OPEN GAMES CONSOLE

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ABSTRACT

This document reviews the historic, current and future technology of game consoles. It's purpose is to evaluate the entire field of game console design and development - as well as can be done - and to identify particular areas of interest for further research.

To this end, the history of popular consoles is reviewed, with an eye towards predicting where they are headed, and anticipating consumer desires so far as functionality and performance are concerned.

The physical requirements of consoles is review - things such as geometry, weight, power efficiency, heat production, etc. These general areas dominate design to a large extent, and are important to establish before running too far ahead picking out functionality and components.

Lastly, current and future technology in numerous areas is evaluated. From processing requirements to user interfacing, batteries to data storage to software. The scope of this research is enormous, so only select concepts are presented for review.

In conclusion, this review finds numerous problems with game console design and development, high lighting those considered particularly important. Possible directions for future work are indicated, one or more of which will likely be adopted by the author for his thesis.

ACKNOWLEDGEMENTS

First and foremost to be thanked is Dr. John Rankin for supervising this literature review, enduring it's slow development and proof reading it's drafts.

Thanks are also warranted for the La Trobe Computer Science department for authorising the thesis and committing to it's research, development and evaluation.

On a personal note, a heartfelt thanks to all those who endured the author's grumpiness, sourness and tiredness during the writing of this review. These include people at home - friends and family - as well as school peers, lecturers and others too numerous to mention. May you never be burdened with this again.

Finally, thanks also to the researchers, journalists and hackers who came before, who walked the road less travelled, and carved a path that might be followed by those such as the author. Without their motivation to disseminate knowledge to others, this review would not be possible. This is, in fact, a special thanks to the human spirit that endeavours to learn and to teach, without which our very lives would not be possible.

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1.0 Introduction

For all their astronomical success, there is a real problem with modern consoles. They are not open. They are produced by commercial entities with strict focus on profit, market dominance and control. You cannot exchange games between any two consoles from different manufacturers - indeed, you frequently cannot exchange games between two consoles from the same manufacturer. It is postulated that this is fundamentally a bad thing - it limits the usefulness of the devices, it dictates consumer behaviour by platform lock-in, and it raises artificial barriers of entry for software and content developers. It is the purpose of this thesis to evaluate how an open console system can be developed. There are two fundamental approaches to solving this problem.

1.1 Hacking an Existing Console

As a path of lease resistance, hacking consoles to open them up has been very popular. The most common application of this, of course, has been in "mod chipping" [62] them[1]. This is the process of removing significant copy protection mechanisms, primarily to allow the use of pirated games. This kind of modification doesn't necessarily open up the system at all, although in some cases it can be used for such purposes. Examples abound of people utilising mod-chips and other hacks for perfectly legal purposes - such as to install Linux on their Xbox[2] or PS2 (PlayStation 2)[3], or to develop their own software for the system. Indeed, Sony officially support and sell components necessary for installing Linux on the PS2[4], which has produced a large, healthy community of 3rd party developers & hackers. Their new PSP (PlayStation Portable) has been extensively hacked and is quickly becoming the preferred portable for the tinkering demographic.

However, the potential for this 3rd party involvement is ultimately limited. Modern consoles largely lack common device interfaces - such as USB, Firewire, Ethernet or Serial ports - and are consequently limited in terms of how easily they can be modified by the end-user. In addition, the legality of the mod-chips necessary to open them up is

[1] http://www.modchip.com/

[2] http://www.xbox-linux.org/

[3] http://playstation2-linux.com/

[4] http://www.us.playstation.com/peripherals.aspx?id=SCPH-97047

murky at best in some countries - notably the U.S.A. and Australia - and consequently the distribution of 3rd party software is stymied.

The advantage, however, with hacking at an existing console is primarily economical, when considered on small scales. Consoles are made in enormous quantities which utilise exceptional economy of scale, and are frequently sold below manufacturing cost, making them worth, in some cases, *less* than the sum of their parts. Witness, for example, the work of Benjamin Heckendorn [63], who has repeatedly converted home consoles - ranging from original Atari's to the modern PS2 - into portable game consoles, complete with machine-made custom cases providing a high quality finish. He has written a book on his exploits in this area [64], although a copy could not be obtained in time for review.

1.2 Developing a New Console

Modern computer technology has advanced so much in recent years that it is now conceivable for everyday people to develop their own game consoles.

An example of a "home-brew" console is the XGameStation[5], developed by Nurve Networks, designed as an educational console for would-be developers. It sports typical television outputs, serial inputs for joysticks, and a parallel port for direct programming with a PC. It is sold in kit form for $200US, which includes the board itself, a CD containing reference material and development tools, and the necessary adapters and peripherals to operate the device. As a console it is hopelessly underpowered by today's standards - it is approaching the capabilities of the original PS (PlayStation), but without the more advanced features such as hardware accelerated 3D. But it does demonstrate that a console can be built cheaply and with relatively little technical knowledge, using standard parts and software such as BASIC and gcc. Unfortunately, it is immediately useful only for those who enjoy tinkering with such things - it would have absolutely no appeal to any normal gamer.

Traditionally, game consoles were developed as dumbed down arcade machines, by manufacturers such as Sega, Nintendo, Atari & SNK. These consoles were derived from existing products with substantial research and development, and mass produced to

[5] http://www.xgamestation.com/

utilise vast economies of scale. In modern times, commercial game consoles have developed in several key ways.

- They have become vastly more prolific, with over 100 million PS's sold during it's 8 year life [11], and 85 million of it's successor, the PS2, sold in just 3 years [47]. Combined video game hardware & software sales exceeded $10US billion in 2002 [31].
- They have developed a substantial market for portable game consoles, starting with systems like the Lynx and Sega Genesis, and evolving into the modern Gameboy Advance, and more recently the Nintendo DS and PSP. In their first week both the Nintendo DS and the PSP sold more than half a million units each, in the U.S. alone [46].
- They have become much more like PCs (Personal Computers). While the original home consoles were proprietary and closed systems - built from either their more powerful arcade siblings or completely from scratch - modern consoles are built from off-the-shelf parts, using standard components and interfaces (e.g. USB & Ethernet on the PS2 [12] and Ethernet on the Xbox [13]).
- They have become cheaper. Modern consoles retail for less than $300, while the first big consoles of the 80's retailed for at least $300 way back then [14] [15] (as much as $2000 in today's money[6]).

It is the last two points which are of particular interest. With systems such as the Xbox being essentially a specially modified PC, the question naturally arises as to what the difference is, and more-so why your average Joe cannot build their own game console using standard PC technology, cheaply and easily.

Indeed, the next generation of consoles embody this cost-efficient, PC-based approach even more. All three major manufacturers - Microsoft, Sony and Nintendo - are expected to use CPUs (Central Processing Units) derived from and very similar to the PPC 970 processor currently used in Apple's iMac and PowerMac computers [16] [17] [18] [19]. Both the PS3 (PlayStation 3) and the Xbox 360 (the next Xbox) are also expected to use

[6] Assuming 10% compounding interest.

other standard components, such as SATA hard drives and NVIDIA or ATI supplied GPUs (Graphics Processing Units).

Given this precedence set by the major console manufacturers, it seems it should be quite plausible to develop an open, standard, off-the-shelf games console. It is the purpose of this document to review the current state of the art in this field, to identify possible problems with developing an open games console, and to compare development of a new console with hacking an existing one.

Figure 1 - The Nintendo DS

2.0 Console History & Uses

Originally consoles were simple, single-purpose machines. The first consoles often supported only a few built-in games, with no options for future expansion. While by the late 70's there were several cartridge-based consoles available, such as the Atari 400 and 800 [20] (pictured left), and the Fairchild Video Entertainment System [21], it wasn't until the release of the NES (Nintendo Entertainment System) - pictured below right - in 1985 [22] that cartridge consoles - and indeed consoles in general - really became mass consumer products. This is not a coincidence - the attraction of expandability to both consumers and developers led to a boom in home consoles. The NES sold more than 60 million units for the sole purpose of playing games.

Figure 2 - Atari 800

Figure 3 - Nintendo Entertainment System

Moving forward a decade to the world release of the PS in 1995 (released in Japan in 1994) [23], consoles had developed little in purpose. The PS sported the ability to play audio CDs, but was without a doubt still designed solely for gaming.

Another decade on to the present day, and most home consoles are capable of playing audio CDs and DVDs. Many, however, are beginning to diverge into other areas, serving as versatile home entertainment systems and - with the PSP - personal information managers.

2.1 GAMING

As the primary purpose of consoles, gaming is the dominant force behind console design. Gaming puts great emphasis on several key parts of console design:

- *Powerful processors and dedicated support hardware for graphics, audio and other tasks.*

  These enable higher quality output to the user, improving immersion and providing more possibilities for game developers. For example, true 3D graphics were not possible on the first generation of consoles - the NES and SMS (Sega Master System). On modern consoles with expensive dedicated 3D hardware - like the PS2's "Emotion

Engine" (pictured right) - 3D is the status quo, with entirely new genres - e.g. first person shooters - arising as a result. Most if not all existing genres also benefit from these advances, from racing & simulation games to sports and even puzzle & arcade games.

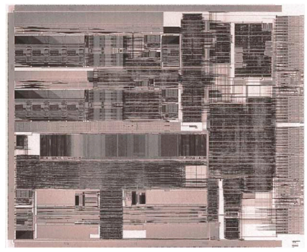

Figure 4 - PlayStation 2 "Emotion Engine"

- *Programmability*

This means the flexibility of the console to run many games, and more-so many very different games - from 2D platformers to 3D simulations to, perhaps, not even games at all, for example movies and music.

There are two key elements in providing high programmability. The hardware must be flexible and general enough to support a variety of uses. Consoles have typically been more focused on gaming than computers, with significant trade-offs of generality for performance. A balance must nonetheless be reached, particularly with modern consoles being applied to a wider range of tasks.

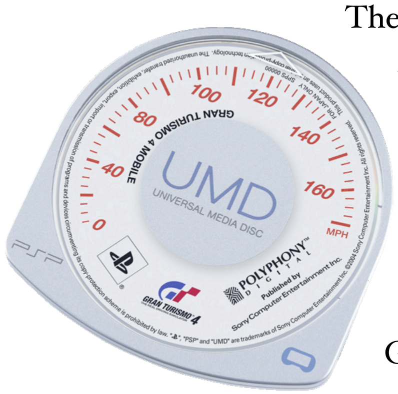

Figure 5 - Sony PlayStation Portable Universal Media Disk

The second element is how the console can be reprogrammed. In layman terms, this means what discs, cartridges or other mediums it supports for 'loading' software. While the very first consoles provided only built-in games, modern consoles provide games on a variety of CD or DVD-like media, such as Sony's UMD (Universal Media Disc) pictured left, as well as via cartridges, Flash memory cards and even over the Internet. Games need to be easy to acquire, store and load in order for end-users to adopt them and the console.

- *Interfaces*

Very few consoles ever shipped with anything resembling a computer keyboard. Many shipped with only a directional pad or joystick and a couple of buttons - e.g. the SMS and NES controllers pictured to the right. Modern consoles have tended more and more towards multiple joysticks, direction pads, buttons and triggers, such as the Nintendo 64, Xbox and PS2 controllers pictured on the next page (in order left to right).

Figure 6 - Sega Master System & Nintendo Entertainment System Controllers

Figure 7 - Nintendo 64, Microsoft Xbox & Sony PlayStation Controllers

Figure 8 - Nintendo GameCube Steering Wheel Controller

Even more interesting are the specific and sometimes obscure dedicated controllers, for particular genres or even specific games. For example, racing wheels were traditionally quite popular, like the GameCube one pictured to the left. There are also things like the GameCube Bongo drum controller (pictured right), which probably falls into the obscure category.

Figure 9 - Nintendo GameCube Bongo Drums Controller

The trend is towards more complex default controllers, to try and fulfil the simultaneous needs of many tasks. The market for use-specific input devices appears to be shrinking on modern consoles - once popular controllers such as light guns, pedals and joysticks are increasingly rare.

2.2 Media

The first several generations of consoles, up until the Sega Genesis and the PS, were built around proprietary, read-only storage mediums, as opposed to standard CDs or DVDs. The reasons for this are now mainly historic - CDs were not invented until 1980 [24], and didn't become popular until the early 90's, long after the first generation of consoles had come and gone. Alternative storage methods were either too expensive, too small or too unreliable (e.g. the venerable floppy diskette), and usually suffered from unacceptable access latencies (still a problem with modern consoles) [25].

Figure 10 - USB Storage Devices

Today, there are numerous new media forms available for home-built consoles. In addition to the traditional optical media such as CDs and DVDs, there is also Flash memory in the form of cards or USB devices. Typically audio CDs and video DVDs are supported by suitably equipped devices, as well sometimes as more esoteric formats such as photo CDs and VCDs (VideoCDs, a low-tech precursor to the DVD). This expands the role of the console as a general entertainment device. They are, however, typically limited by the availability of writable media - no console ships today with a CD or DVD burner, and most still lack any significant amount of permanent storage. Thus, users cannot store their music collection on them, or create original content of their own.

Figure 11 - A 1 gigabyte IBM Microdrive

There are alternate approaches to storage (and transfer) - such as the emerging combination of so-called "microdrives" (1" hard drives) alongside USB or Firewire connections, or even Ethernet connections - possibly via wireless means. These may well expand the abilities of consoles into the areas in which they are presently deficient, such as multimedia authoring and management.

2.2.1 The Digital Hub

Looking towards the future, the constant desire to integrate multiple devices implies consoles will eventually need to import content from many sources - particular digital still & video cameras, music players and other devices. This requires either direct connectivity between these devices (even if only for "live" usage), or sharing of storage (e.g. Flash memory cards). Research by the NPD Group [29] has shown that 34% of the PC-using U.S.A. population utilise home networking - more than 50% of whom do so to share photos, more than the 17% who share music. It appears there is certainly demand for these kinds of services in the home, and that consumers are already adopting the necessary technology.

Figure 12 - Casio Digital Still Cameras

It's worth noting that the Apple iPod, a portable music player with multimedia and [minimal] gaming functionality, sold approximately as many units (more than 5.3 million [4]) in the first quarter of this year as both the PSP and the Nintendo DS[7]. While not a console per se, it emphasises both the consumer desire for portable media, and that there

7 Exact figures not yet available for Nintendo DS or PSP sales over this time - estimate based on known figures and sales estimates provided by Nintendo and Sony.


Figure 13 - The Apple iPod

is more than one way to develop a console - the iPod is not technically comparable with any of the major portable consoles today, but could be made so in the near future. Indeed, rumour has it Apple have adopted the Broadcom VideoCore® II processor for future iPods, which will provide more than enough power for gaming, high definition video, and other purposes - clearly they have something in mind beyond mere music [68].

Conversely, the PSP appears to be trying to expand game consoles into the music player market, with similar - albeit much more limited - functionality to the iPod for storing and playing music. [50] loosely compares various portable devices for their varying abilities in these areas, noting if nothing else the convergence of devices towards some kind of uber-device, capable of performing nearly all a persons computing, communication and entertainment needs.

2.2.2 Online Content Delivery

A future direction for consoles that has not yet been widely explored in the marketplace, but which has been the topic of numerous papers and dissertations, is the possibility of delivering content entirely over the Internet. [3] looks at the plausibility of this for home consoles, with certain expectations about the requirements of Internet delivery (particularly the average or maximum size of a program). In the hypothetical system presented, a tiny OS (Operating System) - 64 KiB or less - is stored in ROM (Read Only Memory) on the device and software of up to 32 megabytes in size is retrieved over an Ethernet network (which may, in turn, be connected to an ADSL, cable or dial-up modem). The authors simulated the system using ordinary PCs. Their conclusion was that it showed great promise, allowing for rapid and cheap delivery of new games and content, and presented viable new business models such as subscription & rental services. They did find, however, that the system was not satisfactory in terms of user experience on anything less than a 10 Mb/s connection. They also highlighted potential issues with reliability of service, particularly for aspects of games such as cinematics. They did not, however, look outside the game market. For example, streaming music and video, which have different requirements to gaming, may well be more suited given current telecommunications infrastructure.

Clearly this technology is intriguing and worth much further investigation, but the infrastructure to support it is not presently available for the vast majority of the population.

2.3 Communication

Communication between players has traditionally been limited to physical proximity - multiple people playing at the same single console. Modern consoles however employ numerous methods of linking consoles and consequently players - at a console level, both the PS2 [12] and the Xbox support networking using TCP/IP over LAN or the Internet. On the portable side the PSP [27] and Nintendo DS [28] both support wireless networking (although, notably, not between each other).

2.3.1 Wireless Networking

Figure 14 - A Verizon 802.11 Wireless PCMCIA Card

In the future, portable consoles may utilise the cellular phone network for long distance networking - as well as to satisfy many other incidental purposes such as web browsing and other connectivity functions - email, SMS (Short Messaging Service), etc. They may even connect together wirelessly to perform key functions, such as providing additional processing power, storage, or other functionality. Wireless controllers are already quite popular for home consoles, and with the rapid adoption of Bluetooth throughout other electronics devices, it seems inevitable that wireless will be a strong focus for the near future.

One application of wireless networking is the possibility of integrating real-world activity within games. [51] is one such example, bringing the famous Pac-Man game off the screen and into reality, utilising various technologies such as portable computers, wireless networking and VR (Virtual Reality) interfaces.

2.3.2 Online Gaming

Online gaming has long been popular with PCs, and has flowed over into the current generation of consoles - particularly the Xbox. The online gaming market (PCs and consoles) was worth $1.9 billion U.S. dollars in 2003, and is expected to grow to nearly $10 billion by 2009 [59]. The market for mobile phone games was over $1 billion alone in 2004 [60].

Figure 15 - "Soldner: Secret Wars", an online-multiplayer FPS

One aspect of online gaming that has not been fully exploited in consoles to date is it's ability to transcend niche demographics. [41] provides a general summary of online gaming over the past few years, but focuses in particular on the types of games played, and by whom. The authors observe that despite the hype surrounding MMPORPGs (Massively Multiplayer Online Role Playing Games) such as *Everquest* & *Ultima Online*, the vast majority of online gamers play games in other genres, using traditional services such as Yahoo Games, MSN Zone and Pogo. It is an interesting possibility that, given the increasing availability of broadband in the home, the demographics of traditional console owners may shift considerably, opening new markets and increasing the industries huge revenues. [6], for example, evaluates a fish-breeding game developed for mobile phones. It breaks the mould on traditional western gaming, and is an elegant solution to the limitations of mobile phones as gaming devices.

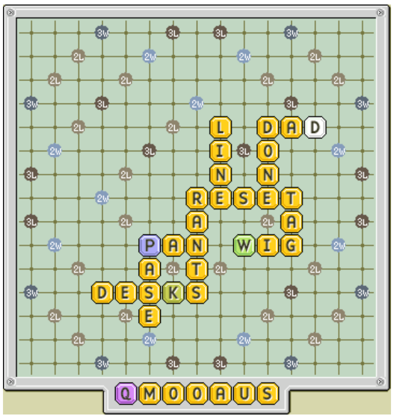

Figure 16 - "Literati", a popular puzzle game at Yahoo Games

2.4 WORK

Figure 17 - Microsoft Word

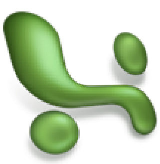

Figure 18 - Microsoft Excel

One aspect of consoles that has been completely untapped to the present day is their potential for 'work' - tasks such as word processing, email & messaging, PIM (Personal Information Management), etc. As they converge more and more towards PCs, the ability for them to do so will no longer be limited by their own technology. Instead, it will likely become limited, as it also is now, by the output quality and the availability of suitable input devices. The majority of current installed televisions are capable of displaying at most 720 x 565 pixels. In reality they rarely display much better than approximately 500 x 300 pixels, which is largely unsuitable for text. They are also deficient in clarity, response times and other factors.

Figure 19 - Microsoft Powerpoint

Figure 20 - Microsoft Entourage

2.4.1 Personal Information Management

Portable devices are unlikely to be suitable for things such as word processing, as their physical requirements don't allow for a suitably large screen, nor a comfortable keyboard-style input device. They may, however, function very well as PIMs. Mobile phones and Palm[8] devices have already demonstrated the consumer desire for such functionality, and the many ways it can be extended - such as the common ability to send and receive digital business cards between all manner of devices, and to sync PIM information between multiple devices, including phones, computers and others (e.g. the Apple iPod).

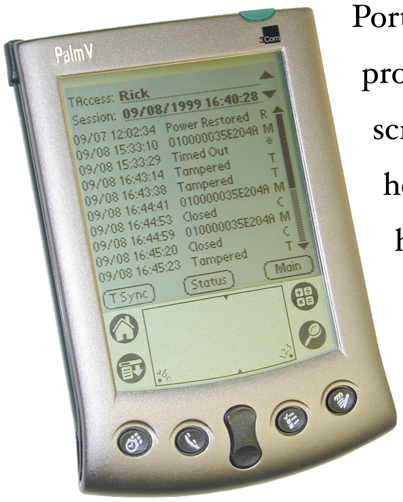

Figure 21 - Palm V Handheld Computer

2.4.2 Education

The use of consoles for education has been somewhat minimal. Some games are designed to be educational, but typically are aimed at a very young audience - pre-adolescents - and often have little real value. In schools the biggest influence consoles have had is in extending the contraband items list to include them, with the perception that they are only for gaming and serve only as a distraction. There have, however, been some strides towards more amicably adopting such technology within schools and universities. Case in point is the experimental iPod program at Duke University in the U.S.A.[9] First year students were provided a free iPod as part of their enrolment, with the university eager to see how the device could be utilised

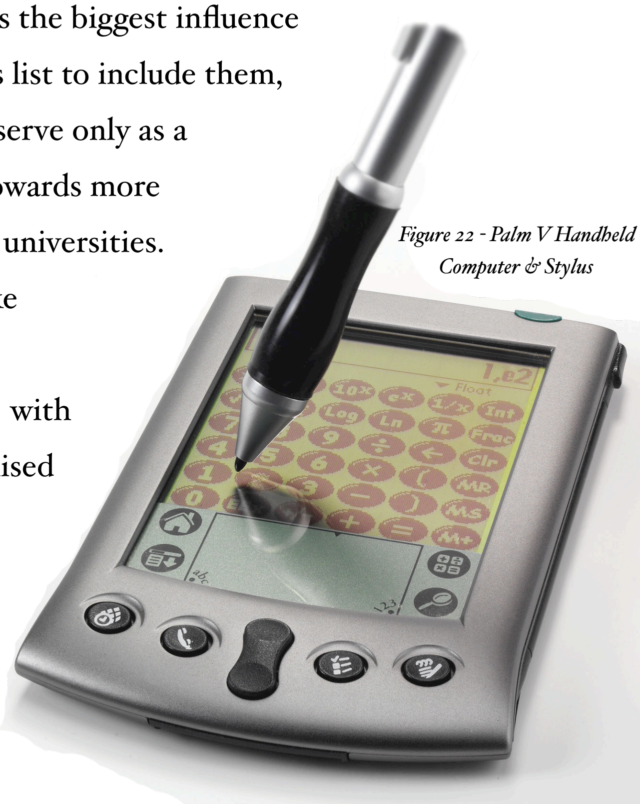
Figure 22 - Palm V Handheld Computer & Stylus

[8] http://www.palm.com/

[9] http://www.duke.edu/ipod/

for educational purposes. While the reaction by some has been hostile [82], the potential for the devices has been realised - they have been used as convenient portable storage devices, as ways for students to explore music and audio relevant to subjects such as Literature and Music History, to record lectures and other notes, and much more [83] [84].

While the iPod is not a games console, it is very similar. For the uses described, a PSP or similar console would serve just as well - and with the game-orientated high-quality screen, possibly be even more useful. The key reason why a game console was not provided instead of an iPod is, again, the perception that these devices are only good for games. Hopefully that perception is rapidly changing, particularly with multipurpose devices like the PSP.

Figure 23 - Sony PlayStation Portable Promotional Shot.

3.0 Physical Requirements & Constraints

A console must be easy to use, and practical for it's given purpose. A home console, for example, ideally needs to fit into the same sort of space as other related devices - VCRs, DVD Players and such. In such an environment, air flow may be restricted and many devices may be gently warming each other constantly, so heat tolerance and production is an important consideration. For a portable, size is vital - if it doesn't fit in your pocket, it probably won't be carried around very much.

3.1 Size, Shape & Weight

The physical dimensions of a console are important, particularly for portable consoles. While the current Xbox has shown that there is reasonable consumer acceptance for "oversized" consoles (as compared to the perceived norm), there have been many negative comments, and it is reasonable to assume this may dissuade some customers from purchasing the console, probably in favour of one of it's competitors.

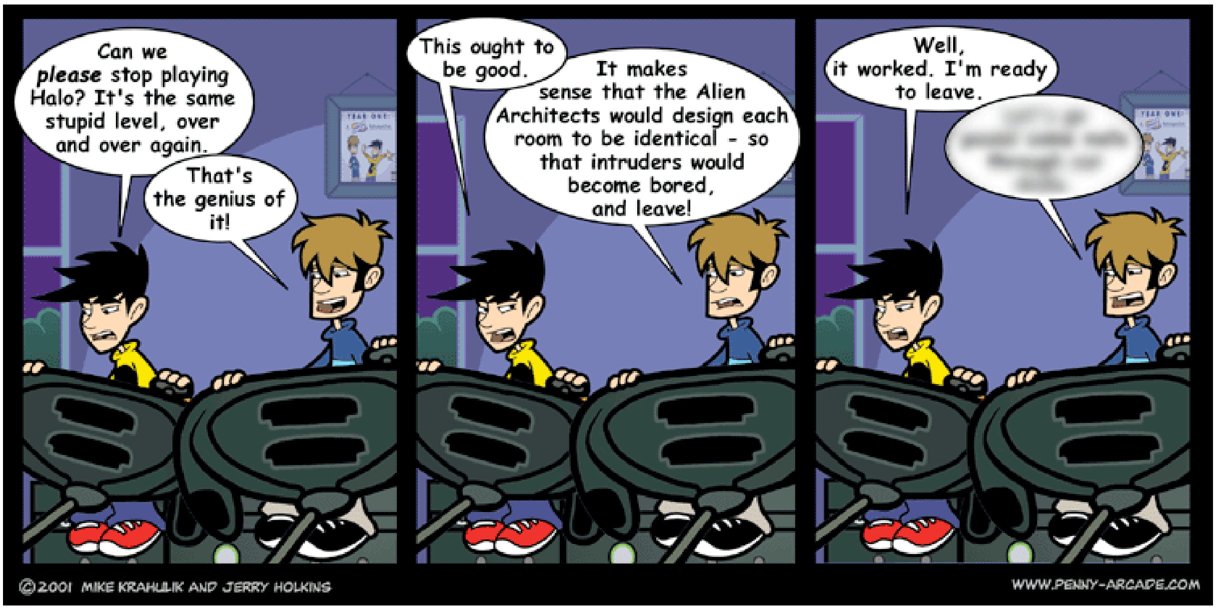

Figure 24 - A Penny Arcade (http://www.pennyarcade.com/) commentary on the size of the U.S. Xbox controllers

3.1.1 Handhelds

The name itself is largely a give-away - if a device is to be a handheld, then it must be possible to do just that, comfortably and for an extended period while using the device. The original Gameboys suffered greatly from this - for the target audience, adolescents, it was quite a bulky device. Modern portables have greatly improved in this respect - the PSP and DS are both compact, relatively light devices, with comfortable controls. For a new entrant into the portable market to stand any chance against these established heavyweights, it must match them in size, weight and comfort.

3.1.2 Contextual Consoles

Moving away from a traditional console experience, there are other forms that consoles may take. [7] talks about a console built around a SuperSoaker™ water pistol, which allows players to walk around in real life and interact with both real objects - including other players - and virtual objects, as represented on the consoles screen or through similar interfaces. The physical requirements of such a console are markedly different from a traditional hand-held console - it must fit into the unusual geometry of the casing (the water pistol) and must be light enough to be freely wieldable by the player, who will need to carry it for significant distances and times. Another example of this use and unusual requirements is presented by the Pac-Man game already mentioned [51].

3.2 Heat

One of the biggest barriers to faster, more powerful devices is heat. All of today's electronics produces some small amount of heat, as an unfortunate by-product of their operation. When millions of tiny transistors are crammed together onto an IC (Integrated Circuit), the collective heat output can become very significant. The latest high-end PC microprocessors from Intel, AMD and IBM all produce up to (and sometimes beyond) 100 Watts of heat [70] [71] [72], like the dual-core Athlon who's die is shown to the left. And it's not just CPUs; these days the leading GPUs from ATI and NVIDIA produce just as much heat - often more, although they're quite cagey about admitting as much. While PCs can tolerate such levels of heat by adopting powerful, elaborate and [typically] noisy cooling schemes, the limitations on size (mentioned in 3.1) and particularly noise make most of them inappropriate for a console. This applies especially to portable consoles, where luxuries like fans and large heatsinks are typically unavailable.

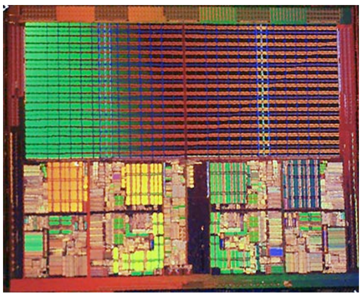

Figure 25 - The die of an AMD Athlon dual-core processor

To counter this, commercial consoles have adopted components that favour efficiency over peak performance - this is shown in more detail in 4.1.1. In portables especially, CPUs are typically years behind the PC industry in terms of absolute performance, but conversely are years *ahead* in terms of performance-per-watt efficiency.

[76] is a review of cooling techniques up to it's time of writing (2004), from the perspective of mainframe and server engineers at IBM. They talk about the various general forms of cooling, and their relative efficiencies and trade-offs. They reiterate well known maxims and confirm some common assumptions - such as the huge improvement liquid-based cooling systems offer over solid-state cooling. They also make the observation that PCs will soon, inevitably, follow in the same footsteps as mainframes many years ago - adopting advanced cooling systems, whether liquid or vapour based, or some other as-yet-unknown esoteric means. [77], a presentation by another researcher from IBM, states this even more clearly with predictions of power usage, chip speed and chip size over the next five years. Inevitably, although neither paper mentions consoles specifically, consoles and other such performance-driven electronic devices will be forced to follow these trends.

3.2.1 Liquid Cooling

There are two key areas of cooling - interchip and intrachip. In the former case, the concern is with dissipating heat away from individual devices on a board, to keep not only those particular devices cool, but also those around them. For this use liquid cooling is already being used within PCBs (Printed Circuit Boards) themselves, as reported in [74], which discusses one particularly implementation and notes it's performance, although they defer any direct comparison with alternative cooling schemes. [75] does, however, compare liquid and vapour cooling to various solid-state heatsinks, using a 1 gigabyte DDR memory module for experimentation. They found the liquid & vapour cooling to be far more effective at rapid and even heat distribution than traditional aluminium heatsinks. Their focus was on space-limited systems, with the assumption that devices such as fans were too bulky to be used - as is generally the case with portable consoles.

On the other hand, intrachip cooling looks at dissipating heat away from certain hotspots within a particular chip, to prevent any single part of the chip limiting the overall performance. There have been remarkable recent developments in miniaturising liquid cooling systems, to make them suitable on such small scales. [69] reports on work at West Lafayette University in the U.S.A., where researchers have begun testing "micro-channel heatsinks", which could be used to greatly improve the efficiency of heat redistributing within a chip and heat extraction from the chip. To do this they had to overcome difficulties with dealing with liquids in such small "pipes" - just 300 µm in diameter. At these scales liquids behave very differently, according to the report, and require new mathematical tools to model such systems, in order to design efficient systems based on them. Unfortunately the report does not discuss any commercial applications or availability, nor does there seem to be any existing such systems available in mainstream devices today. There does seem to be a lot of interest in this area, nonetheless, and has been for quite some time - as far back as 1995 the German government's research department recognised the problem, and formed a task-force with 11 industry partners - including Siemens and the Fraunhofer Institute - to develop micro-cooling systems [73]. Alas for them, the big breakthroughs - such as accurate modelling of fluid dynamics in micro-channels, as mentioned - have only occurred in the last few years, and the fruits of these labours are yet to ripen commercially.

3.3 Power

Power used is usually directly related to heat output, so similar rules apply - consoles typically can't use as much as a full PC, and portable consoles in particular have very strict limits. With portable consoles the power requirements are given an extra dimension by the need for batteries or other sources to operate the device. There are numerous ways to reduce power usage by a device, the most important of which are covered here, although a far more detailed guide can be found in [86].

3.3.1 Power Efficient Devices

The biggest step is of course picking devices that are power efficient to begin with, and suite the use in mind. For example, 4.1.1 will show that while the home consoles might have higher performance, they use three or four orders of magnitude more power than their portable counterparts. Quite obviously, a device which is 10 times more powerful but lasts only two minutes is of no use to anyone.

A big factor in power usage on a portable is the screen. The PSP, for example, has a much larger and consequently hungrier screen the Nintendo DS (despite the DS having two screens), and consequently it's battery life is by any account nowhere near as good - up to six hours at best, and as little as two [85].

3.3.2 Low Power Modes

Most modern systems support some form of "sleep" or low-power mode(s). Some CPUs, for example, support variable clock speeds and core voltages, allowing them to adjust to changing performance and power requirements. The PSP, for example, is able to utilise such technology to greatly extend it's battery life for less taxing games, as noted in the review by IGN Gear [85]. Such techniques are typically used in higher end embedded processors, and gradually filter down to lower end ones as demanded by industry (such as the current commercial console manufacturers).

There have been efforts to adapt devices such as RAM (detailed further in 4.6.1, later), GPUs and other components to operate at very low power levels when not in use, but to still be available at a moments notice. Technologies such as wireless - particularly Bluetooth - are already adept at this, as discussed in [78], where it is noted that a Bluetooth device uses an order of magnitude less power, while still remaining fully functional, when it is not transmitting - allowing the technology to be always on, but always as efficiently as possible.

3.3.3 Careful Device Use

The authors of [78] took pains to extend their device with advanced power monitoring circuitry, and then evaluated it under different usage scenarios. It is interesting to note that on a reasonably powerful embedded system - a StrongARM processor running at 132 MHz, some SRAM, etc - the 802.11 wireless portion of the system can use up to 40% of the systems power. While wireless is popular in modern consoles, particularly portables, it and other new technologies must be careful evaluated on their full merits and drawbacks. As an alternative, for example, the authors proposed Bluetooth, which on the same device typically used less than 5% of the power, and was capable of almost negligible power use while "sleeping".

3.3.4 Power Matching

A final concern with portable systems - particularly as regards to building them from off the shell components - is in matching batteries and other power generation devices with things such as LCDs and CPUs. Many LCDs require a relatively high voltage to operate - typically 12V for those not specifically designed for portable systems. A standard AA rechargeable battery provides approximately 1.2V, meaning at least 10 such batteries would be required, in a naive implementation, to power the LCD. There are electronic tricks that can be utilised to get around these problems without requiring masses of batteries, but nonetheless such things must always be taken into account during design.

3.4 Commercial Viability

While building a console from scratch may be entertaining, it won't spark much commercial interest unless it can ultimately be sold for a profit. The commercialisation issues faced by a console are immense. While (non too surprisingly) the major console manufacturers have declined to release detailed information about their business plans and operations, it is fairly well known in the industry that there is actually very little money available in the console hardware itself. It is rumoured the Xbox, for example, has and still is being sold at less than cost prices simply to remain competitive with the PS2 (which, it has been stated, does sell for a profit, albeit probably small).

Where the money is made by console developers is in 3rd party licensing. All today's consoles include copy protection mechanisms which ensure official developers have to pay a "tax" to the console manufacturers. The magnitude of this tax is unknown, but even if only small, the massive number of games sold is sure to provide a healthy income.

The problem with this approach is that it requires massive investment to begin with, in order to start seeing profits. It is estimated that Microsoft stomached massive losses for nearly the first three whole years of the Xbox's life, before finally pulling into the black. For a hundred billion dollar company, this may not be a big deal. For just about anyone else, it's inconceivable.

Consequently, the open games console must be financially self-sufficient. It is pointless to sell it at below cost, at least in the short to mid term. Thus, it will probably not be able to compete directly with the existing consoles on price.

This "weakness", however, could also be a double-edged sword. Since the hardware itself is profitable, albeit if only a tiny bit, there is little or no need to tax 3rd party developers for their content. Consequently, a truly open console can be created, where anyone is free to provide software for it. This would surely garner significant support from 3rd party developers, particularly those associated with open source, who are by nature interested in exactly this sort of thing.

Furthermore, by utilising alternate business models - such as for content subscriptions, pay-per-play, or similar approaches - the manufacturer (and others) can reap continuing returns on each console sold.

Of course, all this implicitly assumes the console will (eventually) attain the critical mass necessary to provide it with explosive growth and popularity. This is a massive assumption. Each new console, even from established manufacturers, is always a huge risk; an extremely difficult enterprise to succeed in.

But then, there is always other routes to take - such as a not-for-profit enterprise, much like the educational XGameStation discussed earlier in 1.2.

4.0 Console Technologies

To build a console from scratch is no small feat. Indeed, if you were to attempt to build every single component of a console yourself, you might never complete it in your lifetime. Today's consoles are usually built almost entirely from publicly available components and standard technology, with a proprietary system of connecting all those together into the final product.

It should be noted that J. Allard, Microsoft's Corporate Vice President and chief XNA[10] architect, strongly advocated an "open" architecture, familiar to developers and consequently easy to develop for [79]. This is of course in reference to Microsoft's present and future approach to console design - essentially just building their own proprietary PC - and was also a non too subtle dig at Sony's more proprietary approach.

4.1 Central Processing Units

There are a variety of CPUs available today, for various purposes. They range from powerful mainframe units, such as the Power architecture[11], right down to embedded microprocessors, such as the ARM line[12]. Choosing the right processor for a game console lies in finding the very delicate balance between many factors - primarily cost, performance, size and power use. There is a very interesting "shop talk" session from Embedded.com [80], which looks at the painful decision that is choosing a CPU (and corresponding architecture) for an embedded system. It isn't a formal paper, with no outright conclusion, but the many opinions voice in it all appear unanimous when they say that CPUs are never chosen on their technical merits, but rather on the merits of their entire ecosystem - including other developers, tools, debuggers, etc. From a financial point of view, given the relatively tiny cost - tens of dollars - of a CPU, compared to that of an LCD - hundreds of dollars - fighting over a few dollars seems pretty pointless.

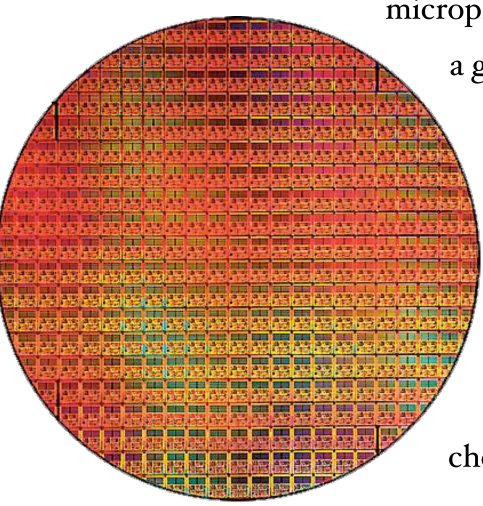

Figure 26 - A 21-billion transistor Athlon 200mm wafer (courtesy AMD)

[10] http://www.microsoft.com/xna/

[11] http://www.power.org/

[12] http://www.arm.com/

4.1.1 Commercial Console CPUs

For reference, the processors used by various existing game consoles (and some future ones) are shown in Table 1 on the next page. Note that many figures are estimates and not provided officially by the manufacturers.

A few general observations stand out - that CPUs are getting faster and more powerful, they're getting hotter and larger, and - notably - portable CPUs are several years behind their larger home siblings. Interestingly, power consumption is generally getting lower - particularly for portables, with many capable of running at just fractions of a milliwatt. ARM processors seem particularly favoured amongst portables, which suits their reputation as very efficient chips.

There are several key priorities in developing a home console, which may not align with those of a commercial console. Firstly, the chip needs to have appropriate software available for it - at the very least a basic OS (Operating System). Second, it ideally should be capable of running a significant number of existing games and related software - meaning it should not be too different from a typical PC that software must be painstakingly ported. Lastly, it must be easily available at a reasonable price - chipmakers such as ARM and MIPS have attractive propositions, but they are primarily focused on designing chips on a per-client basis, and may not have any real common base or even manufacturing facilities of their own.

One very convenient approach to CPU & architecture selection is to choose a PC designed for embedded or mini-system use, and adapt it to it's specific function as a games console. This is not dissimilar from the route taken by Microsoft on it's Xbox system. Indeed, with the recent release of things such as VIA's EPIA-N embedded mainboards [88], such an approach seems easily achievable off-the-shelf. The advantage of such an approach is that the huge existing support for x86-based devices can be leveraged to rapidly develop software for the system - most will simply need to be recompiled for the new system.

Console	Processor	Core Speed (MHz)	Core Size (mm²)	Per CPU Power (Watts)	Release Year
Xbox 360	3x PPC 970 **	≈ 3000	?	≥ 60 †††	2005 ?
PS 3	≈ 2x Cell™ ***	≥ 4000	?	?	2006 ?
Nintendo Revolution	?x PPC 970 ****	?	?	?	?
PSP	2x MIPS R4000	333	≈ 35 †	≈ 1 ††	2005
Nintendo DS	1x ARM9 1x ARM7	67 33	≤ 6 ≤ 0.53	≈ 0.02 ≈ 0.01	2004
Xbox	Pentium III based (similar to a Celeron)	733	≈ 100	≈ 15	2001
GameCube	PowerPC “Gekko”	485	≤ 45	≈ 5	2001
Gameboy Advance	ARM7TDMI	16.78	≤ 0.53	≈ 0.004	2001
PS 2	Proprietary *	294.912	239.7	≈ 15	2000
Dreamcast	Hitachi SH-4	200	42.25	≈ 1.5	1998
N64	1x MIPS R4300I 1x MIPS Unknown	93.75 62.5	? ?	1.8 ?	1996
PS One	MIPS R3000A	33	?	?	1994
SNES	65C816	3.58	?	?	1991
Gameboy	Z80	3.5	?	?	1989
SMS	Z80	3.58	?	?	1986
NES	Motorola 6502	1.79	?	?	1985

Table 1 - Significant Console CPUs in the Last Two Decades

† = The R4000 was originally released in 1991 at 100 MHz with a 213 mm² die, using an 800 nm process. It is likely the revision used in the PSP utilises the now common 130 nm process, producing a die size closer to 35 mm².

†† = Similarly to the point above, power consumption is likely to have been reduced significantly by the reduction in size and other refinements. 1W is typically of current MIPS CPUs, according to http://www.mips.com/

* = The PS2 CPU is of a custom design purpose built for the PS2. It is combined in the same chip with many other system elements, such as GPUs (or approximations there-of). It is rumoured to be contain a MIPS core for typical CPU tasks.

** = The exact model of PPC 970 to be used in the Xbox 360 is not known, nor what modifications will be made to it specifically for the Xbox 360.

*** = The Cell is based on the PPC 970, also used in the Nintendo Revolution and Xbox 360.

**** = The Revolution’s processor is rumoured to be PPC 970 based, but will probably be modified for Nintendo’s use, similar to their PPC use in the GameCube.

4.1.2 Re-configurable CPUs

A slightly different approach to having a particular type of CPU is to instead use devices which can reconfigure themselves at will. The most common type of such device is called an FPGA (Field Programmable Gate Array). FPGAs typically contain some large number of "cells", which are the basic atomic units of operation - each cell can typically perform one basic logic operation, such as an AND, or an OR. They are linked together via numerous links which can be broken and re-established at will. To program the FPGA, the function of each cell and the connections between them are specified. This is not too dissimilar from utilising multiple different software programs on a microprocessor, except that it has the very distinct advantage of being far more flexible - the actual circuit structure of the device can be changed, not just how it interacts with other devices. FPGAs are commonly at least an order of magnitude more efficient than a microprocessor for any given task. They are also more general purposed than a CPU, being able to adapt far more and be much more efficient at any given task - they are a master-of-all-trades, if you like, as compared to the jack-of-all-trades microprocessor.

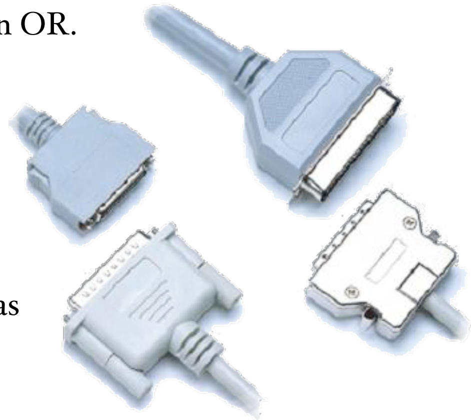

Figure 27 - Parallel Connectors

One particular system that utilises FPGAs is that demonstrated by researchers at the Interuniversity MicroElectronics Center (IMEC) in Leuven, Belgium [66]. Their "Chameleon" system is designed to provide the benefits of an FPGA presented in the traditional form of a microprocessor - the FPGA can be configured on a whim to perform any number of tasks, and is capable of running up to three independent tasks concurrently. It presently operates as an extension to an iPaq, although the researchers hope to integrate their present solution into a single chip, which could make it's way into mobile phones, portable computers and game consoles within five years. In addition to boosting the power of these devices by an order of magnitude, they hope it will greatly increase the useful life-span of these devices by allowing them to be reconfigured as technology evolves, rather than simply made obsolete.

4.2 Graphics

Powerful graphical abilities are paramount in modern consoles. The original PS was the first to introduce hardware accelerated 3D, and no home console since has done without it. Indeed, the current PSP and Nintendo DS both offer such functionality as well, firsts for portable consoles. ATI and NVIDIA, dominant forces in the PC industry, have been making inroads into portable devices with the development of miniaturised, low-power ranges such as ATI's IMAGEON™ line[13] and NVIDIA's GoForce™ line[14]. These offer limited performance - similar to that of consumer level GPUs five years ago - but with very high efficiency, and utilising modern technologies such as programmable pixel shaders.

Unfortunately, neither manufacturer provide any hard details on these products, such as peak power use, voltage requirements, device size, etc. They are primarily concerned with large volume sales to OEMs, and don't appear particularly interested in merely curious researchers.

It is interesting to note though that both the PSP and Nintendo DS appear to use proprietary GPUs, which are less like typical PC GPUs and more like second processors. The PSP, for example, has two MIPS processors, one to act as CPU, one to act as GPU - the latter with an extra two megabytes of dedicated high-speed memory for the task. This seems to indicate the mainstream GPU technology from the likes of ATI and NVIDIA is not yet ready for these sorts of devices

4.3 Audio

The audio options of a home console are immense, while of a portable ironically very limited. Home consoles can have large external speakers, in elaborate 5.1 surround sound setups - indeed, many people connect their home consoles to their stereo's, which is another advantage; their ability to integrate into existing devices in the home. Portables, by comparison, must provide onboard audio (and possibly an audio out plug for headphones), and typically make do with stereo or even mono sound. They cannot support large bass speakers, and thus are also limited by their dynamic range.

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13 http://www.ati.com/products/handheld.html

14 http://www.nvidia.com/page/handheld.html

There appears to have been minimal research into this problem, or alternative ways of presenting audio output to a user. Part of this is invariably because, as portable devices designed to be used in public, they would not be particularly popular if they had loud booming sound, disturbing everyone nearby. While advances in headphone technology may eventually allow for more accurate surround sound and similar effects, there is little evidence of this happening, both in research circles and in the market.

4.4 User Interfaces

The way the user interacts with the console is of course paramount - users must be able to control it to their satisfaction, and it must have have sufficient interfaces to serve it's purpose, both for it's primary use for gaming and others, such as multimedia or work. The style of interface used for consoles has always been very consistent - connection to a TV or a built-in LCD (Liquid Crystal Display) for audio-visual output, and one or more 'gamepad' controllers for input. Nonetheless, in the future we may use other ways to interact with the console - some of which are covered here.

4.4.1 Human Interface Importance

The importance of good interfaces is well-known; [5] for example looks at the effect of ease of use (among other things) on attraction to a variety of online games. They found that ease of use did not necessarily make people like the games, but it did play a big part in their intention to replay it. From the point of view of the console manufacturer, it is vital that people are inclined to use the console as much as possible - this directly drives software sales and increases the popularity of the console, indirectly contributing to further sales. As section 3.4 previously noted, it is typically the software that brings in the real revenue, not the hardware.

4.4.2 Human Interface Research

The mobile phone industry has already extensively investigated control methods for small devices. Most phones, while equipped with at least a dozen buttons, lack any kind of sophisticated pointing device - even those with joysticks typically use them only as digital direction devices. The layout of menus and similar active elements must be carefully considered given a particular interface. In a study by the NPD Group on mobile phone usage [30], Ross Rubin (director of industry analysis for the NPD Group) concluded:

> *"The incredible distribution power of carriers is putting phones that can handle ringtones, photos, and games in more consumers' hands. However, digital camera and MP3 manufacturers have little to fear for now as user interface complexity and conflicting development priorities stand in the way of the cell phone becoming more than a jack-of-all-trades."*

The report also states that while 95% of people with game-capable phones use them for gaming, nearly 14% claim they are dissatisfied with the games. While it is quite likely much of this dissatisfaction arises from the limited power of phone hardware, resulting in technologically simple games, it is also reasonable to assume at least some of this dissatisfaction is a result of poor interfacing provided by mobile phones - relatively small screens and input systems optimised for numeric and text entry, not gaming.

The labelling of interface inputs also needs to be carefully considered. There are many analogues to console controllers, and consequently a rich community of research into the problem, from many fields - notably trained psychologists. [48] investigates the labelling on a television remote control by interviewing and testing a large focus group. Their findings, while probably not specifically interesting, emphasise the need for this kind of research by designers. While they concluded there was reasonable parity between consumer and designer intuitions, they also found great potential for confusion - many subjects could not discern the function of buttons with technically correct, but unexpected names - changing 'Back', common on many newer television and DVD controllers, to 'Cancel', for example, prompted confusion and complaints. Despite the common use of 'Cancel' by PCs, it apparently had little intuitive meaning in another context (television, in this case), and was poorly received.

Many consoles have taken to using entirely symbolic labels to avoid assumptions - things such as the PS, PS2 & PSP cross, circle, square and triangle buttons, or the six different colour buttons on the Xbox controller. There are numerous problems with this approach - including the fact that the button function is no longer discernible from it's appearance, requiring explicit instruction. The use of colour is also problematic for those with visual disabilities, such as those suffering from colour-blindness - between 7 and 12 percent of males worldwide [49].

4.4.3 Game Controllers

In terms of availability, the good news with modern controllers is that they are all fairly similar, and with the standardisation of parts and connectors, many are available with USB or vanilla serial connections. One of many examples is the Gravis GamePad Pro USB controller [26], pictured right, which provides 10 buttons, a direction pad (with optional joystick attachment) for around $25.

Figure 28 - Gravis GamePad Pro USB Controller

4.4.4 Haptics

One area that is frequently overlooked, yet contradictorily has seen great success in home consoles, is the use of tactile and kinaesthetic feedback as an output interface. This means utilising the human sense of touch, an equally important human sense as sight or hearing. In fact, the author of [67] goes so far as to state that the only reason the PS commercially defeated the N64 (Nintendo 64) was because of it's DualShock™ controller, which allowed [limited] tactile feedback in the form of simple vibrations.

All modern home consoles support limited tactile feedback using vibration within the controllers - this can provide feedback about events such as colliding with objects within a game world, being shot by another player, or similar. However, this application seems limited compared to what is possible. [52] looks at the implementation of "tactons", which are 'iconic' tactile sensations, in much the same as graphic icons are for the visual sense. They propose teaching users to distinguish between a variety of 'tactons', which are differentiate by varying one or more parameters - such as physical location, amplitude, frequency [of oscillation], etc. In a console context, this could be applied to make use of the palms of users' hands, which presently serve only to support the console controller.

While the study in question did not evaluate their system in human trials, the success of existing kinaesthetic devices and the large body of research associated with "tactons" suggests the technology is mature and merely awaiting application.

4.4.5 Projection Systems

Another uncommon but promising technology is that which projects a visual display onto a surface, and allows the user to interact with that display intuitively by utilising image recognition to respond to the users interaction with the display. One such implementation is covered briefly by [58], where the authors demonstrate a basic setup that displays still image slide shows. While this system was implemented using a laptop, projector and camera, the real purpose of such a system only becomes apparent when you think of minimising it to fit into, say, a mobile phone.

There has been a great deal of other work in this area, such as the HoloWall [87] created by researchers at Sony and Keio University in Japan. It allows the user to interact with a curtain, wall or similar object using intuitive hand movements, by tracking the user with video cameras. It can considered a kind of low-tech precursor to the kind of device seen in Minority Report[15].

The point of these projection interfaces is that they have extraordinary potential for portable devices like consoles - someday it may be possible to project your console's screen onto any nearby surface, and use it with a huge viewing area, no longer limited to the physical size of the console itself, and possibly even be able to interact directly with that image using fingers, hands or a special stylus.

4.5 Device Interfaces

Inter-device interfaces are very popular on current consoles. Home consoles utilise Ethernet networking, while portable consoles have increasingly adopted 802.11, Bluetooth and other wireless technologies.

4.5.1 Wireless Connectivity

In the dominant market for Bluetooth technologies, mobile phones, the market research group Instat-MDR expect 52% of all mobiles to have Bluetooth by 2008 [33].

Wireless technologies are of interest in particular as they have significant concerns not present in wired networks. The most significant such concern is availability - wireless networks are by nature transitive and cannot guarantee quality or provision of service like

[15] http://www.minorityreport.com/

wired networks. They are also easily subject to malicious interference, as discussed in [1]. In this paper the authors discuss briefly the kinds of malicious activity that can be perpetrated in wireless networks - such as eavesdropping, impersonation & jamming. They also note the problems associated with detecting and defending against such behaviour, given the anonymous nature of wireless networks. Their proposal against such attacks is to use strong encryption to prevent eavesdropping, impersonation and similar behaviour - the same approach taken by traditional wired networks to prevent these types of attacks. They did not present any solution for jamming, which is not unexpected as the problems of noise (whether natural, accidental or malicious) remain largely unsolved in all modern communications, as noted by the fact that the author's home wireless network is rendered completely inoperable by the use of his or his neighbour's microwaves.

One possible solution to many these wireless issues is the use of UWB (Ultra Wideband) radio technology. This utilises a massive spectrum (approximately 10 GHz) and various modulation techniques to broadcast signals below what was traditionally considered the noise threshold. This makes it difficult to detect and consequently jam, especially with the use of automatic "frequency hopping". It is, however, only a very short-range technology - maximum range is typically between 3 and 10 metres. A full coverage of UWB technology is provided in [9], and [10] focuses on interference in particular, finding UWB to be significantly superior (in terms of resistance to interference) to several other radio communication methods.

4.6 Storage

Consoles ultimately require at least one form of internal storage - memory in which to store running software or firmware. In addition, there are numerous new possibilities provided by other forms of storage - particularly non-volatile ones - for saving player information, work and content.

4.6.1 Volatile Storage

Volatile storage is used in consoles (as in nearly all computing devices) to store data relating to the task in progress - for example, level and graphics data for games. It allows devices to become more flexible.

There are three key focuses for volatile storage - density, power usage and speed. Portable devices require all their components to be as small as possible. They also aim for the lowest power usage possible. And speed is often a requirement, as data needs to be retrieved from storage quickly so that it does not create visible delays or loss of performance for the user.

To reduce power usage, there are numerous techniques used. A recent one of interest is documented in [53] - in this the authors explain their system of dividing RAM (Random Access Memory) up into cells of arbitrary size, and then dynamically turning these on and off as needed, significantly reducing power usage where possible. They demonstrated average power savings of 35% in their 'typical' usage. The interesting thing with this technology is that it is applicable to all forms of RAM, is independent of other optimisations for power efficiency, and that it applies very well to a multi-use device. For example, while games may use a large amount of memory to store their data, while playing music very little storage is needed.

The most common memory used today is DDR (full name DDR-SDRAM, Double Data Rate Synchronous Dynamic Random Access Memory). It is widely available and is cheaper than most other commercial RAM types, particularly for high capacity (256 megabytes or greater) modules [56].

In the near future DDR3 memory will become commonly available - as soon as early 2007 according to [34]. DDR3 promises faster memory with lower power usage, critical for portable consoles. In the mean time, [34] also mentions the roadmap for DDR2 provided by a spokesperson for Samsung, indicating increased performance in the very near future with the release of DDR2-667.

Looking even further ahead, there is a lot of excitement regarding holographic storage technology, both as volatile and non-volatile storage. It is covered more in the next subsection, 4.6.2, but is mentioned here to note that it does not appear ready to replace high-speed RAM, with access times on the order of microseconds, versus nanoseconds from conventional RAM [57].

4.6.2 Non-volatile Storage

The most common form of non-volatile storage for PCs is a hard drive. These come in a range of sizes from that of a postage stamp up to that of a thick novel, in capacities from 1 gigabyte to 400 gigabytes or more. Of particular interest for consoles are the so-called "microdrives", measuring less than an inch square, that have been developed in the last few years and have already found their way into mobile phones and similar devices, such as the iPod Mini. Recently, Toshiba, one of the leading microdrive manufacturers, announced an increase in the capacity of their 0.85" microdrives to 2 gigabytes [42]. Hitachi claim to be preparing slightly larger drives (1") with capacities up to 10 gigabytes by the end of this year, and up to 20 gigabytes in 2007, using new perpendicular recording technology [44], comically explained in [43]. Seagate [45], and invariably soon all the other major manufacturers, are now quickly announcing their own plans in this area. It seems very soon the storage possibilities for a portable console will be exceptionally exciting.

Another possible storage technology for future use is holographic media. In a nutshell, this means using the entire volume of a given storage device (e.g. a CD), rather than just the surface. It is introduced in [55], and covered in more detail in [54], where storage densities of 100 bits/μm^2 were achieved in a prototype system. This compares exceptionally well to current hard drive technology, which achieves around about 15 bits per μm^2. And hard drive technology is approaching several fundamental limits, while holographic storage is only just beginning to be explored. At time of writing there are no known sources of holographic media or storage devices, although as reported by Mark Hachman of ExtremeTech [65], a company called InPhase Technologies hopes to ship holographic drives and media next year, with capacities of 300 gigabytes per CD-sized disc - 22.6 bits per μm^2. Their technology only allows a single write to the media, but this limit doesn't significantly detract from their value to game consoles, where the predominant usage is (currently) of read-only media anyway.

4.7 Batteries

Critical for any portable device is it's life-span on a single charge. Unfortunately, battery technology has not advanced significantly in over a decade, and is a constant source of disappointment with portable devices. As mentioned, the PSP manages a relatively weak

6 hours of battery life - the Nintendo DS a slightly more respectable 10. Mobile phones typically average only a few hours when actually used, limiting their usefulness as gaming devices.

4.7.1 Traditional Rechargeables

Not only is battery technology in general limited, but the performance of rechargeables - generally considered a simple necessity for game consoles and similar devices - is even lower than single use batteries. Table 2, below, lists the most common battery types found today. As can be seen, the energy density of things such as zinc air and Lithium thionyl chloride batteries is nearly an order of magnitude above that achieved by any rechargeables. The absolute life span of rechargeables (not shown in the table) is also abysmal - typically just two or three years. This is a constant source of frustration amongst consumers, leading in some cases to law suits such as seen with the iPod [89].

Type	$V_{nominal}$ (Volts)	Maximum Load Current (Amps) *	Energy by Weight (Wh/Kg)	Energy by Volume (Wh/L)	Operating Temperature (°C)	Maintenance (Months) **	Life Cycle (# Recharges)	Shelf Life (Months)
Alkaline	1.5		150	375	-20 to 50			60 to 80%
NiCd	1.25	> 2	45 - 80	125	-40 to 60	1	1500	20% per Month
NiMH	1.25	0.5 - 1	60 - 120	180	-20 to 60	1/3	500	30% per Month
Lithium Ion	3.6	1	100	270 - 325	-20 to 60		50 - 100	10% per Month
Lithium Polymer Ion	3.7	0.2	120 - 160	230 - 270	-20 to 60		500	> 120
Sealed Lead Acid	2	0.2	30	80	-20 to 60	1/6	200 - 500	5% per Month
Zinc air	1.4		300	1150	-20 to 60			1-3 to 50%
Silver oxide	1.55		130	500	-20 to 60			24 to 84%
LiPoly Carbon Monofluoride	3.0				-40 to 85			> 120
Lithium Manganese	3.0		225	550	-20 to 60			> 120
Lithium thionyl chloride	3.6		710	1300	-55 to 100			108 to 80%
Lithium sulfur	3.0		290	500	-60 to 85			120 to 80%

Table 2 - Battery Types Compared (Source: [86])

* = Calculated as the Amp-Hour rating divided by 1 Hour (e.g. for a 1500 mAh battery, C = 1500 mA)

** = Rrequired interval between "deep cycles" - the uninterrupted full discharge of the battery followed by full recharge.

4.7.2 Fuel Cells

An alternative to traditional batteries is the use of fuel cells, which are devices which convert fuel such as liquid hydrogen into energy, very efficiently and with relatively high power densities. [90] provides a very detailed overview of the technology, albeit with only a small mention of reduced scale systems such as consoles and mobile phones. [91] also serves as a useful overview of fuel cell technology, with a focus on it's future. The time scale given for whole-sale adoption of fuel cell technology is in the order of decades, unfortunately - problems listed include finding ways to manufacture the fuel (typically hydrogen) efficiently, building a distribution and sales network for that fuel, and building very small devices with it, safely and cost-effectively.

4.8 Other Hardware

The major topics covered in this section, 4, are only the most common elements of a console system - not an exhaustive list. Some devices are not commonly associated with consoles because they are now outdated, or conversely may yet be new and not yet widely adopted.

4.8.1 Physics Processing Units

An interesting development at time of writing is a new class of support hardware - physics simulators. These are envisaged to [initially] take the form of an add-on card for PCs, but if successful will no doubt be adopted as embedded components in consoles. [35] talks about one such device, named PhysX™, being developed by AGEIA Inc[16]. Claimed to be the worlds first PPU (Physics Processing Unit), recently announced on March 8th this year and possibly due out later this year [40], AGEIA claims it will revolutionise today's gaming in the same way GPUs did a decade ago. Indeed, [36] names the next Xbox console as one customer of AGEIA's technologies, although it doesn't explicitly confirm the use of the PhysX™ PPU itself. AGEIA have have also named Ubisoft [37], Epic Games [39], Atari & Sega [38] as notable game developers already using their software technology, and likely to support PhysX™ devices in future.

4.9 Software

There are three key tiers of software that all game consoles must utilise to function. They are the OS (Operating System), the system frameworks[17] & middleware, and the application software.

[16] http://www.ageia.com/

[17] More commonly known as "libraries" on some platforms, which while not entirely accurate is sufficient for this document.

There are two oft-conflicting approaches to choosing or designing the software for a computer - that of the developers, starting from the hardware and moving up to provide available functionality, and that of the user, starting from the high level user-interface and moving down based on desired functionality. Given the hardware focus up to this point, we will consider the bottom-up angle first.

4.9.1 Operating Systems

The OS manages the application software running on the computer, and provides basic services such as protected memory, multi-tasking & interfaces to the system hardware. Traditionally the OS for consoles has been both simple and custom built. Compared to a PC, the OS for a console is not required to do very much - even modern consoles do not support OS-level multi-tasking, protected memory, or other such features. The assumption is that only one program will operate at a time, to achieve maximum performance. This is not necessarily a good assumption looking forward - users may like their console to perform background tasks while they're gaming, such as periodically checking their email. They may wish to use voice chat software to communicate with other players online (such as Ventrilo[18], or the popular Roger Wilco[19]) - if this software can run simultaneously with the game, game developers don't need to explicitly add support for this themselves. Microsoft has hinted that they will be adopting this approach (where possible) for the Xbox 360 [79].

If the console is used for tasks other than gaming, the need for multi-tasking support grows significantly - many PC users are accustomed to using a web browser, word processor, email client and other software simultaneously. A game console will likely not be taken seriously outside the gaming market if it cannot compete with cheap PCs.

It is a safe assumption that whatever hardware is chosen will be fairly generic - possibly of the x86 architecture - and thus capable of running several operating systems. Building an OS from scratch is quite implausible for a home-brew console, and in any case most likely

[18] http://www.ventrilo.com/

[19] http://rogerwilco.gamespy.com/

unnecessary - there are many fast & robust operating systems available today, such as Linux[20], QNX[21], Nucleus[22] & VxWorks[23].

Beyond the OS, developers for the console will be primarily interested in the development environment they will be using, both on the target system and their host computers. This includes the language(s) used to program the device, what libraries are provided for the system, and what compiler tools are available - not only for compilation, but also debugging.

Traditionally console games were written in low-level languages - assembler, C or similar. Modern consoles have become so powerful that program efficiency no longer dominates priorities, allowing the use of higher-level languages that accelerate development and produce more reliable software. Java is one prominent example today, with many relevant uses in console-like systems such as mobile phones.

4.9.2 Software Frameworks & Middleware

In [2] the authors evaluate a purpose-built middleware system, developed in Java, for developing multiplayer (and incidentally multi-platform) video games. Their focus was on mobile phones, where Java is commonly available, but their work applies equally well to consoles. They evaluated their middleware - which provided generic objects, networking and other functionality - in terms of it's efficiency of execution and efficiency of implementation. Their conclusion was that the trade-offs between the two were overall quite positive.

In another similar paper [8], the authors specify their "Mobile Agent Platform", a middleware system for providing typical mobile gaming services, such as player (called 'agents' in the paper) control, game registration and member management, etc. They also specify the use of various security measures, such as encryption, for security over public networks.

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[20] http://kernel.org/

[21] http://www.qnx.com/

[22] http://www.mentor.com/products/embedded_software/nucleus_rtos/index.cfm

[23] http://www.windriver.com/products/device_technologies/os/vxworks6/

The conclusion emphasised by both the above papers, as well as others, is that the presence and use of appropriate middleware can greatly ease development costs, and improve player experience significantly by providing higher quality end-user software.

4.9.3 Application Software

An introduction alone to writing console games could fill up a large book. The task of writing most of the application software for a console is typically left to 3rd parties, although some manufacturers - such as Microsoft - are keen on developing some of their own (case in point - Halo, the premiere Xbox game).

They key requirements for writing application software are appropriate tools (compilers, debuggers, etc), access to development hardware (i.e. that can easily be programmed for rapid-turnaround debugging) and availability of documentation on the console platform. There is nothing exceptional about any of this - it simply requires a significant investment of time and resources by the manufacturer. Microsoft seems to be leading the way in this regard, with it's distribution of over 3000 development kits for the Xbox 360, six months (or more) before it's release, and before it has even been officially announced [79].

5.0 Conclusion

The author regrets in writing this conclusion that more time was not available for this review. Given the style and scope of the topic, it is indeed quite hopeless to expect anyone to master it in a mere few weeks. While the author could have chosen to focus on particular implementations or areas of research, he endeavoured to provide more broad coverage, in the hope that a more useful level of understanding could be achieved than might be achieved by adopting tunnel vision along a few specific lines.

5.1 Key Problems

The problems with modern game consoles are too numerous to count. Some problems are simple trade-offs - the PSPs superior screen to the Nintendo DS's superior battery life, for example - that can inevitably only be settled by trial and error in the marketplace, to discern what the average consumer prefers. Nonetheless, there are a few bottleneck problems that are worth mentioning specifically.

Firstly is software, the biggest problem, although not covered in detail here. Developing a tools collection for development is possibly the hardest aspect of building a console. In the authors own experience, building a generic embedded system - even *with* expensive vendor support - is no trivial matter, and could take a single person many months to do. It is absurd to even consider a from-scratch approach, even for a large company. This problem consequently enforces certain implications and restrictions on hardware design - particularly what CPU architecture to use, and what other devices to integrate.

Another key problem is user interfaces. This is in some ways another of those unfortunate trade-offs - a device cannot be both conveniently portable (as a game console or mobile phone) and have a usable keyboard. Consequently, intuitive new methods for input must be developed if portable devices are to succeed at many tasks, such as word processing and the more serious "work"-type objectives.

The final key problem to be summarised here is battery life. In lieu of any sudden, revolutionary advance in this area, it continues to dominate portable console design and functionality. New methods must be found to maximise efficiency, reduce power loss, and provide longer lasting devices for end users.

5.2 Future Work

Given these problems, the original goal of building an entire console seems something of an Everest goal. Nonetheless, it can approached in several ways which may selectively avoid certain problems, in order to focus on more attainable goals. For example, if the goal were not to build a portable console, but instead a home one, then many of the physical issues fly out the window, and the problem could be boiled down to economics, or some similar investigation.

Alternatively, an existing console could be adopted and selectively modified to tackle some of these issues - for example, testing alternate battery types with a PSP, or seeing if some of it's devices, such as the screen, can be re-engineered to promote higher power efficiency.

In any case, the author requires some more time to consider these options, and others. More research will be required - particularly with a focus on available technology, it's costs and other factors - before a direction can be chosen.

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7.0 Glossary

802.11 - The predominant technology used for wireless networking. Also known as Airport.

Arcade - A public place which operates some number of Arcade Machines (among other services), which provide interactive entertainment typically on a pay-per-play basis.

Arcade Machine - A computer gaming device design to operate in public venues, typically in Arcades. The device is characterised by a large purpose-built case with built-in screen and robust controls. Typically requires user to pay per play.

Bluetooth - A wireless networking technology designed for short-range, low-power applications. Typically used to connect mobile phones to other devices, and for wireless keyboards and mice for PCs.

CD - Compact Disc. A [typically] circular disc used to store up to 700 megabytes of information.

Console - Used interchangeably with "Game Console" throughout this document. See Game Console.

CPU - Central Processing Unit. The electronic chip inside a computing device which controls all the other chips and devices within the computing system. Typically the CPU runs most or all the software that instructs the computer on how to operate.

CRT - Cathode Ray Tube. Colloquially used to refer to display devices that use CRTs, which are characterised by their significant depth, making them completely unsuitable for portable devices.

DVD - Digital Versatile Disc. A successor to the CD with very similar physical dimensions and appearance, but capable of storing up to 9 gigabytes of information.

Ethernet - A very common networking scheme. In this document Ethernet describes wired networking - the connection of two or more devices via a cable which allows them to interact using predefined protocols.

Flash [memory] - A type of solid-state (non-volatile) programmable memory, typically used for storing medium to long term data such as device firmware or user data (e.g. photos, music, saved games, etc).

Firewire - Apple Computer's brand name for IEEE1394, a connection method for high speed communication between two or more devices. Typically used for external storage devices (hard drives, CD/DVD drives, etc) and video cameras. Also used for networking as a substitute for Ethernet cabling.

Firmware - A specific type of software which instructs the hardware how to configure itself when activated, and serves as an abstraction of the hardware to the software, to simply programming of the device.

Game Console - A computing device traditionally associated with gaming, which comprises either a central unit with associated controllers and outputs (typically to a TV), or in portable consoles the entire unit with built-in display, controls, etc.

GPU - Graphics Processing Unit. An electronic chip [typically] similar in size to a CPU, but designed specifically for performing graphical tasks, such as 2D & 3D rendering.

LCD - Liquid Crystal Display. A display technology that is rapidly replacing CRTs by virtue of it's improved power efficiency, clarity and hugely reduced size (particularly depth).

OS - Operating System. The software that [typically] is loaded first on a computing device, and manages subsequent loading of games or other such software. Often also provides libraries and interfaces that help other software run.

NES - Nintendo Entertainment System. A video game system released in 1985 by Nintendo, which was pivotal in popularising the home console.

PC - Personal Computer, a general purpose computing device in common use. Typically much larger than a console and designed for multiple simultaneous functions.

PIM - Personal Information Management. A recent buzzword used to describe management of personal information - things like a person's address book, calendar, correspondence, etc.

Platform - A particular combination of hardware and software, defined by it's compatibility (or lack there of) between other hardware and/or software. For example, an PC running Windows may be referred to as a "Windows" platform. More generally, a PC running any OS may be referred to as a "PC" platform (as opposed to an Xbox platform, for example).

Platformer - A particular genre of game in which a character navigates a 2D world from a side-on perspective. The dominant playing characteristics are interaction between adversaries and navigation of difficult terrain, composed of numerous separate platforms - ergo the name.

PSP - PlayStation Portable, a particular model of portable game console released by Sony.

Saved Game - Data stored on a non-volatile medium which records the state of game-play at a particular point, allowing this state to be restored at a latter time and thus allowing the player to resume their game.

RAM - Random Access Memory. Memory that can be read and written symmetrically, usually with no limit on the number of each. Typically the term RAM implies volatile memory.

ROM - Read Only Memory. Typically a kind of write-once electronic device, which usually contains the firmware and sometimes the OS for a given device. Older consoles used ROM in the place of CDs on newer consoles, to hold games and other software console content.

SMS (1) - Sega Master System. A home games console released by Sega to compete with the NES. Technically superior, but less popular.

SMS (2) - Short Messaging Service. A method of sending very short text messages between mobile devices over the mobile phone network.

TV - Television. A display device originally for watching audio-visual broadcast content, but with provision for other inputs, such as from a game console.

UMD - Universal Media Disc. A proprietary disc medium developed by Sony specifically for use with their PSP.

USB - Universal Serial Bus. A very common connection scheme for computing devices, particularly peripherals such as input devices and still cameras.

UWB - Ultra Wideband. An upcoming communication technology which avoids licensing issues by broadcasting at extremely low power, and is consequently difficult to detect and robust against interference.

VR - Virtual Reality. Idealistically the ability to present a virtual world to a player that is as realistic as the real world. Typically used to describe any technology or game which endeavours towards this goal.