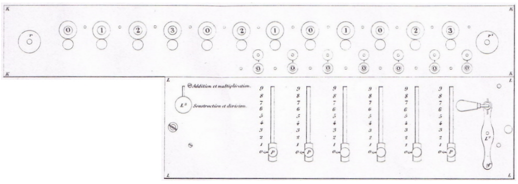


Instruction Manual 1856 [Thomas, 1856]

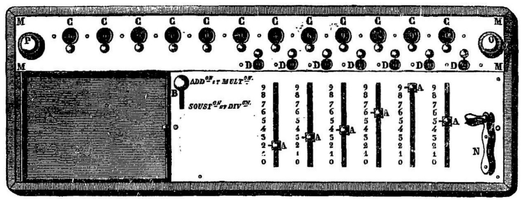
TABLE 4.1: Timeline: Patents, important reports and depictions in Thomas' instruction manuals



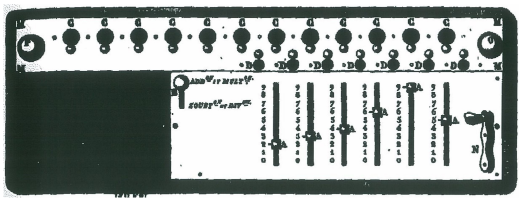
Instruction Manual 1860 [Thomas, 1860]



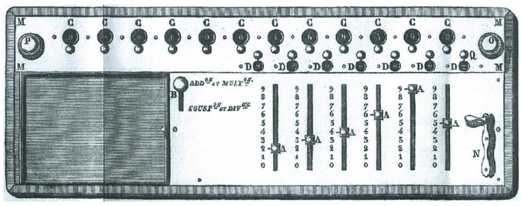
Patent 1865 [Thomas, 1865]



Instruction Manual 1868 [Thomas, 1868]



Instruction Manual 1873 [Thomas, 1873]



Instruction Manual 1878 [Thomas, 1878]

TABLE 4.2: Timeline: Depictions in Patents, important reports and Thomas' instruction manuals

Chapter 5

Software

5.1 Work with Blender

The model was created using the 3D graphics suite Blender, version 3.4.1, developed by the Blender Foundation. The reports, photographs, and measurements from the restoration of the Arithmomètre at the Arithmeum were used as references for the components. The exterior dimensions of the machine were captured as part of this master's thesis. Similarly, all other modeled machines were created based on patent documents or documentation provided by Thomas.

In order to recreate a functional calculating machine in Blender, similar to building a real machine, each component must be created individually. Through meticulous preparation during the restoration process, all internal components were photographed on graph paper and measured with high precision. The implementation in Blender allowed for the replication of these individual components in 2D using curves, utilizing the "images as planes" feature, and then transforming them into 3D shapes using the extrude function.

Furthermore, Blender enables users to multiply repetitive components, simplifying the repeated use of identical parts.

5.2 Work with Agisoft Metashape

Ornaments cannot be accurately reproduced in a reasonable amount of time "by hand" (Blender Sculpting). Instead of replicating the geometry of the objects manually, a solution is sought to digitally capture them. Two approaches are available: laser scanning and photoscanning.

Laser scanning is widely used in industrial applications and offers high precision with the right equipment. Other museums, such as the Victoria and Albert Museum, have successfully applied this technique. For example, they replicated a highly detailed silver-decorated glass vase using a handheld 3D laser scanner and subsequent 3D printing. However, the university only possesses devices suitable for capturing larger-scale objects like rooms and buildings. Additionally, laser scanning can be complicated to apply, and the required hardware is expensive.

Photoscanning, on the other hand, involves capturing the object using image data. By analyzing photographs taken from different angles with specialized software, the geometry of the object can be computed. The advantage of photoscanning is that it doesn't require highly specialized equipment. However, it may be less accurate compared to laser scanning.

In the attempt to digitally capture the objects, the chosen approach is photoscanning. To ensure successful computation of the object's geometry from the image material using software, several considerations must be taken into account.

Firstly, the images must overlap by 80-90% to allow the software to determine the camera's position in space and the viewpoint of the object. Secondly, the object must be evenly illuminated to avoid shadows or dark spots being "burned" into the texture of the 3D model. Indirect and diffused lighting is preferred to mitigate issues with reflective surfaces.

Furthermore, the camera parameters must remain consistent throughout the photo series. This includes settings such as zoom, focus, ISO, white balance, etc. Using a lens with a fixed focal length yields the best results.

Lastly, the image material must have a high depth of field to extract all the necessary information. This requires closing the aperture as much as possible (such as using F22) to ensure sharpness across all areas of the images. Consequently, a longer exposure time is needed per shot, making the use of a tripod essential to avoid blurring.

The chosen software for the digital capture process is Metashape, which follows a workflow consisting of four main steps: alignment, dense cloud calculation, mesh construction, and texture generation.

During the alignment step, the software calculates the corresponding camera positions for each photo. This is done by identifying distinctive image points that can be recognized in multiple photos. Using triangulation and collinearity equations, the positions of these image points, as well as the position and rotation of the recording camera, can be determined. Additionally, this step generates a "sparse" point cloud containing all the points used for the computation.

Next, the dense cloud calculation step uses the previously determined camera positions to calculate depth information for each image. The result is a very dense point cloud, known as the dense cloud, which contains all the extractable image information. This computational step is the most time-consuming, often taking around 20 hours for 300 images with high detail requirements.

Following the dense cloud calculation, the software proceeds to build the mesh. This involves connecting all the points of the dense point cloud to form a polygonal grid, creating the surface representation of the object.

Finally, the texture of the model is generated in the build texture step. The software combines the image data into a single texture image, which is then applied to the surface of the object. This process enhances the level of detail by supplementing the geometry of the object with image-based information.

To prepare the Metashape models for import into Blender, several steps are recommended. Firstly, the mesh should be decimated to reduce the amount of data and optimize performance. Secondly, the texture is "de-lighted" with an accompanying software by Agisoft. De-lighting is necessary to remove shadows that are baked into the texture of the 3D model. When capturing the object through photoscanning, lighting conditions can introduce shadows on the object's surface. These shadows become part of the texture when the images are used to generate a texture map for the 3D model.

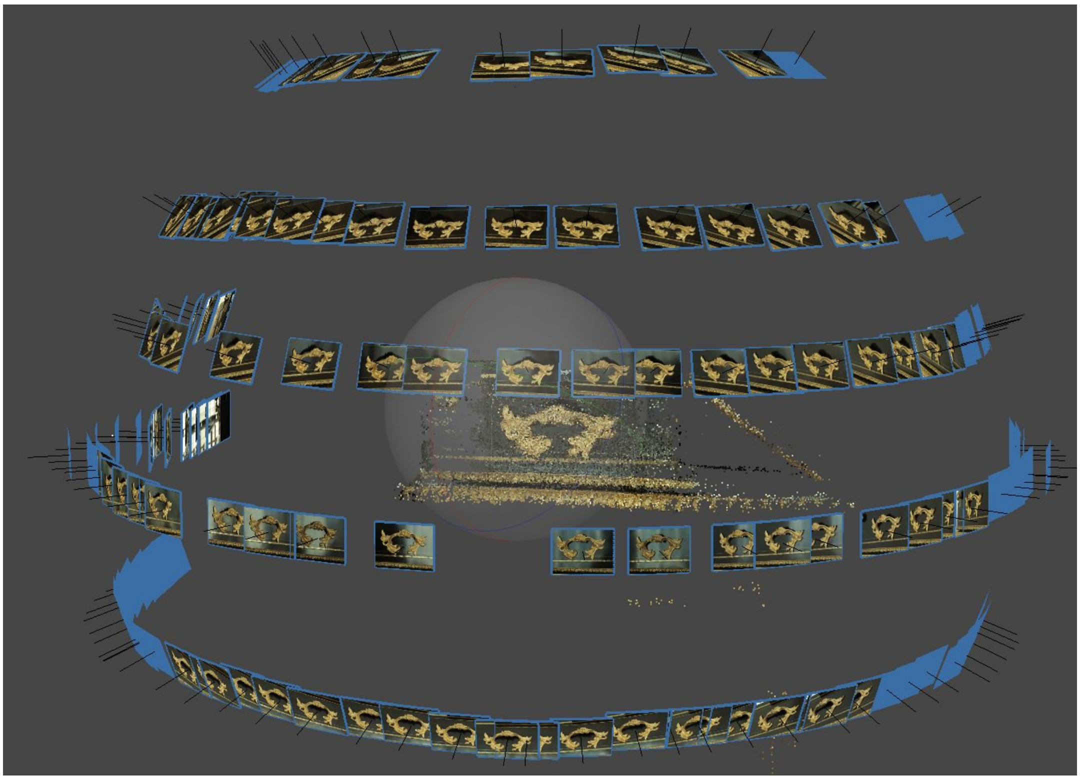


FIGURE 5.1: Metashape model point cloud generation

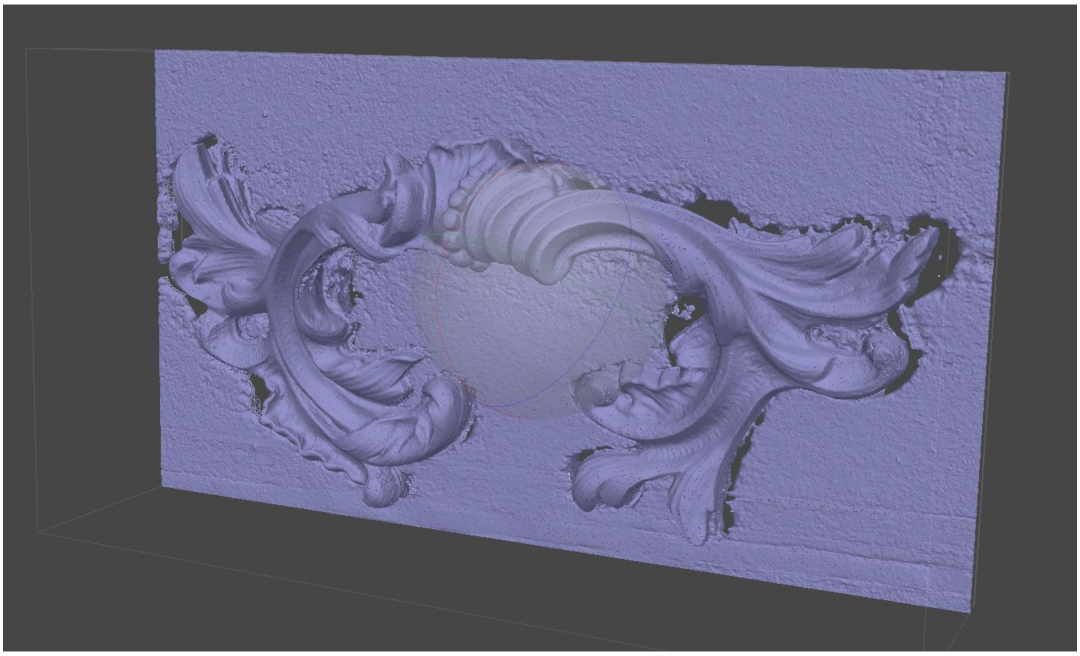


FIGURE 5.2: Metashape model surface wireframe

FIGURE 5.3: Metashape model textured

Chapter 6

Conclusion

This master's thesis examined the mechanics and development history of the Piano Arithmomètre by Thomas. It revealed the changes in components, mechanisms, and input mechanisms across the machines. The work covers all known calculating machines by Thomas, from the initial prototype to the Piano Arithmomètre. Particularly in terms of mechanics and user-friendliness, Thomas made several modifications over time. Throughout the years, Thomas continually improved his design with the goal of achieving high-volume production. Unreliable mechanisms were gradually refined or replaced. The earliest machines were powered by a ribbon drive mechanism and featured numerous springs, which often caused issues. Nearly 30 years after building his first machine, Thomas replaced the use of complementary numbers with double-bevel gears, taking a significant step towards user-friendliness. Initially, the carry mechanism still relied on long springs, but by 1855, Thomas had developed a design that eliminated the need for springs entirely. This allowed him to expand his machines to accommodate more digits without any difficulty. A milestone was ultimately reached with the construction of the Piano Arithmomètre, featuring a result register with 30 digits. Thomas also knew how to garner attention for his invention. Initially, he faced setbacks at several exhibitions. However, convinced of the value of his invention, he increasingly invested in promoting the Arithmomètre. By creating dedication models and presenting them as gifts to rulers across Europe, he received numerous honors and gained fame. His persistence eventually paid off, enabling him to begin the series production of his calculating machines. The objective of this master's thesis is not only to examine the Piano Arithmomètre and its precursor models but also to create a 3D model for the purpose of producing an educational video with narration. This will allow viewers to understand the historical context, development history, and mechanics of the first calculating machine produced in series within a museum context. Through this thesis, new insights into the examined and extensively documented calculating machine by Thomas can be gained. Thomas discovered a way to produce calculating machines in series, thereby creating new possibilities for their perfection during the industrialization era. Further research could focus on examining Thomas' subsequent models and exploring the variations adopted by other calculating machine manufacturers. As the history of calculating machines extends beyond Thomas, there are countless opportunities to examine these development stories from new perspectives and with different emphases.

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