The Personal Computer of the Year 2000

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1. The Concept

Any design represents a compromise between conflicting goals, and the design of the computer of the year 2000 is no exception. We seek something which fits comfortably into people's lives while dramatically changing them. This may appear to be a contradiction which cannot be reconciled. But if the technology does not fit easily into the habits and lifestyles of its human users, it will be discarded by those it was meant to help. And if this new tool does not change the life of its owner, it is only because we have been too shortsighted to imagine the possibilities.

Our way out of this dilemma is to base the design upon something which is already integrated into everyone's life, to take a vital tool and give it more life. We have chosen to improve something that everyone uses everyday, the humble paper notebook.

We have all heard that the computer revolution was supposed to eliminate paper from the workplace. Instead, it has lead to desktop publishing, so now we not only write papers but typeset them. Paper notebooks have many properties which make them particularly friendly. They are light and portable. No one thinks twice about bringing a pad into a meeting, the library, or the toilet. They are friendly and natural to use, as accessible to the toddler as to the octogenarian and as relevant to the artist as the engineer. They are the ideal medium for integrating text and graphics, perfect for creative doodling and drawing the picture that is worth a thousand words. They are forgiving of mistakes, simply peel off the page and start anew. They can be used to communicate with other people, by sliding a note under the door or popping it in an envelope. It is natural to revise and edit written documents. There is something satisfying about crossing out an offending sentence from a written draft, a feeling that word processors have not captured. We aim for a computer which provides all of these benefits and more.

Thus, the computer of the year 2000 will be a portable machine the size of a notebook. We will write and draw with a stylus on a screen which mimics a physical writing surface. Enhancing this with the powers of computation and communication, we create a tool which will improve the way we live and work.

The rest of this essay provides a more concrete depiction of the machine we have in mind. Most of it is devoted to a fairly detailed description of our machine, describing various subsystems, their reasons for being, and technologies to realize them. After this we will forge ahead with some implications and applications of a tool that is much more than the sum of its parts.

2. The Machine

Our machine will have the same dimensions as a standard notebook. It will look like an $8'' \times 11''$ monolith from the movie *2001*, and be reminiscent of the *Dynabook*. This rectangular slab will weigh but a few pounds, and have no buttons or knobs to play with. The front surface will be a touch-sensitive display screen and will blink to life upon touching two corners. On one of the short sides will be a credit card sized slit, while the other three sides support a ridge with a slight reddish tint. It is targeted towards the professional of the year 2000; the engineer, lawyer, or teacher who is willing to pay the equivalent cost of a microcomputer of today.

2.1. The I/O Surface

The most important part of any computer is its interface with the user. The front surface of our computer is a high-resolution touchscreen, which yields slightly to the touch. With this single input device, we can get a tremendous range of flexibility and options. We can use it to create an entirely soft interface.

Fingers are low-resolution devices. They can get in the way in certain applications, especially when they block our view of what they point at. To take true advantage of human motor control and a high-resolution touchscreen, we need a fine-tipped stylus. A walk through any art gallery shows what man can do with stylus type devices.

On powering up our machine, icons representing a typewriter keyboard, a ball point pen, a telephone, a calendar, a TV, and a host of other applications will appear. By touching and dragging with the stylus, we can manipulate the icons as with a mouse. We can move rapidly through a series of pop-down, drag-off menus by checking off what we want with the stylus. Pressing the typewriter icon will cause a keyboard pattern to appear on the screen. This pattern can be redrawn like MacPaint objects and so be customized to the user's finger size and taste. Since it is soft, the key pattern can be QWERTY, Dvorak or based on one of the new, non-standard shapes like the chord. As we traverse down a menu and we need text input, the keyboard will pop up.

But if we are holding a stylus, why bother with the keyboard? Pressing the ball point pen icon will cause a ruled notebook page to appear on screen, right down to simulated looseleaf holes if desired. With the stylus, we can write and draw directly on the surface of the screen. As we stroke the stylus across the screen, a simulated ink trail is left behind. Nothing beats a pen for writing or doodling, so this will permit the ultimate integration between text and graphics. Some people feel more comfortable composing on paper than on a computer, and this presents the illusion that they are. And, if we wish, handwriting recognition software will convert to type all the text we scrawl out.

This metaphor will extend easily to the applications we are familiar with. Text editors can be built around the standard editorial symbols used by proofreaders, where slashing out a word means deleting it and circling two words transposes them. Despite the interactive nature of word processing programs, almost all writers print out a draft and scratch corrections upon it before pronouncing it ready. Our text editor will support this style, and graphics and mathematics will be integrated in a similar fashion.

Without question this is technologically feasible. Our interface relies on three different technologies: display, touchscreen, and optical character recognition. Each of these is progressing nicely towards what we need in 2000. The density attained in liquid crystal display (LCD) technology has increased by a factor of 100 every 7 years [1]. For an 8" by 11" color display with laser printer resolution we need less than 3×10^7 pixels, which by extrapolation will be available by 1991 and cheap by 2000. In addition, LCDs represent the perfect foundation for a touch-sensitive display. The capacitance of an LCD cell is pressure sensitive, so we can easily detect the tip of a stylus and even how hard it is being applied. Already, LCDs have been used as digitizing tablets [2] and given the resolution of our display we will have no difficulty mimicking the finest ball point.

Cursive character recognition is a difficult problem, and smacks of artificial intelligence. However, there has been enough progress to show that it is coming. Today, there exist systems with 97% character recognition accuracy for neat handwriting. Combined with spelling correction, such systems achieve near 100% accuracy [3]. Adjusting for variations in handwriting is equivalent to breaking a substitution cipher [4,5], a trivial task for our computer. Training on the owner's handwriting will lead to the highest possible recognition rate. Of course, no system will recognize 100% of handwritten text, but what isn't recognized can be highlighted in a different color and reentered by the user.

A high resolution, color display can do more than just imitate a notebook page. It will be fast enough to support video. The entertainment possibilities are amusing, such as having a display of thirty-six $1'' \times 1''$ moving icons, each one a different television channel, permitting us to monitor the action over a large section of the dial. We can watch the bad guy being rubbed out on channel six while the passion heats up on channel forty. A more important application is video communications. Video is the next obvious step in the communication evolution which started with text and has progressed to voice.

It might seem surprising that our design is not built around speech recognition as the major input technology. Science fiction seems to specialize in talking to computers and listening to what they have to say. However, people do not really want to talk to their computers. In many of the contexts where a portable computer will be used, such as the classroom, the airplane, or a shared office, talking out loud is not acceptable behavior. Further, dictating letters and memorandas is a skill which takes time to master, and is something most people are uncomfortable with. Our handwritten interface is much less intrusive than speech.

2.2. The *LaserCard* Mass Storage Units

The high density read-write storage card unit represents the next milestone in mass storage technology. Replacement of the classical rotating-disk/movable head format will result in spectacular improvements over current mass-storage systems in terms of data capacity, data rates, and integrity of physical construction.

These credit card sized optical RAMs will be a convenient, inexpensive, and physically robust data storage medium. People will carry them in their shirt pockets and trade them like baseball cards. "Can I borrow your reference library, please?" Customized cards will be ordered from information services via electronic menu-driven catalogs, offering a wide variety of books, video and data, all paid for by the gigabyte.

The vast storage capacity of *LaserCard* devices will alter our conception of what should be stored on a computer. Through data compression techniques, a single one-gigabyte card will hold four hours of video or two thousand books from a personal library. Current optical media are limited by the resolution at which a laser can be focused, currently about around one square micrometer, and require a head that sweeps back and forth mechanically over a rotating disk [6]. Advances in high-resolution optical films (such as LCDs) will allow the fabrication of huge arrays of independently addressable “light-gates,” which can be used to direct the beam of a short wavelength, solid-state laser directly onto a specific site of the storage medium for reading or writing. The surface-emitting lasers will be paired with photo-detectors, in a relatively low-density grid positioned above the optical gating system, defining a set of independently read-writable “laser” sectors.

This technology will have no spinning disks, no servoed read-write heads, and no rotating mirrors. The only moving part in the whole machine will be the lid which keeps the optics dry if we use it in the rain. Because of its size and durability, the *LaserCard* will be an integral component of a powerful portable machine.

2.3. The Infrared Interface

Along three sides of the box will be an infrared bar interface. This is how we will connect our machine to its immediate surroundings. What might we want to connect to? Printers and projectors, stereo headsets and video cameras, toasters and roasters, and just about anything else. Microprocessors have already become inexpensive enough that many household items are being made "smart." Smart devices are most useful if they can communicate with other smart devices. Using a 256 bit key, we can give every atom in the universe a unique identification number, let alone give every separate memory location in each smart device its own unique ID. Thus, when devices talk to each other, they will know to whom and to what they are speaking.

On clipping a device to the bar, the computer and device will start to talk to each other at near gigabaud rates via infrared [7]. The device can be identified, causing the appropriate icon to appear on the screen. An advantage of using infrared light is that devices need not be physically clipped on while indoors. When you are within the reception area of your printer, the printer icon will appear. There is a tradeoff between dispersal and bandwidth with infrared, and trouble occurs when the scattering delay approaches the distance between bits. Clip-on lightguide cables will be necessary to achieve data rates above 500 kbits/second, and infrared repeaters stationed in large offices will improve accessibility.

What types of peripherals will people need? One of the most widely owned peripherals will be a tactile keyboard. For rapid text entry, nothing beats a good solid keyboard. The fastest recorded human information transfer is music pouring out of the fingers of a concert pianist. The handwriting interface and simulated keyboard will suffice for portable applications, enough so that we will not want to be hampered by the dead weight and fragility of a keyboard when we are on the move. But it will be nice to have a real one for some applications and why not? When we move our machine within infrared range of our keyboard, a typewriter icon will pop up on the screen, which we can open and then start typing.

Another peripheral which will be extremely popular will be a lapel sized video camera. Charge-coupled devices (CCDs) make inexpensive and rugged solid-state cameras. As with LCD, CCD production methods are similar to VLSI, and prices will follow the corresponding learning curve. The upshot is that camera devices will be so cheap that everyone can afford one. They will be useful for recording meetings, self-recorded email videos for instruction and personal communication, and as a digitizing device for printed documents which remain in the year 2000. The notion of digitizing documents is important, because a substantial number of printed documents will remain, such as old books and new contracts. After digitization, the image can be processed to cleanup and recognize the text. Imagine not only carrying a Xerox machine, but one which will permit you to search your xeroxed documents by keyword and context.

It takes only a little more courage to predict a GPS (Global Positioning System) receiver on our machine, either as a clip-on or a built-in component. GPS [8] is a satellite-based positioning system which enables objects to determine their location in the world to within a few *meters*, or even better if the U.S. Department of Defense allows it. By plugging in the *Rand McNally Road Atlas LaserCard* and taking our computer for a drive, it can provide us with an ideal route between two points by considering the possible routes, the time of day, and current traffic patterns (using an on-line data base, discussed below). The capacity of a *LaserCard* is such that we can store all the parking spaces in the state, and have the best spots near that French restaurant in the city read to us through a speech synthesizer.

In addition to communicating with peripherals via infrared, we can also talk to other computers. Each machine can continually broadcast what the owner wishes the world to know about him or her: perhaps their name, face, interests, and marital status for openers. Setting your machine in “get acquainted mode” will display the location of all machines in the vicinity and who their owners are. While sitting in your seat on a plane you can scope the crowd, and maybe find someone interesting to talk to during the trip. Just imagine turning this loose in a singles bar!

2.4. The *DataLink*

If we can take our computer anywhere, we need to be able to use it anywhere. This includes the communications capabilities. Through our national telephone network, we can access any person or machine within seconds. Historically, this depended upon direct physical connection with the phone grid. Cellular telephone technology has changed all this and will change computers as well.

What can we expect from cellular telephones? Clearly voice communications, but more important for our purposes will be data. Cellular telephones supporting the ISDN standard transmit approximately 56 kbits/second for each of 400 users per cell. With compression, this is sufficient to transmit video at conference quality rates today [9] and will increase performance dramatically with new adaptive algorithms.

To use this link for voice communications, we will need a microphone and speaker built into the unit. These are inexpensive and justified by other applications. However, for privacy, in most applications we will use a headset attachment clipped onto the infrared bar.

The main use for the cellular link will be to talk to other computers and the people using them. Electronic mail is a wonderful medium for ideas and does not intrude the way a telephone does upon its recipient. It sits there quietly waiting to be read. We will be able to integrate video and graphics as well as text in our email documents. It will also improve more traditional forms of communication. Filters can be used to eliminate unwanted junk mail. This will alter the face of advertising. Future advertising will be done by subscription, so if you want to be kept informed about new cars, let the industry know. Finally, it will be welcome news for romantics. The touchscreen and cellular link will conspire to transmit handwritten love letters anywhere in the world in seconds!

2.5. The Traditional Computer

The aspect of our design which deals with what today is described as the computer, i.e. the processor and its memory, is rather mundane. It is clear that there will be mega-MIPs and giga-bits available to work with, but since our machine is intended to be a commodity, the speed will not be a constraint. This is not to say that we will fail to exploit whatever computational power we can get, but nothing we foresee needs more power than is granted us by very conservative projections [10]. Whatever processor we have under the hood is irrelevant to the rest of the design. Thus we avoid the temptation to guess the exact number of MIPs or the memory size of our machine. We also avoid citing exactly how many processors the machine will have. There will obviously be some form of parallelism, in the tens of processors rather than the thousands, several of which will be special purpose devices for graphics, image compression, and analog signal processing.

One would hope that from all the attention focused upon instruction sets in the RISC vs. CISC debate a standard instruction set for general purpose computers will be established by the year 2000. Odds are that it will be quite RISCy, and this will permit object code compatibility across a wide range of computers. There is really not a significant difference between the instruction sets of different manufacturers, and enough of them have been burned producing incompatible chips for the industry to lead the push for standard processors. Microprocessors will be pretty much generic, coming in fast, extra fast, and economy sizes. This degree of uniformity already exists with memories and will drift to more sophisticated components.

There will also be standardization among user interfaces, to the extent that all will be constructed in layers, where all but the highest layer will be a universal standard. Running on these generic processors might be a standard version of UNIX, appropriately updated for parallel architectures, which will come out of its shell into a standard Postscript interface. Other hardware standards, like the RS-232 interface and MIDI will be simulated over the infrared-bar interface.

What will these processors be made out of? Odds are silicon, because of the accumulated manufacturing experience. The only gallium arsenide you will see will be in the infrared bar interface for the LEDs. More exotic technologies such as optical computers, molecular or chemical computers, or superconductors will not mature by that time. Currently, we are only a few years and few orders of magnitudes away from some fundamental limits on feature size in silicon. These will essentially be reached by 2000, and so research will change direction towards more reliable processing and higher yields. This makes possible wafer-scale integration with all the circuitry sitting on one six-inch diameter wafer. Putting both memory and processor on the same chunk of silicon will improve performance by reducing buffering and capacitance delays. There will be so much room on a wafer that there will be at least two of each functional unit onboard, dramatically improving yield and reducing costs.

Between improvements in semiconductor processing and improvements in design technology, the complexity of IC's should continue to quadruple every five years [11]. With generic processor architectures and room for a wafer full of circuitry, what will there be for the new generation of silicon compilers to do? Crank out special purpose processors, no doubt. Traditionally, co-processor chips were used because there was not room on the chip for the arithmetic or graphics hardware. Now, there will be room for a large graphics processor, analog and digital hardware for image processing, and much more.

Perhaps the most interesting special purpose processor will be a general adaptive data compressor sitting between the memory and the main processors. It will be a hardware implementation of an adaptive algorithm such as Lempel-Ziv [12] or LZW [13], or perhaps some higher level algorithm recognizing features in text and video. This will permit video to be stored on laser cards and transmitted over low bandwidth lines, because image expansion will occur at video rates. If a picture is indeed worth 10,000 words, imagine what can be saved by image compression! Already, through compression researchers have fit 72 minutes of video [14] on a CD-ROM, which is about half the size of our projected *LaserCard*. This same technology will be essential to transmit video over the cellular phone link. It is ironic that compression becomes even more important as memory size increases, because there is so much more to transmit and access.

2.6. Power

This machine is designed to bring power to its users. However, with a portable computer, the user must bring power to the machine. Either the machine must contain its own power source, or it must take energy from its environment. The only significant power from an indoor environment is light, and we can expect no more than 0.3 Watts even if we cover the entire surface of our box with very ugly and efficient solar cells. Fortunately, recent developments suggest we can plug into battery power.

Lithium battery performance has approximately doubled each decade since 1946 [15]. Already, lithium D-cells can deliver 45 W-hr. This provides all the power we will be able to use without running into heat dissipation problems. Rechargeable lithium batteries exist, and a cute way to recharge them will be with inductive coupling. Park the machine in a holster plugged in an electric outlet and the batteries can be recharged without a wire link.

2.7. Other Computers in Other Places

Much of the communication with other machines will be with those of the same model, through email. We will also make use of large data base machines which will spring up as resource centers. Despite the large storage capacity of *LaserCard*s, there is no hope that everyone will physically be able to own all the data they will ever need. This information will sit on a data base machine which we will pay for by the gigabyte whenever information is accessed. There are significant and difficult economic issues about who will pay to create new information, and it is reasonable to expect newer information to be more expensive than old. Simple calculations show that the Library of Congress contains about twenty terabytes of information, which will fit on about 20,000 *LaserCard*s. Thus the actual size of a data base machine is not necessarily large. The biggest task for such information centers will be to keep up with and make available new knowledge being created around the globe.

Of course, there will exist problems for which the processing power available in an $8'' \times 11''$ box is not enough. Large, parallel, special purpose supercomputers will be readily tapped for such applications. One fanciful solution would be for the US government to pull the plug on the six billion dollar supercollider (pending the inevitable progress in high temperature superconductors) and use this money to produce a massively parallel computing "power station." With this amount of resources, a *billion* processor Connection Machine [16] or a thousand processor Cray could easily be constructed and maintained. Anyone could call up and use some section of this machine, paying for the time and number of processors used. For research applications, perhaps the entire machine would be devoted to a single problem, making what was once intractable almost instantaneous. Applying such a tool to genetic sequences or long term weather forecasting has the potential to truly improve the quality of life for everyone. And applying small portions of it to such amusements as interactive movies present interesting possibilities.

3. The Implications for Work

A growing number of professionals, bothered by the hassle and inconvenience of commuting to the city and work, are opting to work at home. This has been made possible largely by the development of personal computers, since the facilities of the office can be replicated at home. Communication with co-workers can be maintained via telephone and occasional office visits. Our machine has the possibility of accelerating this trend and pushing it in a new direction.

The insight is that with a truly portable computational and communication tool, we are not restricted to working in the office or at home, but anywhere! Our machine will provide access to anything we are used to having at the office, so there is no reason not to work somewhere else. On a sunny day we can take our work to a park, and not fear being out of touch for an important message. The distinction between work and vacation will blur. A one-month stay with the family can and should be possible without upsetting anyone's work schedule. Perhaps the biggest drawback of work-at-home is the loss of social contact with co-workers. But now we can take our work to where people are, instead of moving people to where the work is.

Video conferencing will be vital if people are to communicate effectively from afar. The CCD camera, video compression processor, and cellular link make this a reality almost anywhere. Today's video conferencing requires a studio and a heavy investment. Now we can take our conference to where the work is actually being done.

Carrying an expensive computer is unnerving for many people for fear of breakage or theft. Our design is simple and robust enough to survive a healthy jolt. The threat of theft will be eliminated, since each computer will have a unique identification number. We can call up the computer after it has been stolen and use the GPS receiver to let us know exactly where it is. Try and fence merchandise that is *this* hot! To protect personal information, it is reasonable to take handprints with the touchscreen for identification.

Perhaps even more important than physical security is data security. A great deal of personal information will be stored on these machines, and communicated by infrared and cellular telephone. To safeguard this, encryption and digital "signatures" will be used with all data transfer. By 2000, the general public will be familiar enough with the notion of digital signatures to trust them more than physical signatures. This will be necessary because of the ability of ray traced computer graphics to simulate any desired scene or image. The time is almost here when photographs will no longer be admissible as evidence in a court of law, because they will be so easily and successfully faked.

By 2000, the marriage of computers and science will be complete. Algebra, calculus, and all aspects of mathematical calculation will routinely be done by computer, just as all arithmetic has now been relegated to calculators. Scientific journal articles will have live equations built in, so they can be automatically checked by the reader.

In the past, there were two basic approaches to science: doing experiments, where one measures how a system behaves, or doing theory, where one works out how a system should behave. Computers make possible another approach to science: computer experimentation, which will become the dominant method for investigating many kinds of systems. One implements an algorithm which simulates a physical system and then finds out what happens by watching the program run. There are many kinds of systems for which this approach is not only convenient, but fundamentally necessary [17]. Research in physics, biology, economics and other areas is already being directed by models inspired by digital computers. Our computer will not be big enough to predict the weather, but will be able to simulate the results of any college physics experiment. There will be very few scientists in 2000 who do not spend the majority of their time in front of their computer.

The notion of "programming" will change substantially. Programs in low-level languages like C will start dying out like dinosaurs. Filling their ecological niche will be scripts for high-level interpretative systems. These programs will not be created by entering a sequence of lines of code, but rather by linking together operations using a graphical representation of the program's function. At the simplest level, a program will be just "replaying" a sequence of commands to a high level system. With these systems, fewer people will call themselves programmers, since a wide class of people will be able to use them.

4. The Implications for Play

Computers such as ours will provide new dimensions for recreation and education. People will have tools available for the creation of art sufficient to alter the way ideas and feelings are expressed.

Descendents of programs like *Hypercard* will lead to a redefinition of what exactly literature is. On-line books can have animation, and textbooks can have live formulae to experiment with and manipulate. Initial efforts to create hypertext novels will no doubt be artistic failures, but with time legitimate hyperliterature will be created. The time will come, perhaps not by 2000, when the Nobel Prize for Literature will be awarded for hyper instead of linear text.

Using CCD cameras and ray traced graphics, home movies take on a new meaning. By digitally splicing home "footage" with simulated scenery, the amateur will be able to produce professional looking movies the way any author can now typeset his own material. As the technical and financial obstacles to entry for such arts fall, more and more people will participate.

One interesting problem is who will appreciate all this new art? Some form of "shareware video" might arise. Other distribution channels will no doubt sprout up, but much of this art will be only for private consumption. An analogous situation already exists, as publishers have known for years that more people write poetry than read it. So it might be with shareware video.

Just having a studio available doesn't make someone an artist!

5. Conclusions

Predicting the future is obviously not a well-defined task, representing a tradeoff between imagination and reality. What passes for science fiction is often based more on hopes and dreams than technological or even physical possibilities. Twelve years is not a lot of time, but it is all we have until the year 2000. This sets some hard limits on what is possible. Many futurists may choose to ignore these, but as Spanish painter Francisco Goya said, "imagination abandoned by reason produces monsters."

There is no major aspect of our machine which is not in some sense sitting in a laboratory today. We do not suppose a breakthrough in artificial intelligence, superconductivity, or any other sexy technologies, as foretelling their destiny is still the province of psychics, not scientists. We do not rely on the construction of a new, national infrastructure such as a fiber optic link to each home, since this will require at least a generation to complete. We look at what is possible and start from there. The creativity in our design involves synthesis, uniting disparate elements into a clean and satisfying whole.

Reading through old issues of *Popular Science* shows how difficult it is to predict the future. Cover stories have focused on such "discoveries" as polywater and such "budding technologies" as the flying car. If fact, one might suspect that an appearance on the cover of *Popular Science* is the kiss of death for any breakthrough.

This serves to provide us with some humility concerning our predictions. Still, our vision is both realizable and desirable. We all want this little machine, and twelve years of engineering will make it a reality. The sooner Apple gets to work on it, the better for everyone.

6. References

[1] F. J. Kahn and H. Birecki. "Multiplexing Limits of Twisted Nematic Liquid Crystal Displays and Implications for the Future of High Information Content LCDs," In: *The Physics and Chemistry of Liquid Crystal Devices*, Gerald J. Sprokel, ed. Plenum Press, New York, 1980, pp. 79-93.

[2] T. Tanaka and S. Kobayashi. "Entry of Data and Command for an LCD by Direct Touch: An Integrated LCD Panel," In: *1986 SID International Symposium Digest of Technical Papers.*, 1986, pp. 318-320.

[3] C. C. Tappert. "Cursive Script Recognition by Elastic Matching," *IBM Journal of Research and Development* (November 1982), Vol. 26, pp. 765-771.

[4] R. G. Casey. "Text OCR by Solving a Cryptogram," In: *Eighth Int. Conf. on Pattern Recognition*. IEEE, New York, 1986, pp. 349-351.

[5] G. Nagy, S. Seth, K. Einsphahr and T. Meyer. "Efficient Algorithms to Decode Substitution Ciphers with Application to OCR," In: *Eight Int. Conf. on Pattern Recognition*. IEEE, New York, 1986, pp. 352-355.

[6] W. H. Meiklejohn. "Magnetooptics: a Thermomagnetic Recording Technology," *Proc. IEEE* (1986), Vol. 74, pp. 1570-1581.

[7] K. Pahlavan. "Wireless Communications for Office Information Networks," *IEEE Communications Magazine* (June 1985), Vol. 23, pp. 19-27.

[8] G. Hudak. "NAVSTAR Global Positioning System Collins User Equipment: an Evolutionary Assessment," *Navigation* (1986), Vol. 33, pp. 1-19.

[9] C. N. Judice and D. LeGall. "Telematic Services and Terminals: are we ready?," *IEEE Communications Magazine* (July 1987), Vol. 25, pp. 19-29.

[10] S. Lundstrom and R. Larsen. "Computer and Information Technology in the Year 2000 - a projection," *Computer* (September 1985), Vol. 18, pp. 68-79.

[11] A. Baker. "Silicon Compilers: Chip Design for Systems Designers," *Computer Design* (July 1986), p. 60.

[12] J. Ziv and A. Lempel. "A Universal Algorithm for Sequential Data Compression," *IEEE Transactions on Information Theory* (May 1977), Vol. IT-23, pp. 337-343.

[13] T. Welch. "A Technique for High-Performance Data Compression," *Computer* (June 1984), Vol. 17, pp. 8-19.

[14] R. Bruno. "Making Compact Disks Interactive," *IEEE Spectrum* (November 1987), Vol. 24, pp. 40-45.

[15] T. R. Compton. "Small Batteries," In: *Primary Cells*. MacMillan Press Ltd., London, 1982.

[16] D. Hillis. *The Connection Machine*. MIT Press, Cambridge MA, 1985.

[17] S. Wolfram. "Computer Software in Science and Mathematics," *Scientific American* (September 1984), Vol. 251, pp. 188-203.