A brief history of arcade video game display technologies

— From CRT displays to real time graphics —

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Since the rise of the market in the 1970s, arcade video games have evolved via the adoption of various display technologies. Initially transistor-to-transistor logic (TTL) was used, then bitmapped display—as seen in the smash hit Space Invaders—was adopted. Later display technologies include sprite display technology, an arcade industry innovation that played an important role in expanding the market, and real time polygon displays incorporating very fast numerical operations such as DSP. The arcade business has been an early adopter, introducing, developing, and utilizing new display technologies years before they appear in other industries. These arcade game technologies led to the development of many other new entertainment systems, such as home console games, mobile phone contents, and even network (downloadable) karaoke. This paper describes the evolution of arcade game display hardware technologies and its background.

Keywords **:** Video game hardware, arcade game, sprite display, real-time polygon display

1 Introduction

The world video game market is about 5 trillion yen in size.[1][2] Japan's share is 20 % of this figure, with the Japanese domestic market divided into home console games and arcade games (also called "game center" games or commercial games). Japan has the largest arcade game market in the world, and the industry is driven by the introduction of new technology. While arcade games provide players with extraordinary experiences, the industry is strictly business. Even if a game features excellent hardware and programming, its development will be terminated if it fails to generate sufficient profit during the prototype's standard two-week period of arcade location test. Only about 20 % of game prototypes survive this income test, and only a few percent of completed games go on to become hit products. Those game concepts and the hardware that survive such harsh competition are invariably excellent in terms of business and technology. This author has been involved in the R&D and marketing of entertainment devices including arcade games for over 30 years, since the 1970s. This paper describes the history and background of the arcade video game display technology and its unique, little-discussed evolutionary path. (While concepts are an important factor in an arcade game's success, they will not be discussed in this paper, and shall be a subject of another paper.)

2 The development of video game displays

2.1 The earliest video games

It is said that the first video game was created in 1958 by William A. Higinbotham at the Brookhaven National Laboratory, USA,[3] but commercial success did not come until the early 1970s release of the arcade PONG by Nolan Bushnell's Atari, Inc. Gaining inspiration from this game, Japanese arcade game engineers engaged in their own original research and development. Worldwide hit Space Invaders (1978, Taito Corporation, developed by Tomohiro Nishikado) was one success story from this period. In the fierce competition with the United States, the display technology of arcade video games progressed along a unique path in a seven to eight year cycle, in step with the advances in the electronics technology. The progress will be described in sequence.

2.2 Early video games: electromechanical games from the 1960s

In the 1960s, before the arrival of the video games, game machines like the one shown in Fig. 1 were already available, and the play field was approximately equivalent to the

Fig. 1 Electromechanical game machine

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current video games. During this age there were no central processing units (CPU) or high-speed logic parts; instead mechanical parts, motors, light bulbs, and sequencers using magnetic relays were used. In the example of Sky Fighter II (1971, Taito Corporation, developed by Tomohiro Nishikado), the game machine was composed mainly of five electromechanical units that handled: 1) the display of clouds drifting in the background, 2) the display of enemy aircraft, 3) the display of enemy explosions, 4) the display of bullet trails, and 5) hit detection. Although this and other electromechanical game machines dominated the market for a while, engineers shifted their focus to the development of interactive games using cathode ray tubes (CRT). Unlike electromechanical games that were prone to mechanical deterioration and magnetic relay contact failures, game machines using CRTs required less maintenance and were also able to display fast-moving graphics.

2.3 Video game display fundamentals

While video games debuted in the 1970s, the fundamental display technology remains the same today. A raster is drawn by passing the electron beam right-left and up-down on the CRT, and the image is displayed by placing graphical elements on top of the raster (Fig. 2.1). Figure 2.2 shows the generation of the basic signal for display, and Fig. 2.3 is a diagram that shows the concept of the display time and the blanking time in video game display. In this example, one horizontal scanline is drawn in 63 μsec (blanking time in that time is 10 μsec) and one vertical scanline is drawn in 16.6 msec (blanking time of 1.3 msec). These frequencies are close to the National Television System Committee (NTSC) television display. Figure 2.4 shows the sprite display blanking period (to be discussed later), where weak memory performance was compensated for by increasing the horizontal blanking time. (Although these ratios will shorten the width of the display in the horizontal direction, an ordinary TV receiver absorbs the difference, and there is no interference with the screen display or the synchronizing behavior of the TV.)

2.4 The TTL method: early 1970s

PONG, made by America's Atari, Inc., was released in 1972 and became an instant hit when it was introduced to Japan. Lacking almost any reference materials, Japanese arcade game engineers gained technical inspiration from their analysis of PONG's logic circuit. Within six months they began releasing totally new and different video games using original technology. The core of the electronic circuit used transistor-transistor logic (TTL), which delivered high speed at a low cost, further spurring the development of arcade video games. Figure 3 shows the functional block of the racing game Speed Race (1974, Taito), and how graphics are drawn on the desired display position on the CRT using the digital counter's preset function. The all-important hit detection—in this case, collisions between competing cars and the curb—was handled by the hardware, which checked for overlapping pixels among the on-screen graphics. This process was primarily controlled by TTL, as CPUs had not yet been adopted.

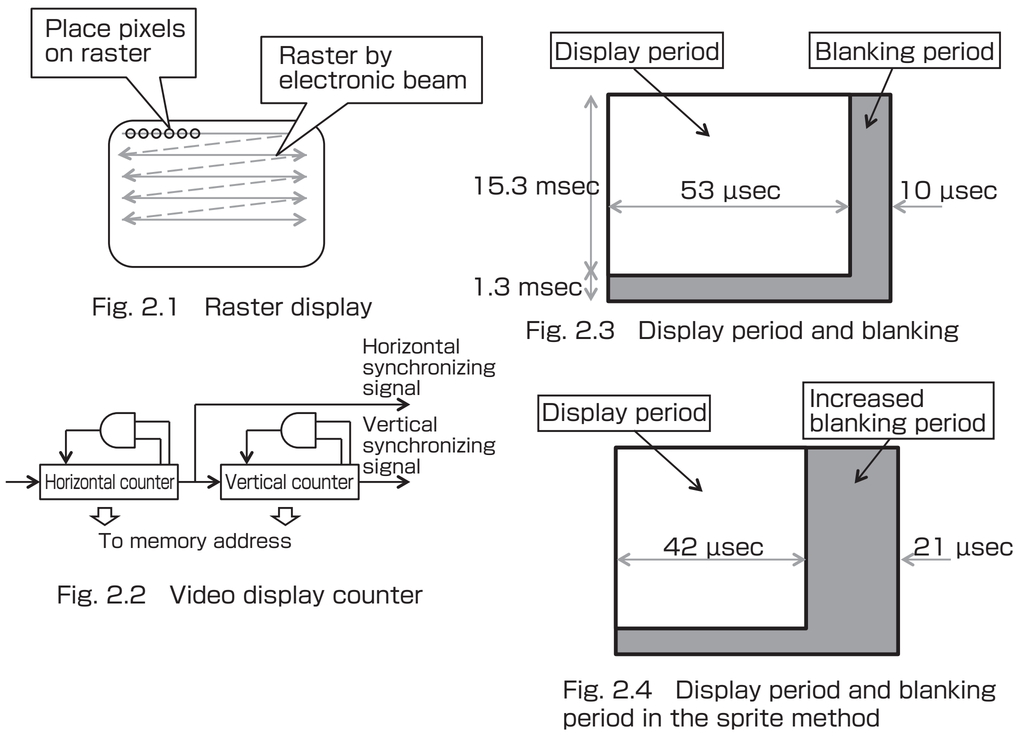

Fig. 2 Video signal fundamentals

[TTL video game limitations]

During this period, the hardware (TTL circuit) itself was responsible for realizing the game concept. However, hardware engineers with an understanding of game concepts were few in number, and human resources were limited. Initially, around 200 TTL circuits were sufficient for commercial video games, but the number of TTL circuits required increased as demand grew for more complex games with more on-screen objects, and hardware costs soon became prohibitive.

2.5 The age of CPU bitmapped graphics: late 1970s

In the mid 1970s, an American company introduced a CPU-based game called Gunfight (1975, Midway Manufacturing Co.). While it was not a commercial success in Japan, it inspired the use of CPUs in Japanese arcade games. CPUs added flexibility to game development, and for the first time it was possible to separate game concepts from the physical hardware used in the game. Japanese engineers studied foreign CPU-based games, and soon began to produce their own, designed with their own scratchbuilt development tools. The highly successful Space Invaders is one example of a game designed entirely with handmade development tools.

At the time, character display, commonly used as the console for mini computers, was the dominant image display method. The advantages of this method were that it used only a small amount of memory, the circuit configuration was simple, and the cost was low. However, there were many display limitations, since only a small number of characters and graphics could be displayed, and in limited positions at that (Several commercial products used this method, including card and mahjong games.) However, arcade engineers aimed to create games where objects could move freely around the screen, so they shifted to bitmapped graphics despite their expensive memory requirements. Figure 4 shows the functional block used in Space Invaders, which used a bitmapped graphic method where the image display memory was time-shared between the CPU and the display. Bitmapped game display technology delivered much more flexibility compared to the TTL logic game machines.

[The introduction of game development tools]

The Japanese game developers of this period were multi-talented engineers that engaged in the fabrication of hardware, software, and graphics, and they even developed their own unique tools in an effort to work more efficiently. Graphic work was digitized by hand, using paper and pencil in the early days, but specialized graphic rendering tools were created and used to correct graphics, change colors, and check the animation. Also, in game software, several subroutine programs ran concurrently and cooperatively, and engineers created and implemented the original real-time OS to integrate and run them. Finally, scratchbuilt debuggers were used as a program development tool. In addition to their basic debugging function, these debuggers worked with the hardware and allowed the real-time measurement and display of the CPU occupation time for each program, an innovative feature at the time.

[CPU bitmapped graphics limitations]

Using the bitmapped graphic method as seen in games like the aforementioned Space Invaders, to move a displayed object, a new object was drawn in the new display position, and the old one drawn in the former position was deleted. These processes were handled entirely by the CPU program. As a result, the processing limit was readily reached in games with fast-paced action. For example, in the Space Invaders hardware, the area of the screen that could be filled in at real time was only about one-fourth the whole screen, and that was insufficient for games with vigorous action. As a solution, faster CPUs were used to increase the rendering speed of bitmapped graphics, as seen in QIX (1981, Taito Corporation) and Halley's Comet (1986, Taito Corporation), but it was not long before this solution reached its limits.

2.6 Age of the sprite: 1980s

In 1978, Atari, Inc.[4] launched the sprite display method, in which the desired graphic is displayed by the hardware as the CPU entered the location coordinates and graphical code of the object to be displayed. Figure 5 shows the functional block of a video game system using this method. In sprite display, the line buffer memory was configured

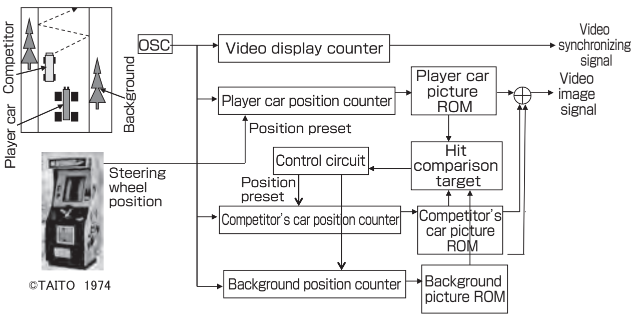

Fig. 3 Video game circuit block by TTL

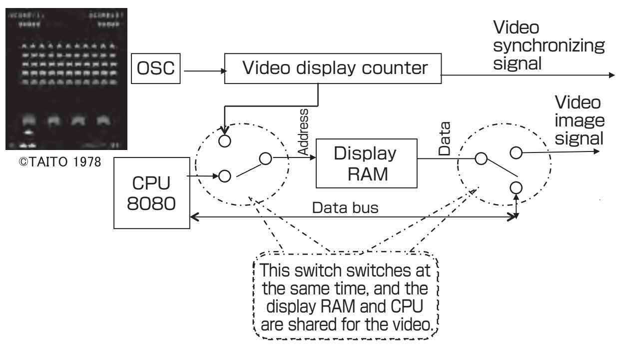

Fig. 4 Video game circuit by bitmapped graphics

using expensive high speed memory, and the hardware and software processes were separated in a good balance. Galaxian (1979, Namco Limited) was the first game to use sprite graphics. The speed of the memory elements (accessed at about 70 nsec) and the processing speed of the surrounding TTL circuits was just barely enough to produce the line buffer circuit, and the craftsmanship of the circuit designer really shined through (however, leaving such little room for error occasionally contributed to problems after the game was released to the market[5]). Many ways were devised to write as many graphical elements in the line buffer within the TV's horizontal blanking time such as leaving room in the design by widening the blanking time to twice the standard TV signal (NTSC). While the bitmapped method struggled to slowly move 55 Space Invaders around the screen, as a result of these design efforts sprite technology allowed more than ten times as many objects to be moved around freely at high speed. During the 1980s, many video game concepts were based on this basic method. Most of the video game categories seen today were established during this period, and this display method was carried over to the early home console games.

[Division of labor]

During this period, development roles including the programmer, hardware engineer, game concept creator, graphic designer, and the producer who organizes the group (in many cases, a middle level manager) became specialized and defined. Particularly, the producer assumed the important roles of realizing the game concept for the next age while directly being exposed to external competition, integrating the programmers, hardware engineers, and game concept creators, and then opening the way for future technological developments.

[Market expansion and sprite display limitations]

The market expanded rapidly with the huge hit of the Space Invaders, and while many games were being developed using the sprite method, there was a great deal of demand for newer expressions and more complex video games. On the other hand, with the sprite method it was necessary to prepare many graphics for the enlargement, reduction, and rotation of each displayed object. Therefore, the graphic work and the memory to store the pictures increased exponentially, yet while costs increased display quality remained insufficient.

2.7 Age of the DSP polygon: early 1990s

When Taito Corporation released an electromechanical flight simulation game in 1986, the prototype was well-received during the market test. While electromechanical games were easy to understand, there were durability and cost-related problems. In response, the commercialization of a similar videogame with dramatically expanded sprite display technology was attempted, but there were many technological difficulties in the enlargement, reduction, and rotation of the displays of daytime landscape and landing strip during take-off and landing. Therefore, the flight simulator game that showed only the nighttime guiding lights was developed by expanding the sprite technology. If only the guiding lights were involved, then the rotation, enlargement, and reduction of the linear arrangement of lights were no longer needed, and this could be accomplished by the sprite technology and by relatively small amount of numerical operations. This game received high marks in the market introduction test. Meanwhile, display technology that allowed the simulation of daytime take-off and landings was developed concurrently, and this led to the concept of polygon display hardware.

Figure 6 shows the polygon display block diagram at the time. Here, a digital signal processor (DSP) is used to calculate the vertex coordinates of the polygon. Although I

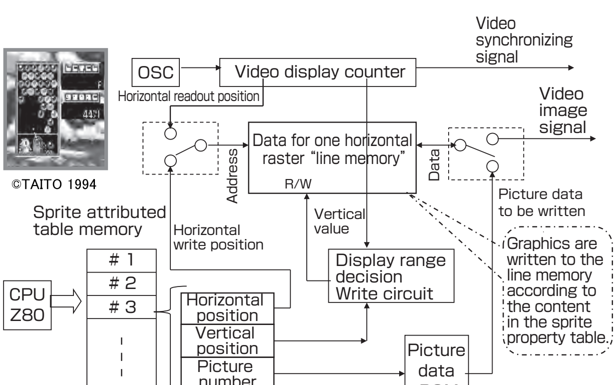

Fig. 5 Video game circuit by sprite display circuit

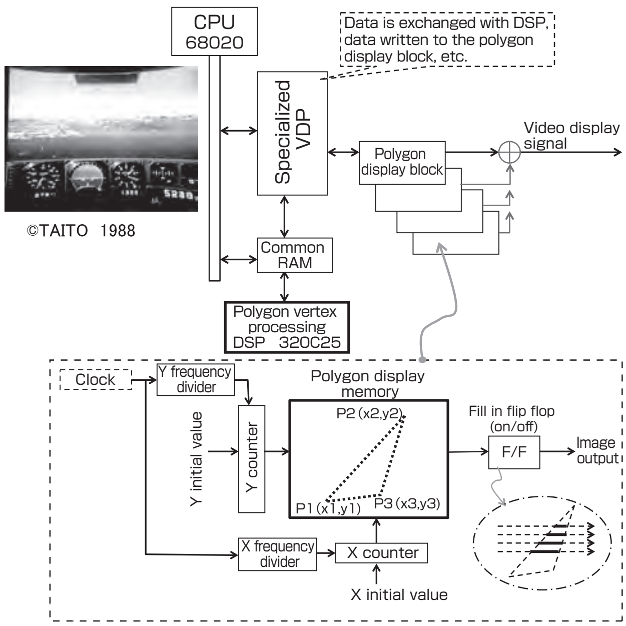

Fig. 6 Video game circuit for DSP and polygon displays

shall omit a detailed explanation, the “polygon display block” in the figure is a block where the inclined line set by the X and Y frequency dividers is rendered according to the count up of X and Y counters on the polygon display memory, and the triangular polygon formed by these three lines are rendered.[6] The polygon display memory used here has ten times the width of the memory needed for TV display, and the circuit configuration allows the polygon to be rendered completely even if the position of the polygon runs off the edge of the screen. For displaying on TV screens, only the display area is cut out and the triangular polygon pixels are displayed sequentially on the raster of the TV screen. To fill in the polygon during the raster rendering, the area from the first intersection of the raster and the triangular polygon line to the intersection with the next line in the horizontal direction is filled in. The screen image of Fig. 6 is from the flight simulator game Top Landing (1988, Taito Corporation), which implemented the polygon display for the first time in Japan.

[DSP polygon display limitations]

In the above flight simulator game, the relatively monotonous ground surface seen from the sky and a few high-rise buildings were displayed by polygons. In the train driving game, Densha De GO! (1997, Taito Corporation), many more polygons were needed compared to the flight simulator. In the early polygon games, multiple DSPs were used to handle the high number of polygons and hardware in which the polygon processing capacity was enhanced were used, but technical limits were reached in no time. Also, the effect of single colored images was unnatural, like a coloring book. Therefore, the next development goal became the creation of a hardware device that could display irradiating and reflected light as well as subtle differences in color.

2.8 Age of GPU rendering: 2000s

A three-dimensional image is created in three steps, as shown in Fig. 7. First, all the objects (people, building, background, etc.) composed of multiple polygons are arranged in the desired location using enlargement, reduction, or rotation in the “world coordinate,” a miniature landscape space. After “clipping” and other processes by which the objects are cut out in a two-dimensional plane from the direction of the point-of-view, colors are added with the direction of light in mind by the “rendering process.” Immense amount of real time numerical operations are necessary for all these processes. In the early period, multiple DSPs were used, and specialized graphic large-scale integration circuits (LSI) were designed and developed originally by arcade game companies such as Taito Corporation, Sega Corporation, and Namco Limited. However, the design work gradually became overwhelming, and after 2000, partnerships were signed with the specialized graphics processing unit (GPU) manufacturers that expanded their business to personal computers. Currently, NVIDIA Corporation of the United States and ATI Technologies, Inc. (later incorporated into Advanced Micro Devices, Inc.) of Canada are the two major GPU manufacturers. Figure 8 shows an example of the internal configuration of the current polygon display LSI (GPU).[7] Stream processors that excel in product-sum operation are arranged (SP in this diagram), and a micro-program (called the thread) is carried out. These engage in various tasks including vertex computation, clipping, or texturing, as needed. The main CPU provides the GPU with a certain data sequence (the data format is standardized in either Microsoft Corporation’s DirectX or Silicon Graphics International Corporation’s OpenGL), and the GPU conducts the desired process as it switches the thread and then writes the result to the video memory. In a sense, this part is a black

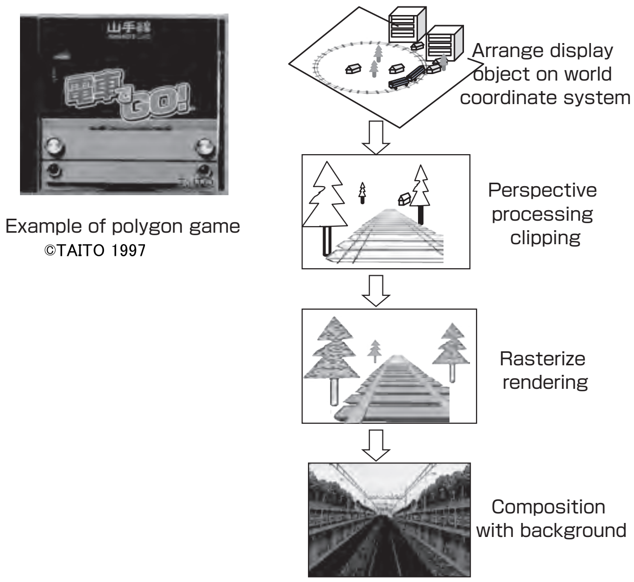

Fig. 7 Processing steps for three-dimensional display

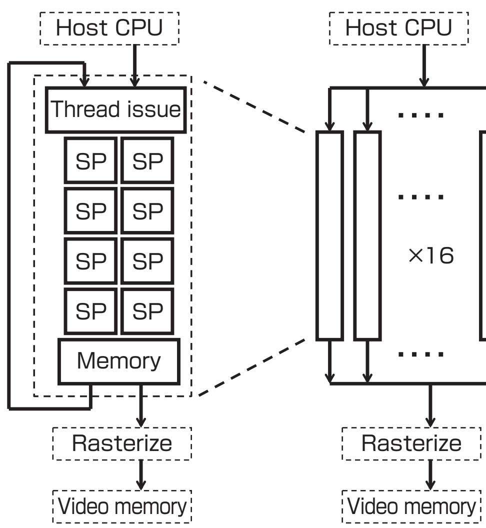

Fig. 8 Internal configuration of GPU
(created by author from *NVIDIA GeForce 8800 GPU Architecture Overview*)

box process. In the latest model, over 1,000 SP processors are installed, and the same GPUs are utilized in some supercomputers.

3 Introducing new technologies

In the arcade game industry, new technologies are often commercialized several years before other industries. The author feels there are three primary reasons for this: 1) the process of planning, prototyping, and market testing for arcade games runs in a short time cycle, 2) relatively expensive new technologies can be used, and 3) multi-talented human resources are available.

3.1 Short-term testing

In the arcade game industry, consumer feedback can be readily obtained by experimentally installing the prototype in the video game arcades, even with incomplete experimental products. In addition to the examples described above, various other original video display technologies were tested. Some of these technologies include the vector scan display method[8][9] that enabled the enlargement, reduction, and rotation of multiple displayed objects by directly rendering with electron beam of the CRT, the method that enabled the enlargement and reduction of the sprite displayed pictures on the hardware,[10] and the method that combined the game display and the laser disc (LD) that stored the moving image.[11] The consumer, regardless of the game manufacturer or the brand, puts in a coin (typically 100 yen), plays the game, and does not return if he/she does not like the game. The result is definitive, and various new technologies can be tested using the market as the testing ground. On the other hand, with home console game software, commercial success is determined by the number of games sold. This process is slow, since real consumer demand can only be measured after the game software has been finalized and the game discs pressed and distributed to the market.

In any industry, there are mechanisms for market tests such as provision of samples, but the process in the arcade game industry is particularly quick and accurate.

3.2 The costs of introducing new technology

The wholesale price of a standard arcade video game machine in the 1970s was about 500 thousand to a million yen, and about half of the cost was dominated by electronic parts. The CPU and memory were still expensive then (about 50 thousand yen), but the reason they could be actively deployed in the arcade games was because of the relatively high trading price of the game machines. Figure 9 shows the cost of introducing new technology to various markets. The left side shows the technologies that are innovative but still have issues in reliability and implementation costs; these technologies are generally reserved for research laboratory use. The right side shows consumer-oriented technology, and many are technologies that may take time before going over to the general consumer but the reliability and implementation cost have been thoroughly considered. The center portion is where the relatively high-cost new technologies and ideas are utilized, and this is where the arcade game market resides. For example, several years before microcomputer CPUs were widely adopted for general use, their appearance in the arcade game market stimulated use in related industries. Also, for polygon arithmetic processing, arcade games incorporated and popularized DSP in the early days of the technology, while it was still expensive and difficult to use. As known widely, the DSP has since come down dramatically pricewise, and multiple units are installed as the main part of the cell phones.

3.3 Multi-talented human resources

As mentioned earlier, the early arcade game industry was led by multi-talented people who engaged in the design of hardware, development of software, creation of graphic and sound effects, as well as hand-making their own development tools. This trend is still in place, and even in recent arcade game development,where the roles are specialized and divided, the producer tends to be well-versed in multiple technologies. (Specializations mainly include: 1) creating game concepts, 2) designing electronic circuit hardware, 3) programming, 4) graphics, 5) creating sounds, 6) networking, 7) mechanical configuration, and 8) production.)

Despite a different business model, this same background is found in the development of network karaoke, which grew from arcade game companies such as Taito Corporation and Sega Corporation,[12] and then led to the cell phone ringtone business.

Video game players enjoy novelty, and producers seek out new game concepts and technology that enables new forms of expression in an effort to respond to this demand, thereby

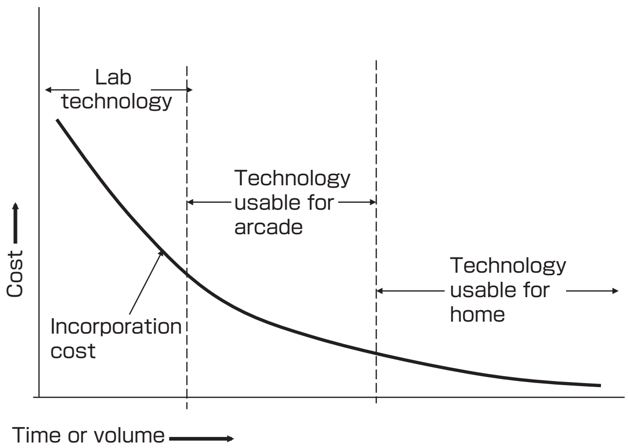

Fig. 9 The cost of introducing new technology

spurring technological innovation. The introduction of sprite and polygon technology are two examples of this. On the other hand, “novelty” is an abstract and intangible concept. Novelty can only be achieved through experimentation and implementation, which is why game machine prototyping and market testing are so important.

4 Display technology timeline and background

Figure 10 shows a summary and timeline of the evolution of arcade video game display technology.

The fundamental goal of video game display technology is to achieve a wide variety of hardware-based visual effects without overloading the CPU. To achieve this, circuit designs that enable the efficient and effective read-write of the video memory are important. The circuit design technology is utilized as follows: in the design where CPUs compete for the access to the video memory during the gaps in CRT display in the CPU bitmap method, in the logic where the pixels are directly written to the high-speed memory without mediating the CPU in the sprite method, and in the logic in which the polygons that reflect the result of the DSP computation is directly written to the memory in the DSP polygon method. Most of the electronic elements such as TTL and memory that were available at the time required design that enabled action at approximately their speed limit, and many design engineers found out from experience that even a slight oversight would lead to later problems.[5]

The background factors that promoted such technological evolution are summarized as follows.

[TTL → CPU bitmap] 1) There was a shortage of people who have both the ability to design hardware and to develop games, and it became necessary to separate the hardware and software. 2) In game development, fine-tuning and revisions were mandatory to increase the quality of the game, and the introduction of CPU was important to simplify these processes. 3) Independent display circuits (mainly logic circuit combined with a counter) were necessary for the display of moving objects, and when the number of objects increased the circuit size increased accordingly, and the measures against increased cost became necessary.

[CPU bitmap → sprite] To achieve exciting graphics, the sprite method was devised where the hardware logic was responsible for displaying 1) in high-speed, 2) multiple moving display objects, 3) without overloading the CPU.

[Sprite → DSP polygon] This was devised to display three-dimensional objects. While polygon technology was used in large-scale or specialized computers, their costs were way beyond what could be used for arcade game machines. Therefore, the following measures were taken for use in game machines: 1) thorough simplification, 2) employment of DSP as numerical operation element, and 3) design of specialized LSI for high-speed rendering. On the other hand, as a method to replace the polygon method, the vector scan display mentioned earlier, was available and used in many games in

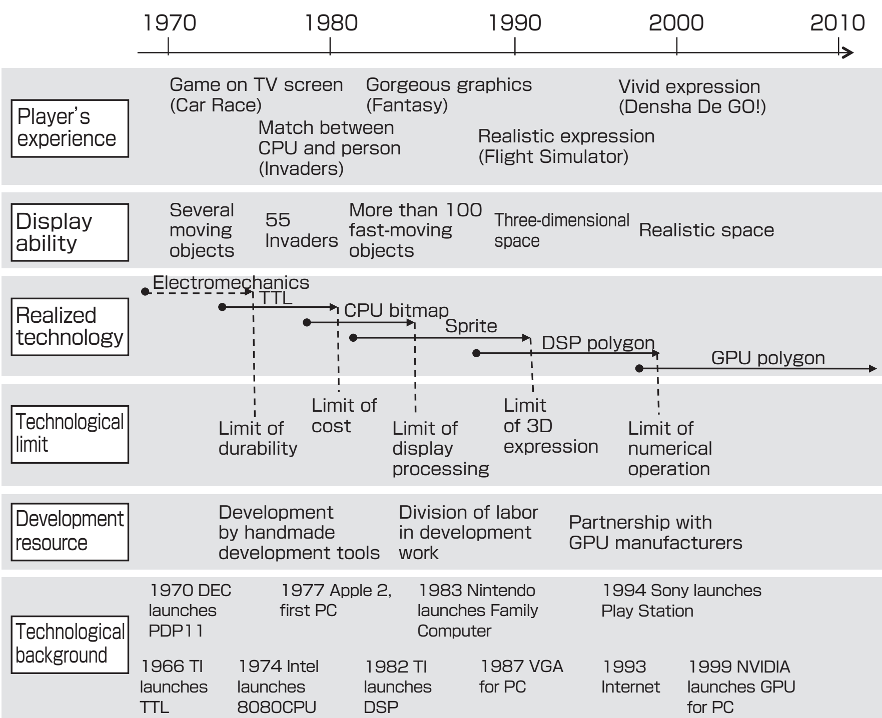

Fig. 10 Display technology timeline and background

the United States.[8][9] However, this method dropped out of favor because it was mainly line drawings so the objects were geometrical and could not be colored.

[DSP polygon → GPU rendering] In the polygon display, the vertex data are arithmetically processed, but the processing capability became insufficient when several DSPs were simply arranged in line, because 1) the polygon display of nearly hundred times more than in the DSP polygon was needed, and 2) the natural rendering and coloring with attention to lighting were demanded. The method of arranging dozen or more DSPs was considered at the time, but the data transfer speed between the memories was slow, and it became apparent that the cost and development time would be too great if they were done within the company, so partnership with specialized GPU manufacturers began.

On the other hand, because of the partnerships, the arcade game manufacturers now have less opportunity to utilize their original display technology. As a result, many games end up having similar visual expressions. Fresh technological innovation is awaited in the future.

5 Conclusion

Taito Corporation has been providing the Type X arcade video game hardware equipped with the graphic hardware of the aforementioned GPU manufacturer companies since 2004 (Fig. 11). It has a similar configuration to a high-performance personal computer, and an ordinary PC can be used directly as its development environment. Over 20 game companies including Taito create game software for this platform, and over 70 game titles have been marketed. The conventional arcade video game companies including Taito are now focusing on the development of the software library to maximize the performance of this hardware.

As mentioned earlier, arcade game technology is closely linked with business, and there are many games that were buried without ever seeing the light. On the other hand, technologies with little known history are actively incorporated, and may appear several years before their adoption by other industries, making arcade game developers technological pioneers.

Fig. 11 Video game hardware
TYPE-X (Taito Corporation)

There were times when video game arcades were considered delinquent hangouts, and something to be kept on the fringes of society. However, through the efforts of many engineers, creators, and the game arcade center operators, social recognition and legitimacy has been achieved. Currently, half of all game arcade visitors are women. I believe that the game industry—which is often discussed with Japan's other specialty, anime—will continue to advance, and new entertainments will be born.

Acknowledgement

I have learned much from Mr. Tomohiro Nishikado, who almost single-handedly built the foundation of the electromechanical games, TTL video games, and Space Invaders, during the earliest days of Japanese video games. He has my gratitude. Also, in writing this paper, I received a great deal of advice from the reviewers, Dr. Motoyuki Akamatsu and Dr. Masaaki Mochimaru of AIST, about how to meet the objectives of *Synthesiology*. I am thankful.

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Discussions with Reviewers

1 Overall structure

Comment (Masaaki Mochimaru, Digital Human Research Center, AIST)

This paper is an overview of the evolution of video games, the changes in software development system, and the ripple effect to peripheral technologies, with focus on the changes of arcade game image display technology. Finally, it offers prospects for the future arcade game technology. I think the overview and prospect of how the technologies are synthesized with focus on image display technology is beneficial content for *Synthesiology*.

Comment (Motoyuki Akamatsu, Human Technology Research Institute, AIST)

This paper describes the changes of the arcade type video game technology, addressing the technologies introduced over time, and it is a good example of the social introduction of technology. To avoid it from becoming a history paper of technology, please describe why the new technologies changed in the course of technological progression (goal setting), the basis of the selection of technologies to achieve the objective, and the technological issues that were solved to achieve the goal (development scenario and process).

Answer (Yukiharu Sambe)

Thank you very much for pointing out the places where clarifications are needed. I have revised the manuscript. Here are some additional perspectives:

Goal setting: Video game players enjoy novelty, and producers seek out new game concepts and technology that enable new forms of expression in an effort to respond to this demand, thereby spurring technological innovation. The introduction of sprite and polygon technology are two examples of this. On the other hand, "novelty" is an abstract and intangible concept. Novelty can only be achieved through experimentation and implementation, which is why game machine prototyping and market testing are so important.

Development scenario and process: The fundamental goal of video game display technology is to achieve a wide variety of hardware-based visual effects without overloading the CPU. To achieve this, circuit designs that enable the efficient and effective read-write of the video memory are important. The circuit design technology is utilized as follows: in the design where CPUs compete for the access to the video memory during the gaps in CRT display in the CPU bitmap method, in the logic where the pixels are directly written to the high-speed memory without mediating the CPU in the sprite method, and in the logic in which the polygons that reflect the result of the DSP computation is directly written to the memory in the DSP polygon method.

2 Progression of the developed technology to other products

Question (Motoyuki Akamatsu)

Since the technology and cost shown in the figure are very important points, I think it will benefit the readers if you discuss using specific examples. Specifically, can you describe, for individual technologies that were introduced as arcade game technology, how much was completed in the laboratory stage, how these technologies were improved so they could be used as game technology, and how they could be used as home-use technology through the progression of arcade game technology?

Answer (Yukiharu Sambe)

I added simple descriptions about CPU and DSP in the revised paper. Additional perspectives are as follows.

・In the 1970s when the CPU was still expensive and was not widely used industrially, it was used actively in arcade games. The TK80 (1976) that was sold by NEC Corporation as a CPU learning kit for engineers was priced at about 100 thousand yen. During this period, CPUs were already installed in some arcade video games. However, it took more than ten years before CPUs were installed in home-use machines.

・As you may know, DSP was introduced in the early 1980s by NEC Corporation and others for digital signal processing of audio compression, and was offered to various research institutes and some specialists. Later, Texas Instruments, Inc. of USA started shipment of DSPs, and the latest TI DSP (MS320C25) was installed in the arcade game Flight Simulator (1988). The trading price at the time was over 10,000 yen, and it was one of the most expensive semiconductors, but it is still used in various devices today.

・In creating the flight simulator game, we considered the flight simulator technology that was used for actual pilot training. However, the cost was so high just for the image display (several tens to hundreds of millions of yen), and it became obvious that direct transfer was not possible. As a result, original consideration and design of the simplified polygon display function (1988) was created. Polygons were used in home game machines seven years later, in 1995.

・Copy-protect method. This was not described in this paper, but after the Invader game, many game copiers proliferated throughout the world (early 1980s). As a copy countermeasure, we employed a method inspired by the "knapsack cryptosystem (1978)" that was being researched at the time. Specifically, a stored-program single-chip microcomputer that cannot be read externally was developed jointly with an American company, and copy prevention was achieved by conducting encrypted communication between the microcomputer and the main CPU. This was used in games including Front Line (1983, Taito Corporation). It had the same mechanism as the USB dongles that are currently used to prevent unauthorized copies.

3 Social objective of the technology

Question and comment (Masaaki Mochimaru)

One of the objectives of *Synthesiology* is to accumulate papers on how technologies were selected and synthesized when an objective was set to make some change in society, and what the results were. What are the social objectives of arcade games? For example, can you define them as "new user experiences" or "efficient development and management of devices"? This paper describes the changes of technology from electromechanics, video, TTL, CPU, polygon numerical operation, and GPU rendering. I think there were "new user experiences" or "efficient development and management of devices" that you wished to realize through the introduction of the technologies in each period.

When describing the changes of the image display technology, if you set the "new user experiences" or "efficient development and management of devices" that were demanded at the time as the objectives of that age, to achieve this goal, what kind of core image display technologies were selected (what were the reasons for their selection), and how were the peripheral technologies such as the CPU and memory, display device, and software development methods changed and combined? I think the paper will become significant to *Synthesiology* if you give an overview of the history of technology in terms of "selection and integration of the technologies for an objective."

Answer (Yukiharu Sambe)

・The social objective of the arcade games is to have the players experience the extraordinary and to provide richness to life. The player will continually seek the next "extraordinary experience," and the game company must create new game concepts to respond to such demands and develop new technologies, such as for display. As a result, expressions that could not be conceived in 1970 are now possible, and it has grown into a major industry.

・I revised and added the descriptions on the selection and integration of the technologies toward a goal. Particularly, I described the process of the shift from sprite to polygon.

4 Technological development in one's discipline and the introduction of technology from outside disciplines

Comment (Masaaki Mochimaru)

Considering that the new image display technologies are selected and integrated according to the social demand for "new user experiences" or "efficient development and management of devices," aren't there two courses: 1) the developed technology is transferred from the technological progress in other fields (TTL?), and 2) the technological development is led by the arcade games (sprite? GPU?)? You present a framework where even if the sprout of the synthesized elemental technology belonged to one's discipline, if the technology progresses elsewhere, one can incorporate the technology that progressed in another discipline without being trapped by the technologies of one's own realm. I think the paper will be significant as a *Synthesiology* paper if you also include the description of how the synthesis of such technologies were effective in achieving the objective of "new user experiences" or "efficient development and management of devices."

Answer (Yukiharu Sambe)

I added descriptions to part of the revised paper. Additional perspectives are as follows:

・As you know, TTL was developed for use in general-use computers, and it was recognized from the beginning that its ability to provide easy digital processing was essential in video games.

・The DSP that was used in the early polygon display was introduced for digital signal processing for audio compression in the late 1970s, and the game industry that realized the excellent numerical calculation capacity used it for the numerical calculation of polygons.

・For GPU, there was a plan for using a dozen or more DSPs to display complicated polygons, but the cost was too much for the development and product, and we started partnerships with external GPU companies. As a result, the game development environment could be purchased from the GPU companies (i.e., it was no longer necessary to prepare them within the game company), this reduced the development cost, and realistic three-dimensional expressions became possible by using the GPUs that evolved along with the advancement of PCs. On the other hand, since many arcade game companies deployed similar products, the expressions became similar, and this is one of the most important points of consideration when thinking of the future direction that must be taken by the arcade game industry.

5 Prospect of the arcade technology

Comment (Masaaki Mochimaru)

In looking at the prospects for the "next arcade technology," I think the point of the whole paper would become clear and easy to understand if you take the viewpoint of what objectives are set as "new user experiences" or "efficient development and management of devices."

For the category, "new user experience," hasn't it reached the saturation point? Because the "new user experience" has been taken to the limit for certain users, I feel many users have quit following games. Seen by the reviewer, the three-dimensional display and hemispherical screen display are directions for heightening the "new user experiences" in terms of the advancement of image display, and the "return to electromechanics" is suggesting a "new user experience" through interface with different physical capacity other than high-speed motion or high-quality display. In terms of home-use machines, the former may be positioned as the Sony Computer Entertainment product and the latter may be Wii. I think it will be interesting if you discuss this area deeper and provide prospects for future technology.

Answer (Yukiharu Sambe)

・As you indicated, the category, "new user experience," has somewhat become saturated. There are probably more than a hundred different shooting games like Space Invaders on the market, and this genre has become saturated except in certain areas. It is also a genre where some enthusiastic fans sought increasingly difficult games and the general users dropped away.

・In the initial draft of the paper, I wrote about the hemispheric screen and return to electromechanics as part of the "new user experiences" category. As you indicated, these are new experiences through the advancement of image display and interface. However, because they depart from the "evolution of video games" that is the core of the paper, and also because of the rather unclear descriptions, I omitted this section in the revised version.

6 Change in the number of people involved in the development

Question (Motoyuki Akamatsu)

It is interesting that the numbers of people involved in the development changes in each generation. Can you describe for which technology how many people became necessary?

Answer (Yukiharu Sambe)

The specific number of people involved in development cannot be counted easily, and I didn't include them in the paper, but the number of people that increased the most was those in charge of graphics. Initially, simple graphics were used, but recently, the number of developers increased for 3D modeling and motion creation. While the number of programmers increased, due to the evolution of development tools (OS environment and development language), it has not increased as much as for the graphics. For the people of electronic circuit hardware, the number was highest during the age of the polygon when we designed the LSI on our own, but hardware specialists decreased since we changed the policy to using the GPU of NVIDIA, etc., during the rendering age.

7 Background for entering the video game industry

Question (Motoyuki Akamatsu)

Taito Corporation was a jukebox company in the beginning, but what was the motivation for going into video games? Also, I think placing the Space Invaders game machines in the cafés was a new business model. Can you describe why you decided to do so?

Answer (Yukiharu Sambe)

On jukeboxes: As you indicated, Taito was engaging in the business of importing and renting jukeboxes in the 1960s. At that time, imported pinball machines were placed next to the jukeboxes. We decided to place our original electromechanical games there, and this led to the development of video games.

On why the games were placed in cafés.: On the tables in the cafés in the 1970s, there were Peanut Vendors, which were small vending machines that sold small amounts of peanuts in exchange for coins. As peanut sales dropped, games were considered as a possible replacement service to keep customers spending coins while sitting at the café tables. In fact, table-form TV games for cafés were already on the market before the arrival of Space Invaders, but I think because Space Invaders became so popular, it became strongly associated with cafés.

I am made aware once again that technology and business continue to grow as they gradually change their forms.