Sensitive Skin

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***Abstract*—Sensitive skin is a large-area, flexible array of sensors with data processing capabilities, which can be used to cover the entire surface of a machine or even a part of a human body. Depending on the skin electronics, it endows its carrier with an ability to sense its surroundings via the skin's proximity, touch, pressure, temperature, chemical/biological, or other sensors. Sensitive skin devices will make possible the use of unsupervised machines operating in unstructured, unpredictable surroundings—among people, among many obstacles, outdoors on a crowded street, undersea, or on faraway planets. Sensitive skin will make machines "cautious" and thus friendly to their environment. This will allow us to build machine helpers for the disabled and elderly, bring sensing to human prosthetics, and widen the scale of machines' use in service industry. With their ability to produce and process massive data flow, sensitive skin devices will make yet another advance in the information revolution. This paper surveys the state of the art and research issues that need to be resolved in order to make sensitive skin a reality. The paper is partially based on the report of the Sensitive Skin Workshop conducted jointly by the National Science Foundation (NSF) and Defense Advanced Research Projects Agency (DARPA) in October 1999 in Arlington, VA, of which the three co-authors were the co-chairs [1].**

***Index Terms*—Automation, electronics, large area sensor arrays, material science, robotics, sensing, sensitive skin.**

I. Introduction

IN THE famous Russian novel *Master and Margarita* by Mikhail Bulgakov, one of the characters, a high-level Moscow bureaucrat, offends the Devil. For a swift and terrible punishment, he is banished from his suit, but his suit continues to sit at his desk, signing papers, barking commands, and generally functioning in the same way as its former wearer. This talking suit evokes the image of sensing and acting cloth—a bendable, stretchable skin with intelligent processing capabilities. Present-day electronics technology does not allow us to produce such sensitive skin. Not yet. But the needs for it are big and increasing. And the necessary tools are at hand. Several novel technologies can be used in order to fabricate sensitive skin, and many novel ideas have already emerged. They will allow us to fulfill our dream for machines sensitive to their surroundings and operating in unstructured environment.

This paper focuses on the principles, methodology, and prototypes of *sensitive skin*-like devices, and the related system intelligence and software that are necessary to make those devices work. As discussed below, sensitive skin represents a new paradigm in sensing and control. These devices will open doors to a whole class of novel enabling technologies, with a potentially very wide impact. Far-reaching applications not feasible today will be realized, ranging from medicine and biology to the machine industry and defense.

Some applications that sensitive skin devices will make possible are yet hard to foresee. Flexible semiconductor films and flexible metal interconnects that will result from this work will allow us to develop new inexpensive consumer electronics products, new types of displays, printers, new ways to store and share information (like electronic paper and "upgradeable" books and maps). New device concepts suitable for large area flexible semiconductor films will lead to new sensors that will find applications in space exploration and defense, specifically in mine detection and active camouflage.

An ability of parallel processing of massive amounts of data from millions of sensors will find applications in environmental control and power industry. These areas will be further developed because of the highly interdisciplinary nature of the work on sensitive skin, which lies at the intersection of information technology, mechanical engineering, material science, biotechnology, and micro- and nanoelectronics.

Availability of sensitive skin hardware is likely to spur theoretical and experimental work in many other disciplines that are far removed from robotics. This stimulus is comparable to that which triggered the explosion of control theory in the 1940s and 1950s, in direct response to the challenge posed by the appearance of fundamentally new hardware, such as jet fighters and radars.

To exemplify the concept of sensitive skin, a prototype of a sensitive skin module is shown in Fig. 1. The module contains $8{\times}8 = 64$ active infrared sensor pairs (LED + detector), each of which can sense objects within a narrow cone at a distance up to about 20 cm. One of the most powerful abilities of the sensitive skin as applied to motion control is demonstrated in Fig. 2. Here a skin-equipped robot arm manipulator dances with a ballerina. She does not hesitate to turn her back to the "partner," fully expecting a "human" reaction. Since every point of the robot body has its own sensing, no artifacts such as occlusions (a typical problem, e.g., for vision devices) can interfere with the sensing. A block-diagram of the sensitive skin interconnects is shown in Fig. 3. Fig. 4 illustrates some of the numerous potential applications of sensitive skin envisioned by Motorola Co. researchers.

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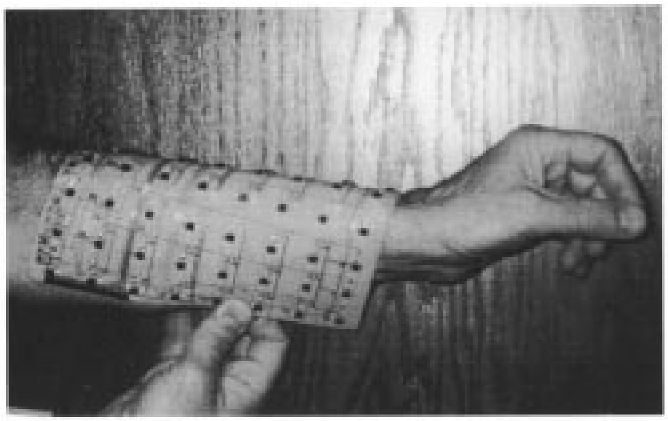

Fig. 1. Sensitive skin module: $8 \times 8 = 64$ infrared sensor pairs (LED's and detectors); the distance between neighboring pairs is 25 mm; surface mounting technology; Kapton substrate. (V. Lumelsky, Robotics Laboratory, University of Wisconsin-Madison.)

Fig. 2. Ballerina dancing with a robot manipulator. As with two human partners, the whole dance is pre-rehearsed, but their actual positions at any given moment differ from one "performance" to the other. Since the robot's sensitive skin allows it to continuously sense the ballerina, she can trust her partner enough to turn her back to it and expect a "correct," collision free reaction. (V. Lumelsky, Robotics Laboratory, University of Wisconsin-Madison.)

Some of the issues in the sensitive skin research are discussed below. After a general sweep in this Introduction of the questions relevant to this area, the requirements to sensitive skin are considered in Section II, followed by a tentative list of disciplines whose development is expected to be affected by availability of sensitive skin devices (Section III), and by the description of specific technologies relevant to sensitive skin (Sections IV–VIII). Section IX concludes the paper. Further details can be found in the Sensitive Skin Workshop Report [1].

A. Machines in Unstructured Environments

Imagine we want to design a home-helper machine for senior citizens. We want this Helper to handle a modest range of tasks—pass a glass of juice, help the person to make a few steps, go to the door to let in a visitor. The machine should be powerful enough to support a walking person; it should have some kinematics—let us say, an arm manipulator—to move things around.

Assume for a moment that the desired functions do not require much intelligence—the person who will use the Helper is able to make decisions on what it should do and how. Assume also that motion dexterity, such as in the human five-finger hand, is not necessary. We are willing to accept simple functionality, perhaps below the sophistication of modern industrial robots. In other words, the basic components necessary for our Helper—the drive system, sensors to see the object of a task, basic kinematics, and intelligence to execute those tasks—do already largely exist. And yet, *such a machine cannot be designed and built today—at any cost*.

Why? Because with today's sensor technology, most of the Helper's body surface would be left insensitive, unable to sense most of close-by objects. Sooner or later our Helper would topple over a shoe, crush a glass, step on a cat, clasp the person's finger. To prevent this from happening, designers would have to significantly constrain the machine's environment. They must *structure* the environment. For example, they would require that the arrangement of objects in the room be fixed, that no unaccounted-for pets or socks appear at the scene, and that the person always sits in the same position when requesting the Helper's services. Not surprisingly, this design would be unlikely to succeed.

The fundamental problem here is that our Helper must work in an *unstructured environment*—that is, a place that cannot be modified at will and thus has to be taken as is. An apartment is a good example of an unstructured environment. In contrast, the design and redesign of a *structured environment*, such as a factory floor, is only a matter of cost and efficiency. Today's machine automation is almost exclusively limited to the structured environment of the factory floor. The rest of the world, with perhaps 99% of all tasks that involve motion and could in principle be automated, goes unautomated. Think of the unstructured environments in agriculture, construction sites, offices, hospitals, etc. The majority of tasks that are of interest to us take place in unstructured environments, to which today's automation simply cannot be applied.

Automated moving machines can be divided into unattended—those that can operate without continuous supervision by a human operator, and semi-attended, which are controlled by the operator in a remote (teleoperated) fashion. Today the use of both types of machines is limited exclusively to highly structured environments—a factory floor, a nuclear reactor, a space telescope. Such machines can operate successfully with relatively little and fairly localized sensing. However, expensive resources are used to compensate for these machines' inability to handle their environment. Today the "sanitized" environment of the factory floor is designed very precisely and at high cost. This is true even for the so-called universal robot arm manipulators. The automotive industry pays, say, \$70 000 for a painting or welding arm manipulator, and then another \$200 000–\$300 000 for a specially designed work cell to house it. Many existing machines could, in principle, be useful in an unstructured environment, if not for the fact that they would endanger people, surrounding objects, and themselves.

The same is true for remotely controlled machines. Unless the work cell is "sanitized" into a structured environment, no serious remote operation could be undertaken. Otherwise, at some

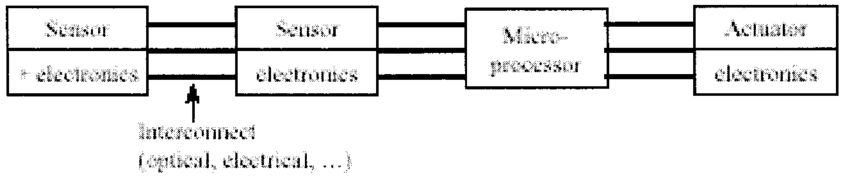

Fig. 3. Sketch of interconnects between sensors, intelligence, and actuators.

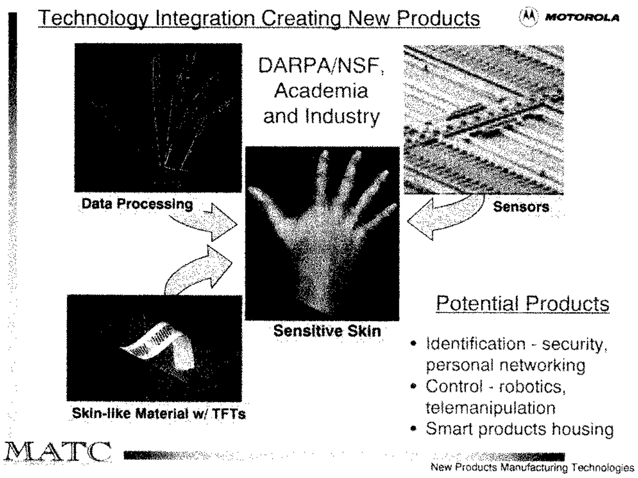

Fig. 4. Potential applications of sensitive skin. (Courtesy of S. Ghaem, Motorola Advanced Technology Center.)

instant the operator will overlook a small or occluded object, and an unfortunate collision will occur. And so the designers take precautions, either by "sanitizing" the environment, or by enforcing maddeningly slow operation with endless stops and checks. Much of the associated extra expense would not be necessary if the machines had enough sensing to cope with unpredictable objects around them.

B. The Way Out is All-Encompassing Sensing

We emphasize again that today's difficulty with making moving machines operate in our midst is not in the machine's ability to perform the task. After all, very sophisticated tasks are done on today's automated assembly lines. The bottleneck is in the amount and density of sensing. When moving a glass of juice in a kitchen, any point of the machine's body, not only its hand, may hit surrounding objects. Since in an unstructured environment those objects cannot be anticipated, all-around sensing is the only way to know about them.

Sensing that is needed is not, however, the sensing as we know it today. Supplying our home-helper with a few video cameras or a few dozens of tactile or sonar sensors distributed over its body or on the surrounding walls will not be enough. Sooner or later an object will obstruct the line of view of those discrete localized sensors, and an impending collision will go undetected. It is precisely for this reason humans and animals have some kind of sensing means at every point of their bodies. In the few known exceptions, an impenetrable shell, like in turtles, replaces sensing. *To operate in an unstructured environment, every point on the surface of a moving machine must be protected by this point's "own" local sensing.*

This sounds a bit counter-intuitive: why wouldn't vision, or laser, or sonar, or other individual sophisticated sensors suffice? Think of humans and animals. Patients with lost skin sensitivity due to diabetes or burned skin are warned by their doctors that they cannot have normal life anymore and must be extra careful for a danger of inadvertently wounding themselves. It is known that people who lose sensitivity in the lower foot skin have difficulty standing and walking. Or, that severing the nerve that passes touch information to the cat's brain causes major changes in the animal's gait and its handling of obstacles. Surprising as it may sound, while many blind people learn to have a productive life, a person with completely lost skin sensitivity is not likely to do so. Machines operating in unstructured environments face the same difficulties. Only the concept of a whole-surrounding sensitive skin can resolve these difficulties.

All-sensitive machine bodies are not a literary allegory or a whimsical sci-fi construct. If we want to move machine automation beyond the factory floor, it is a bare necessity. The need for all-encompassing sensing for machines operating in unstructured environments has been shown both theoretically and experimentally. We happened to stumble upon a principle that is a necessary condition for existence of a large class of technology, and the one that the natural evolution discovered a long time ago. *The lack of sensitive skins is the bottleneck in today's machine automation.*

C. Sensitive Skin—A Universal Paradigm

Sensitive skin systems require a fundamental turnaround in design paradigm. Today the designer adds sensors to a machine as needed, analyzing carefully how many sensors are required and in which places. There is a good reason behind this approach—individual sensors and their electronic control are relatively expensive; adding components decreases system reliability. This "poor man's" design strategy hides significant costs. Even in cases where limited sensing might work, it may be cheaper and more reliable to use the universal and often even redundant sensitive skin, rather than go to an expensive custom design.

More than one sensor type may be necessary—proximity, touch, pressure, temperature, and chemical/biological sensing are a few examples. The functionality needed is quite generic, and so a few types of skin will cover a wide spectrum of applications. We know such examples: the Intel's Pentium microprocessor has much more functional power than any of us needs, but—being mass-produced, it becomes an economically viable solution in a huge number of applications, each of which could do with much less computing power.

D. Impetus for Information Technology

Sensitive skin devices will include thousands and millions of elements that generate and process tremendous amounts of information, in parallel and in real time. This will hence be *a new physical basis of information technology*. With the eventual ubiquity of the sensing skin on various machinery, it is likely to bring the biggest leap in information technology hardware since the introduction of computers. In fact, the sheer amounts of information continuously generated and processed by sensitive skin devices will make them *challenge humans as predominant producers and users of information*.

E. Societal Needs and Concerns

1) Unstructured Machine Automation: Sensitive skins will reduce the need for low value-added services by vastly expanding the reach of automated machinery. They will bring the kind of productivity gains to service industries that integrated circuits have brought to manufacturing. Machines that by virtue of their size, power, and operation of their moving parts can present danger to the surrounding objects or be damaged by them will be able to operate safely in their environment when equipped with the sensitive skin. For example, with the help of the sensitive skin covering its body, a semi-autonomous machine helper in a senior citizen's house or a robot probe in a deep space experiment will be carrying out its function without jeopardizing its own safety and that of the surrounding objects. No such machinery exists today. *Automation for unstructured environments can completely transform the face of machine automation in the 21st Century.*

a) Health industry: Sensitive skin will supplant sensing ability of the human skin in limb prosthetics and as a replacement of damaged human skin. It will augment human sensing in wearable clothing, by monitoring, processing and wireless transfer of information about the well-being of the person wearing sensitive skin. This will advance the post-traumatic health care, care for disabled and elderly persons, and monitoring of military personnel on the battlefield.

b) Environment-friendly technology: For the first time in history, machines will be endowed with a *capacity to be careful*. By its very nature, sensitive skin will contribute in a dramatic way to the reversal of the well-known negative impact of machines on our environment, across a wide spectrum of natural and man-made settings. We often hear about the role of computer revolution and office automation in the growth of economy and improved efficiency, which *in turn* affects the quality of life. Note the difference: while unstructured machine automation will have a similar effect on the economy, its use in service industry will have *a direct impact on the quality of human life*. Biology and medical science thrive to prolong human life; the unstructured machine automation will constitute a systematic effort by engineers to improve the quality of life.

c) Difficulties of acceptance: As with any fundamentally new and powerful technology, sensitive skin technology may evoke adverse psychological reactions, with a potential of diminishing its impact. Today we are psychologically unprepared for automatic moving machines operating in our midst. We are not sure we need them. We are uneasy about the idea of living side by side with a powerful unattended moving machine. It is difficult to imagine that one could stand next to a powerful moving machine and trust it enough to turn one's back to it, or expect it to step aside when passing. Do we not have more than enough invasion of machinery in our lives? To need a very new product, one must first experience it. Recall the skepticism about the Xerographic copier (even in the parent company) when this technology was just appearing—people were still unaware of the multiplicity of needs that easy copying could satisfy.

II. Requirements to Sensitive Skin Devices

Four groups of research issues must be addressed in order to develop sensitive skin: *Skin Materials*, *Sensing Devices*, *Signal and Data Processing*, and *Applications*. Consider them one by one.

A. Skin Materials

Sensitive skin material (substrate) holds embedded sensors and related signal processing hardware. It needs to be flexible enough for attaching it to the outer surfaces of machines with moving parts and flexible joints. The skin must stretch, and desirably shrink and wrinkle the way human skin does, or to have other compensating features. Otherwise, machine parts may become "exposed" as they move relative to each other. For example, Kapton® material, by the Dupont Corporation, can hold electronics, can bend, but cannot stretch. Stretching is especially challenging, as it may require materials that have never been used in printed circuits.

Wiring must keep its integrity when sensitive skin is stretched or wrinkled. This requirement calls for novel wire materials, e.g., conductive elastomers or vessels carrying conductive liquid, or novel ways of wire design with traditional materials, such as helical, stretchable wires.

Still another possibility is semiconducting textiles, a technology that will find applications in wearable computing and wearable electronics. The efforts in developing such materials are now under way at several universities and several companies, including NCSU, IBM, Phillips, BIT's, Inc., and Printed Transistors, Inc.

B. Sensing Devices

Sensitive skin components have to be deployed in two-dimensional (2-D) or even quasi-three-dimensional (3-D), layered) arrays of sufficiently high density. A representative model would be a piece of skin of 1×1 m^2, with sensors spread uniformly at a pitch of 1×1 mm, with the total of 1 million sensors. This model immediately points to the need to mass-produce sensitive skins as large-area integrated circuits. Smaller arrays may be of use as well: the key feature is that the skin should allow, by itself or with appropriate data processing, to identify with reasonable accuracy the points of the machine's body where the corresponding sensor readings take place.

Ideally, sensors and their signal processing hardware should be spread within the array so as to allow cutting it to any shape (disc, rectangle, an arbitrary figure) without losing the entire sensing and control functionality. This suggests interesting studies in hardware architecture. Any sensing modalities, including proximity or tactile, discrete or continuous, are acceptable. Sensor arrays with special or unique properties are of much interest, for example a cleanable and washable skin for "dirty" tasks in nuclear/chemical waste site applications; radiation-hardened skin for nuclear reactor and space applications; and skins that can smell, taste, or react to ambient light. The ability to measure distance to objects would be a great advantage for enabling dexterous motion of the machine equipped with the skin.

For self-diagnosis and reliability, "self-sensing" ability of the skin is highly desirable; this may include sensing of contamination, dust, chemical substances, temperature, radiation on its surface, as also detection of failure of individual skin sensors and an ability to work around failed areas.

No existing types of sensors are likely to satisfy all requirements. For example, a light sensor is fast and accurate; sonar and capacitance sensors require less power but have poor resolution. Consequently, new sensors, or new combinations of existing sensors, or new ways of packaging existing sensors may be developed to satisfy these needs.

C. Signal/Data Processing

To produce continuous motion, the sampling rates of today's typical computer-controlled moving machines should be in the range of 30–50 Hz. Taking 50 Hz as an example, within the available 20 ms sampling period all skin sensors must be polled, information from those sensors that sense objects passed to the machine control and analyzed, and motion commands for the next step sent to the drive motors and executed. With possibly millions of sensors per 1 m^2 of the machine's surface, this requires a very high data bandwidth and sophisticated data processing algorithms.

Large numbers of discrete sensors on the sensitive skin make it advantageous to use lower level data processing locally at each sensor. This can include analog-to-digital processing, sensor calibration, individual sensor based distance measurements, etc., and calls for highly parallel processing and efficient software architectures.

Sensitive skin is a natural network of nodes–sensors distributed along a 2-D surface lying in 3-D space. There is a natural notion of neighboring nodes and far away nodes, the notion of distance between the nodes along the skin and in 3-D space, and the notion of skin topology—expressed, for example, in the skin multiconnectedness. This situation points to a multiplicity of schemes for intelligent control. Can, for example, such a network be taught motion algorithms, or learn motion strategies from observing the machine's environment during its operation?

III. New Hardware Stimulates New Research

There is a number of disciplines that are not directly tied to the development of sensitive skin but will likely be stimulated by its availability.

A. Sensing and Dynamic Control

Consider our home Helper mentioned above. When its arm senses an obstacle, the control system must analyze it and modify the motion accordingly. Here, the arm dynamics, sensing resolution, and the allowed speed of motion are all tied in some relationship. For example, if the sensing is "myopic" and the arm is heavy, the Helper will move slower, "fearing" a collision, no matter how good its control system is. Since the Helper's arm is a highly nonlinear system, realizing good real-time control is a challenging problem of control theory.

B. Need for New Control Theory

Note, for example, that the admittedly complex control system of today's flying aircraft focuses primarily on achieving desired properties of motion at a single point of the aircraft—say, its center of gravity. Other characteristics, such as accounting for body dynamics, appear as constraints on control. However, when controlling a sensitive skin-equipped machine, the control system should be able to focus intermittently on various single and multiple points of potential collision on the machine's body, and modify the control accordingly, all within the draconian constraints of real-time operation and changing kinematics of the body. Perhaps a better analogy is the control of a bat flying among tree branches, or attempts of reconfigurable control for the changing shape of a jet fighter in battle. These complications call for novel, exciting control theory.

C. Motion Planning Based on Sensitive Skin Data

This research is likely to make use of tools from graph theory, search algorithms, computational geometry, differential geometry, and topology. One serious issue, largely not addressed today, is the symbiosis of real-time motion planning algorithms with control of the machine's body dynamics and with nonholonomic constraints on the machine motion. That is, based on the continuous stream of data from the sensitive skin, the planning algorithm not only has to produce collision-free motion for every point of the machine's body, but it has to do it within the system's dynamic constraints (masses, accelerations, etc.) and the design constraints of its actuators (e.g., an automobile cannot turn on the spot and must move along a curve).

D. Use of Sensitive Skin in Bioengineering

There is an intriguing possibility of combining this artificial skin and natural living skin, to help people with lacking or diminished sensing abilities, or in prosthetic devices, or in augmenting human sensing via wearable clothing, such as for military personnel.

E. Man–Machine Systems

Human and machine intelligence could be merged in real-time motion planning. Envision, for example, a pilot trying to keep his helicopter hovering low above the ground to collect samples from the rain forest without colliding with the underbrush. Besides informing the pilot of any undesirable contacts with plants below, data from the sensitive skin-covered helicopter underbody can be directly used for automatic control of the hovering height to avoid collision. Prototypes of control systems that combine human and machine intelligence in real time have already been demonstrated [2].

F. Collective Behavior, Multi-Agent Systems

Taken to a still higher level, sensitive skin can help address such issues as coordination of and interaction between multiple machine agents (e.g., between two or more arms); decentralized and distributed control; relationship between the local behavior of an individual agent and the group's global goal. For example, since the limited sensing of today's arm manipulators does not let them sense each other at every point of their bodies, they cannot be used in tasks with shared space except within a very rigid control scheme.

IV. Electronics and MEMS on Large Area Flexible Substrates

Starting with examples, shown in Fig. 1 is a module of a sensitive skin prototype containing $8 \times 8 = 64$ active infrared sensors [2], [3]. Each sensor presents an LED+detector pair, which can sense objects within a narrow cone at a distance up to roughly 20 cm. With appropriate module-to-module interconnects, such modules can be tiled together to cover a surface as needed, as in the robot arm manipulator shown in Fig. 2. The related control electronics is designed to allow scaling up or down. A skin module can be cut to shape in a number of ways to accommodate various needs (e.g., in circular, various rectangular, etc. shapes) without losing its functionality. This module is just a harbinger of more advanced and complex technologies needed for skin modules containing millions of sensors. Some of the technologies potentially suitable for such sensitive skin are discussed in this section.

A. Rationale for Silicon Devices and for Low Cost Processes

A large number of transduction principles and transducer types does already exist [4]. Specific types must be adopted and developed in the configuration appropriate for thin, flexible skin. An important lesson from biological sensing is the need to throw away much of the information that the sensors gather early enough, passing to the "brain" only the "essential" information. Experience with large-area electronics suggests that electronic sensitive skin will function best if made with a simple structure. We expect that early sensitive skin will rely on just one or two simple sensing devices, with arrays arranged in an ordered, pixilated cell structure. On-cell and off-cell signal processing will be implemented in simple hierarchies. One important lesson drawn from biological systems is the need for fault tolerance during manufacture and in use. Design for fault tolerance will be also design for high manufacturing yield. The sum of these requirements points to the adoption of a well established device technology for sensitive skins, such as amorphous or polysilicon technology.

Large-area transistor backplanes for displays can be made in sizes up to a square meter, but cost is an issue. The cost of sensitive skin must be brought down from that of typical integrated circuits (\$50 000–500 000/m^2) and active matrix displays (\$8000/m^2), closer to the cost of thin film photovoltaic modules (\$400/m^2) or even that of printed paper (high quality mail order catalog, \$0.10/m^2). Therefore, the manufacture of devices for sensitive skin will likely rely on new processes based on the direct printing of active devices on sensitive skin materials

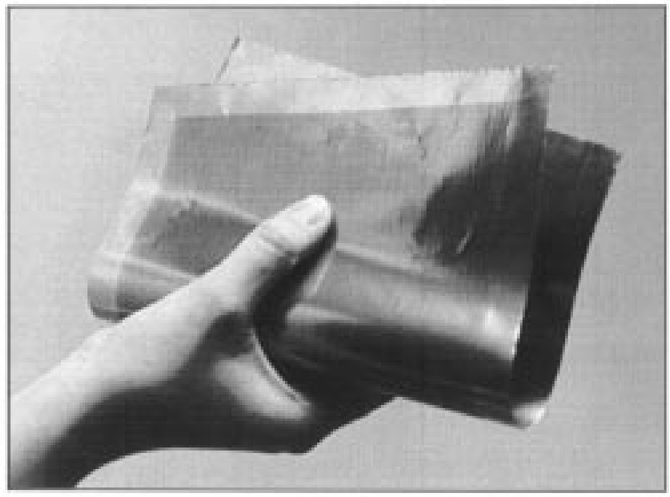

Fig. 5. Transistor mask pattern laser printed on 1-mil thick stainless steel. (S. Wagner, Princeton University.)

(metallic conductors, insulators, semiconductors, etc.). The direct printing of electronics is becoming a new technology in its own right [5]. As an example, a transistor mask pattern shown in Fig. 5 is laser printed on 1-mil thick stainless steel.

B. Device Capabilities Sought for Sensitive Skin

From the device point of view, one wishes that the sensitive skin be flexible or deformable, and can be tiled or cut. This aspect ties in to cost and repair ability. Any on-pixel generation of interrogation signals and signal processing/computation reduces the complexity and cost of the skin circuit, and raises the speed of sensing and response. The number of wires to each element/pixel also is a cost issue because of the levels of insulation needed to separate multiple wires. While devices can be quite tolerant to mechanical deformation [6], the first approach to designing sensitive skin is to keep active electronics on tiny rigid platforms (as in Fig. 1) and relegate mechanical deformation to passive interconnects [7]. Of the several mechanical configurations that are possible for the sensor cells and the interconnect wires, the rigid cell/flexible wire configuration appears the most realistic for early application.

Analysis of the wiring needs of a wide range of types of sensors illustrates the tradeoff between the numbers of on-cell transistors, wires to each cell, and interconnects. In a fully interconnected X–Y matrix only up to four wires are required to each cell. In a configuration where wires run only in one direction (either X or Y), as for example on a flat fiber, seven wires will be needed to enable separate addressing of each cell. The number of transistors per cell may range from one or two to approximately 100. At this time putting 100 thin film transistors per cell of large-area electronics is an ambitious goal. A large number of on-cell transistors are required for A/D conversion to counter the high noise levels anticipated in sensitive skin. Noise depends highly on the specific device, its configuration, and its fabrication.

Each sensor will have to be analyzed separately for its prospect to provide a low-noise signal. The dark current density of a reverse biased amorphous silicon photodiode is $\sim 10^{-10}$

A·cm^{-2}, while its photocurrent in daylight can reach $\sim 10^{-2}$ A· cm^{-2}. Thus the dynamic range of these photosensors is very large, and very high signal-to-noise ratios can be achieved; one still desires sensitivity down to very low light levels. In sensitive skin many signals are collected simultaneously over a large area. These signals are susceptible to cross talk, and the skin may function as an antenna. Therefore, sensitive skin may be particularly sensitive to noise generated in transmission between the individual elements and the central processor. This situation motivates on-element D/A conversion, which is entirely feasible.

C. Transistor Materials, Gate Delay, Bit Rate, and Bandwidth

Amorphous silicon (a-Si) dominates large-area electronics at present. The key performance metric of a-Si is its electron mobility of 1 cm^{2}V^{-1}s^{-1}. A thin-film transistor made of a-Si typically has an ON state output resistance of 1 MΩ. Its OFF state resistance is $\sim 10^{12}$ Ω. The gate feedthrough capacitance is a few tenths of a pF. Thus the typical time for charging a gate through an a-Si TFT is a few tenths of a μs. Polycrystalline silicon, made by the crystallization of a-Si at high temperature, has an electron mobility of close to 100 cm^{2}V^{-1}s^{-1}, and a hole mobility of $\sim$30 cm^{2}V^{-1}s^{-1}. TFT's of polycrystalline silicon have an ON state output resistance of the order of 10 kΩ, with charging times of tens of nanoseconds. All the new semiconductors that are under study for large-area electronics have transport properties that lie between those of a-Si and polycrystalline Si. These include organic semiconductors and new forms of silicon, such as deposited microcrystalline silicon, laser crystallized silicon, polycrystalline silicon made on steel at high temperature, and A_2B_6 and A_4B_6 semiconductors deposited on flexible substrates of cloth from water solutions at temperatures close to room temperature. It is useful to keep in mind that in sensitive skin circuits the gate delays will lie between $\sim$10 ns and 1 μs.

The ON resistance of a typical amorphous silicon thin film transistor with channel width-to-length ratio of 5 is $\sim$ 1 MΩ, and its gate insulator capacitance $\sim$1 pF. Assume conservatively that this transistor is incorporated in a circuit with a gate delay ten times the RC value, thus $\cong$10 μs. Note that the electron transit time through the TFT channel would be of the order of 0.1 μs, and therefore would not limit the circuit speed.

Let us configure these transistors as an on-element A/D converter. Pixel-level A/D conversion with a $\Sigma\Delta$ converter using only 18 transistors has been reported [8]. However, $\Sigma\Delta$ conversion needs oversampling at 64 or 128 times the Nyquist rate. The necessary high clock rates may pose a problem. Therefore, let us consider a simple 4-bit or 8-bit dual-slope A/D converter, including latch and shift register for serial readout, which could be designed from $\sim$100 transistors. This transistor count assumes seven transistors for each operational amplifier, 32 transistors for control logic, and two transistors per bit for each of counter, latch, and shift register. The rate of the A/D converter is set by the flip-flops of the counter, and the shift register. Then a 4-bit counter will have an A/D speed of $\sim$0.2 ms, and an 8-bit converter of $\sim$3 ms.

The A/D speed may be slowed down by the propagation of the clock signal that is distributed from the central processor. If this processor controls 0.1 m^2 of sensitive skin, the clock (and also the address/readout lines) lines will be up to $\sim$30 cm long. Assume that each line serves 30/0.1 = 300 elements, that the capacitive load per element is three times the TFT gate feedthrough capacitance, and that the lines are printed with the resolution of 10 μm (except at the gates, where they are 20 μm wide to account for misalignment). Then the line delay can reach $\sim$10 μs for the elements farthest away from the processor. This delay is equal to the TFT gate delay, which suggests that the A/D conversion rate in sensitive skin could come to be dominated by clock delay unless clock synchronization schemes, e.g., clock trees, are designed into the skin.

If the elements are read out with the same maximum value of line delay, approximately ten samples per second could be read from each sensor element to the central processor.

The prospect is good for raising the electron mobility by close to two orders of magnitude in the low-temperature semiconductor process technologies needed for sensitive skin. Furthermore, the use of novel printing techniques such as imprinting would enable shortening the TFT channel by an order of magnitude. Introducing these new technologies would reduce the channel resistance by a factor of $\sim$100 to 10 kΩ, and the gate delay to 0.1 μs. These developments would raise the sampling rate to 1000 per second.

D. Thin Film MEMS on Flexible Substrates

The fabrication of silicon electronics into sensitive skin backplanes can be integrated with silicon based sensor devices. Among these, silicon photodetectors are the most prominent. Silicon transistor/photosensor cells would follow the structure of amorphous silicon based photosensor arrays [9]. An important recent development is thin film microelectromechanical (MEMS) devices on plastic substrates [10]. These devices demonstrate that mechanical sensors (and actuators) can be built on the type of flexible substrate that sensitive skin requires.

V. A_4B_6 AND A_2B_6 SENSORS ON FLEXIBLE SUBSTRATES

As discussed above, one of the key challenges to the successful development of sensitive skin devices is the development of large area sensor and detector arrays, which can be fabricated on flexible and, ideally, stretchable substrates. Such substrates would include also textiles, and, hence the sensitive skin technology will also be enabling technology for wearable electronics and wearable computing. Several technologies now compete for such applications. Amorphous Si integrated circuits have been used to drive 25″ flat panel displays, and prototype a-Si integrated circuits have been demonstrated on flexible substrates (see Section IV). Another technology, which might be suitable for such applications, is based on organic semiconductors, such as pentacene (see Section VI).

In this section, we briefly review recently emerging technology of polycrystalline A_4B_6 and A_2B_6 compounds deposited on flexible substrates and even on cloth, at temperatures close to room temperature [11]. These polycrystalline films, with grains oriented on average in the same direction, might be used for photosensors, as well as for proximity and tactile sensors. As an example of such a system prototype, shown in Fig. 6 is a one-dimensional photoconductive array

Fig. 6. One-dimensional photoconductive array fabricated on a flexible substrate. (Courtesy of BIT's, Inc.)

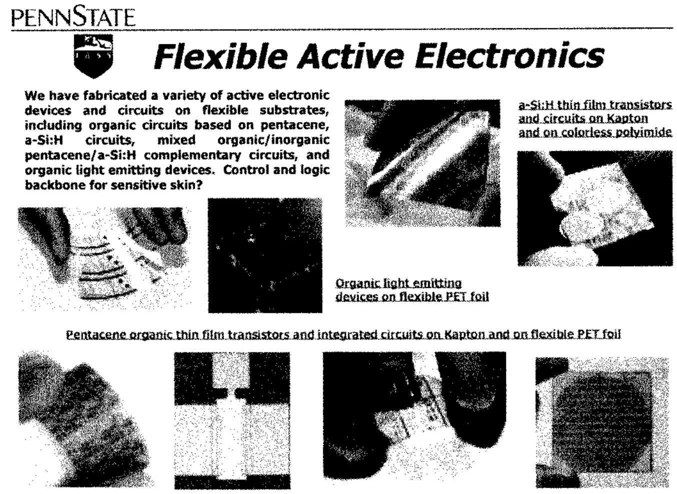

Fig. 7. Flexible active electronics. (Courtesy of T. Jackson, Penn State University.)

fabricated on a flexible substrate (a piece of a view foil) [12]. Another application of these materials is for flexible solar cells for on-board power supply for sensitive skin and/or wearable electronics applications.

This approach to fabricating sensitive skin is based on a new process of depositing polycrystalline CdSe (1.75 eV), CdS (2.4 eV), PbS (0.4 eV) [13], PbSe (0.24 eV) and Cu_xS (semiconductor/metal) films on flexible substrates at temperatures close to room temperature (eV here are electron-volts). Large area surfaces can be covered. Also, ternary and quaternary compounds as well as heterostructures can be deposited. The work is under way to develop all basic device building blocks and basic devices—from ohmic contacts to p–n junctions, heterojunctions, solar cells, and thin film transistors [14]. Samples with areas up to 8×10 inches have been reported (see Fig. 6); the process can be scaled up.

Also under way is the work to develop semiconductor threads and semiconductor cloth. These semiconducting and metal films will serve as building blocks for thin-film technology, which will enable us to develop the sensitive skin arrays. Their properties are strongly affected by processing. For example, the dark resistance of the CdSe films can be reduced by more than five orders of magnitude using thermal annealing in the temperature range from 100 °C to 200 °C. The photosensitivity of PbS films can be increased by few orders of magnitude by annealing in the temperature range of 110–140 °C and optimized ambience. More recently, a new technique of increasing photosensitivity of CdS films processed at temperatures close to room temperatures has been proposed [15]. These new material systems are ideally suited for sensitive skin applications, since these films are suitable for development of optical, thermal, piezoelectric and pyroelectric [16] sensors.

VI. Organic Electronics and Optoelectronics on Flexible Substrates

The performance of organic semiconductor devices has dramatically improved in recent years. Gundlach *et al.* reported a mobility of 2.1 cm^2/V-s for organic pentacene thin film transistors (TFT's) with the on-to-off ratio as high as 10^8 [17]. These mobility values exceed the values obtained for mainstream α-Si : H TFT technology. Klauk *et al.* also demonstrated pentacene-based electronic circuits such as five-stage ring oscillators with propagation delay of 73 μs per gate [18]. This technology needs fairly low gate dielectric and active layers deposition temperatures [19], and, therefore, might be quite suitable for fabricating organic semiconductor sensor and transistor arrays on flexible substrates (see Fig. 7). Organic TFTs (OTFTs) can be also used as drivers of organic light emitting diodes (OLED's) for applications in high-resolution active matrix displays [20].

VII. Manufacturing of Large-Area Sensitive Skin

Because the material properties and the material patterns are optimized best when done in separate steps, the application or modification of active material in IC fabrication is separated from its patterning. To directly print active circuits, one must devise materials that can be applied and patterned in a single step. The materials needed for the printing of sensor circuits include metallic conductors, insulators, semiconductors for transistors and light emitters, piezoelectric materials, etc. This approach to the printing of active circuits explores the territory that lies between IC's and printed-wire boards. In effect, sensitive skin devices will contain active circuits monolithically integrated with their packaging.

Completed thin-film circuits are at most a few micrometers thick. Therefore, the substrate and encapsulation constitute the bulk of the finished product. Reduction of their weight and thickness becomes important. When the substrate is reduced to a thickness where it becomes flexible, it also becomes usable in continuous, roll-to-roll paper-like production. The finished circuit then is a flexible foil, and using equally thin encapsulation will preserve this flexibility. Rugged thin-film circuits are a natural consequence of the mechanics of thin foil substrates.

In devising printing techniques for fabricating sensitive skin, the questions of feature size and of overlay registration must be answered. The development of microelectronics has shown that the search for high pattern density is one of the main drivers of IC technology. Therefore, it is instructive to estimate the density of active devices that could be produced by using conventional printing techniques.

Let us look at the density of amorphous-silicon thin-film transistors achievable by printing. The smallest size of a TFT will be set by two parameters. One is the smallest size of a pattern that can be defined by additive printing, which in IC technology is specified as the design rule. We give it the symbol λ. The second parameter is the accuracy of overlay, or registration, of subsequent patterns, which is quantified as the overlay alignment error $\pm\delta$. We assume that any subsequent layer can be registered to any preceding layer with an accuracy of $\pm\delta$ and that the inactive fringe has width δ. Assuming the area taken by the transistor proper is W, the area occupied by the device is thus $(\lambda + 8\delta) \cdot (W + 6\delta)$.

The value of the W/L ratio will depend on the TFT application. Let us assume that we are building a logic circuit made of switches that need an ON current of $I_{\rm ON} = 5\ \mu$A. For the typical values of the electron mobility μ_e of 1 cm^{2}V^{-1}s^{-1}, insulator dielectric constant ε_{ins} of $7 \cdot 5$, insulator thickness d_{ins} of 320 nm, and $(V_g - V_{th}) = V_{S/D} = 10$ V, I_D (sat) becomes $(W/L)\ \mu$A. The equivalent source-drain resistance is $R_{SD} = 10 \cdot (L/W)$ MΩ. A TFT that delivers $I_{\rm ON} = 5\ \mu$A will need $W/\lambda = 5$. Therefore, the area of each TFT will be 4000 μm^2 and the TFT packing density will be 25 000 transistors per cm^2.

Note that this packing density of a-Si TFTs is less than 1/1000 that of IC MOSFETs, and that the speed of a printed a-Si : H TFT will be 1/10 000 the MOSFET speed. Obviously, printed TFTs will not make sense as competitors of IC MOSFETs. But at a packing density of 25 000 cm^{-2}, printed TFT's will be acceptable for many large-area applications such as sensitive skin. Assuming, as above, that each sensor cell may need 100 transistors, we would be able to fit 250 sensor cells on a square centimeter.

The physical limits of the resolution λ and the overlay registration $\pm\delta$ depend on the tools and materials that are used for printing. For one, the ink must have sufficiently fine grain. This condition is easy to meet in principle by using molecule-based inks (solutions) or inks containing fine particles like polystyrene latex, which is available commercially in sizes down to ~10 nm. Two, the tools for printing and alignment must have sufficient resolution. If light is used for both printing (as in electrophotography) and alignment, the physical limits for both λ and $\pm\delta$ will be $\leq$1 μm. Thus, in principle, both ink and tools can easily meet our requirements of 10 and $\pm$5 μm, respectively.

Commercial printing is carried out in two steps. In the prepress step, text or image is transferred to a printing plate. In a second step this plate is used to do the printing [21]. The resolution of plate making and printing techniques can be as high as 2000–4000 dpi ($12 \cdot 7 - 6 \cdot 4\ \mu$m). By using either three-point mechanical or optical alignment the overlay registration can be brought to $\pm$5 μm. Thus the know-how and the components for the printing of active electronics at useful resolution and registration do exist.

Fig. 8. Cu_xS transparent metal film deposited on flexible view foil. (Courtesy of BIT's, Inc.)

The ratio of resolution to registration accuracy appears to be the same at all scales ranging from microelectronics to large-scale printing. The IC resolution is $\sim 0 \cdot 25\ \mu$m and the overlay tolerance $\leq 0 \cdot 1\ \mu$m. High-speed gravure presses print a linewidth of ~150 μm with a registration of ~50 μm. The printing speeds are very different, though. While a modern IC plant produces approximately 10 000 m^2 of IC's per year, a modern gravure press prints on this surface in about 5 min. Indeed the speed of today's printing presses is so high that large-area electronics may first be printed on plate-making equipment rather than printing presses. Note that a ratio of $\lambda/\delta = 3$ is easily compatible with the assumptions we used in calculating the packing density of printed TFTs.

The physical limits of several printing techniques are considerably finer than the resolution and registration of conventional printing equipment. Laser writing can produce a resolution of the order of 1 μm. Nanoimprinting has demonstrated a resolution in the tens of nanometer range [22]. Therefore, the density of directly printed devices can be raised orders of magnitude above ~10 000 per square centimeter. We can anticipate continuous improvements of resolution and registration once a direct-printing industry for sensitive skin electronics has come into existence.

VIII. Other Technologies

Examples of materials and devices for sensitive skin given above might point to a general trend in implementing sensitive skin, which is the trend toward using amorphous (such as a-Si), polycrystalline (such as CdS or CdSe), transparent conductors on flexible substrates (such as CuS, see Fig. 8), materials for sensors, with possible combination with higher mobility polycrystalline materials (such as laser annealed polycrystalline silicon) and deep submicron crystalline silicon technology (for fast data processing). We will also need sensors with multiple sensing capabilities, learning, once again, from the design of human or animal skin. These are new and exciting challenges for material science and device physics.

IX. Conclusion

Sensitive skin is a large array of sensors embedded in a flexible, stretchable, and/or foldable substrate that might cover the surface of a moving machine. By endowing these machines with an ability to sense their surroundings, sensitive skin will make it possible to have unsupervised machinery in unstructured, unpredictable surroundings. Sensitive skin will make the machines "cautious" and thus friendly to their environment. With these properties, sensitive skin will revolutionize important areas of service industry, make crucial contributions to human prosthetics, and augment human sensing when fashioned into clothing. Being transducers that produce and process information, sensitive skin devices will be generating and processing data flows in real time on a massive scale, which will lead to yet another leap in the information revolution.

Sensitive skin presents a new paradigm in sensing and control. It is an enabling technology with far reaching applications, from medicine and biology to industry and defense.

The state of the art in the areas that are basic to development of the skin technology shows that highly efficient devices should be feasible, meaning by this high densities of sensors on the skin and hierarchical and highly distributed real time sensor data processing. All this nonwithstanding the fact that the existing prototypes are clumsy, have low resolution, accuracy and reliability, and are not yet ready for commercialization. Serious research issues elaborated in this paper have to be resolved before sensitive skins can become a ubiquitous presence in our society. We hope the readers will view this paper as our first effort to map out the new territory, and as an invitation to join in the exploration.

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