

1. Background

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. But the necessary tools are at hand. Many novel technologies can be brought to bear, and many novel ideas already have emerged. They will allow us to make our dream of sensitive machines become a reality.

This Sensitive Skin Workshop targeted the principles, methodology, and prototypes of *sensitive skin*-like devices, together with relevant system intelligence and software. These devices and their use represent a new paradigm in sensing and control. While the Sensitive Skin concept may seem narrow and sharply focused on one novel enabling technology, it is actually not so. By opening doors to a whole class of novel enabling technologies, this multi-disciplinary research program will have a very wide impact. This impact will derive from the realization of far-reaching

applications that are not feasible today, and will range from medicine and biology to the machine industry and defense.

Some of the applications that Sensitive Skin will play are 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 can find applications in environmental control and power industry. These areas will be enhanced and further developed because of the highly interdisciplinary nature of this project, which lies at the intersection of information technology, biotechnology, and micro- and nano-electronics.

Availability of Sensitive Skin is likely to spur theoretical work in disciplines that today are far removed from it. This stimulus will be comparable to that that triggered the explosion of control theory in the 1940s and '50s, in direct response to the challenge posed by the appearance of fundamentally new hardware, such as jet fighters and radars.

1.1 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 a visitor in. The machine should be powerful enough to support a walking person; it should have some kinematics – say, a simple arm – to move things. 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 to do and how. Motion dexterity, such as in the human five-finger hand, is not important. We are willing to accept simple functionality, perhaps below the sophistication of some modern industrial machines. Now we can see that the basic components necessary for our Helper - the drive system, sensors to see the object of the task, intelligence to execute those tasks - largely do exist already. And yet, today such a machine cannot be designed – *at any cost*.

Why? Because using today's sensor technology will leave most of the Helper's body surface insensitive, unable to sense a close-by object. Sooner or later our Helper will topple or crush a glass, step on the cat, clasp the person's finger. To prevent this from happening with today's machines, designers must significantly constrain the machine's environment. They must make it *structured*. For example they will require that the arrangement of objects in the room be fixed, that no unaccounted-for pets or socks appear on the scene, and that the person always sits in the same position when requesting the Helper's services. Not surprisingly, this design is not likely 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 or 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. The majority of tasks that are of interest to us take place in unstructured environments, to which today's automation simply cannot be applied. Think of the typical unstructured environments of agriculture, construction sites, offices, hospitals, etc.

Let us call a moving machine *unattended* if it can operate without continuous supervision by a human operator, and *semi-attended* if it's controlled by the operator in a remote (teleoperation) fashion. Today the use of both types of machines is limited exclusively to highly structured environments, such as a factory floor, a nuclear reactor, a space telescope. Such machines operate successfully while using relatively little and quite localized sensing. This statement hides, however, the fact that expensive resources are used to compensate for the machine's inability to handle its 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. Already many existing machines could be useful in an unstructured environment, but they would endanger people, surrounding objects, and themselves.

Remotely controlled machines face the same difficulty. Unless the machine's environment is "sanitized" by providing a structured environment, no serious remote operation is possible. At some instant the operator will overlook an object and an unfortunate collision will occur. To prevent this from happening, designers take precautions, either by "sanitizing" the environment, or by enforcing an artificially slow operation with endless stop-and-checks. Much of the associated extra expense would not be necessary if such machines had enough sensing to cope with unpredictable objects around them. In an unstructured environment such sensing becomes imperative.

The sensing required for unstructured tasks must be massive. While individual vision, laser, sonar, and other existing sophisticated sensors are useful, they are not sufficient for a machine operating in an unstructured environment. Observations and theory show that massive, all-encompassing sensing must *cover the whole body of the machine* to empower it to function in a fully unstructured environment. Hence the idea of the *Sensitive Skin*.

1.2 Sensitive Skin - a universal paradigm

Sensitive Skin systems imply 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. This approach has a good reason - individual sensors and their electronic control are relatively expensive. This “poor man’s” design strategy actually hides significant costs. Even in cases where limited sensing might work, it will be cheaper and more reliable to use the universal and oftentimes even redundant sensitive skin, rather than go to an expensive custom design.

More than one sensor type may be necessary - e.g., proximity, touch and pressure, temperature, and secondary chemical/biological sensing. The functionality needed is quite generic, and so a few types of skin will cover a wide spectrum of applications. Take the Pentium microprocessor. It has much more functional power than any specific application needs, but – being well designed and mass-produced, it becomes an economically viable solution in a huge number of applications, each of which could do with much less compute power.

1.3 An impetus for information technology

Sensitive Skin systems will include thousands and millions of information generating and information processing elements, all operating in parallel and in real time. They *will* introduce *a new physical basis of information technology*. With the eventual ubiquity of the Sensing Skin on various

machinery, it is likely to produce the biggest leap in information technology hardware since introduction of computers. In fact, the sheer amount of information continuously generated and processed by Sensitive Skin devices will make them challenge humans as *predominant producers and users of information*.

1.4 Societal needs addressed by Sensitive Skins

a) *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. Sensitive Skin systems will enable moving machines to acquire real-time information on surrounding objects and use it to operate safely in their environment. Here we consider machines that by virtue of their size, power, and operation of their moving parts can present danger to the surrounding objects or can be damaged by them. For example, a moving machine with the Sensitive Skin covering its body - say, an automatic vacuum cleaner in a department store, a semi-autonomous machine helper in an senior citizens home, 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 is feasible today. *Automation for unstructured environments can completely transform the face of machine automation in the 21st Century.*

- b) *Health industry.* Sensitive Skin will supplant sensing ability of the human skin, such as in limb prosthetics and replacement of damaged human skin in health industry. Sensitive Skin also will augment human sensing as in wearable clothing, by monitoring, processing and wireless transfer of information about the well being of the person who wears it. *This area will advance the post-traumatic health care, care for disabled and elderly persons, and monitoring of military personnel on the battlefield.*
- c) *Environment-friendly technology.* For the first time in history machines will be endowed with their own *capacity to be careful*. By its very nature sensitive skin will contribute in a dramatic way to reversing 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 also 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*.

1.5 Societal concerns

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 moving machinery operating in our midst. We do not feel a need for these machines. We are uneasy about the concept of living side by side with powerful unattended moving machines. One has difficulty imagining 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 by.

Don't we have more than enough invasion of machinery in our lives? Whatever needs we have, aren't they of economical and societal, rather than technical nature? To need a very new product, one must first experience what it can do. Recall the skepticism about the Xerographic copier (even in the parent company) when this technology was about to appear, and people were still unaware of the multiplicity of needs that easy copying could satisfy.

1.6 The bottleneck is all-encompassing sensing

We emphasize again that the problem with making moving machines operate in our midst is not in the machine's ability to perform the task. After all, more sophisticated tasks are done on today's assembly lines. The bottleneck is in 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 those objects cannot be anticipated due to the unstructured environment, the only way to know about them is via sensing.

Sensing that we need 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 do. Sooner or later an object will obstruct the line of view of those discrete localized sensors, and an impending collision will go undetected. For precisely this reason humans and animals have some kind of sensing means at *every point of their bodies*. In the known exceptions, an impenetrable shell, like in turtles, replaces sensing. The loss of tactile sensing in humans due to diabetes or skin transplantation is life threatening, even though all other senses - vision, hearing, taste, smell - remain intact. *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.*

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 dry necessity. The need for all-encompassing sensing for machines operating in unstructured environments is convincing, both theoretically and experimentally. We happen to stumble upon a principle that is a necessary condition for a large class of technology, and one that the natural evolution discovered long ago. Our concept is to enable sensing at all surface points of a machine by covering it with one of a few varieties of a generic sensitive

skin. The lack of such skins is the bottleneck in today's machine automation.

1.7 Research issues

Four groups of research issues must be addressed to develop Sensitive Skin: Skin Materials, Sensing Devices, Signal and Data Processing, and Applications.

A. *Skin material*

- Sensitive Skin material will hold 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, shrink, and wrinkle the way human skin does, or to have other compensating features. Otherwise, some machine parts may become "exposed" due to the machine's moving parts, and have no associated sensing. For example, Dupont's Kapton material 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.

B. Sensing devices

- Sensitive Skin sensor components will be deployed in two-dimensional arrays of sufficiently high density. A representative model would be a piece of skin of 1x1 square meter size, with sensors spread uniformly at a pitch of 1x1mm, with the total of 1 million sensors. This model immediately highlights the need for mass-producing of Sensitive Skin as large-area integrated circuit.
- 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.
- Any sensing modalities, including proximity or tactile, discrete or continuous, are acceptable, as long as they fit the representative model above.
- "Self-sensing" ability of the skin is highly desirable; this may include sensing of contamination, dust, chemical substances, temperature, radiation, as well as detection of failure of individual or multiple skin sensors and the ability to work around failed areas.

- No existing types of sensors are likely to satisfy all requirements. For example, a light sensor may be fast and accurate but brittle and power-hungry; sonar and capacitive sensors may require less power but have poor resolution. These issues need to be understood and perhaps must be addressed by developing new sensors, new combinations of existing sensors, or new ways of packaging existing sensors.
- The ability to measure distance to objects would be a great advantage for enabling dexterous motion of the machine that carries the skin.
- Ideally, sensors and their signal processing hardware would be spread within the array so as to allow cutting it to any shape (disc, rectangle, an arbitrary figure) without losing its sensing and control functionality. This suggests interesting studies in hardware architecture.
- Sensor arrays with special or unique properties are of much interest, for example a cleanable/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, react to, or disregard ambient light.

C. Signal/data processing

- To produce continuous motion, the sampling rates of today's typical computer-controlled moving machines are 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 must be passed to the machine control and analyzed, and motion commands for the next step must be sent to the drive motors and executed. With thousands or millions of sensors per 1m^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 could include analog-to-digital processing, sensor calibration, individual sensor based distance measurements, etc., and calls for highly parallel processing and good software architectures.

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

1.8 Related research issues

There are a number of disciplines that will not be directly engaged in the development of Sensitive Skin but will be stimulated by its availability.

- *Sensing and dynamic control.* Consider our machine 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, quality of sensing, 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 not be able to move fast without a danger of 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.
- *New control theory needed.* 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 will be able to focus intermittently at various single and multiple points of potential collision of the machine's body, and modify the control accordingly, all within the draconian constraints of real-time operation and changing kinematics of the body. A better analogy will thus be control of a bat flying among tree branches, or attempts of reconfigurable

control for a jet fighter in battle. These complications call for novel, exciting control theory.

- *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.

- *Use of Sensitive Skin in bioengineering.* There is an intriguing possibility of combining this artificial skin and natural living skin to help people who lack or have diminished sensing abilities, or in prosthetic devices, or in augmenting human sensing via wearable clothing, such as for military personnel.

- *Man-machine systems.* Human and machine intelligence could be merged in real-time motion planning. This may or may not involve unattended automatic machinery. 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 trees. Besides informing the pilot of any undesirable contacts with plants below, the 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.

- *Collective behavior, multi-agent systems.* Taken to a still higher level, sensor-based motion planning could address such issues as coordination of and interaction between multiple machine agents; decentralized and distributed control; relationship between the local behavior of an individual agent and the group's global goal. One obvious example here is formations of pilot-less military aircraft. Availability of the sharply increased amounts of complex data from Sensitive Skin systems is likely to give boost to this area of research.

. Workshop Agenda

October 14

- 7:30 – 8:30 am Breakfast and registration
- 8:30 - 8:35 Vladimir Lumelsky, NSF: Opening Remarks
- 8:35 – 8:45 Gene Wong, NSF: Welcoming Remarks
- 8:45 - 8:55 Art Sanderson, NSF: Related Programs at NSF
- 8:55 - 9:05 Dick Urban, DARPA: Related Programs at DARPA
- 9:05 – 9:30 Vladimir Lumelsky, NSF: Introduction
- 9:30 – 9:35 Michael Shur, RPI: Workshop structure
- 9:35 - 9:45 Sigurd Wagner, Princeton: Devices for Sensitive Skin
- 9:45 – 10:15 Discussion (entire group)
- 10:15 – 10:35 Coffee break
- 10:35 - 10:45 Jim Sturm, Princeton: Materials for Sensitive Skin
- 10:45 – 11:15 Discussion (entire group)
- 11:15 – 11:25 Bill Mangione-Smith, UCLA: Signal Processing for
Sensor Data
- 11:25 – 11:55 Discussion (entire group)
- 11:55 – 12:05 Ron Fearing, Berkeley: Applications
- 12:05 - 12:35 Discussion (entire group)
- 12:35 – 2:00 Lunch
- 2:00 – 5:00 Break-up sessions of the four sections

October 15

- 8:30 - 8:45 am Michael Shur, RPI: Introductory remarks.

Section reports and discussion:

8:45 - 9:45	Devices
9:45 - 10:45	Materials
10:45 - 11:00	Coffee break
11:00 - 12:00	Signal Processing/Software
12:00 - 1:30	Lunch
1:30 - 2:30	Applications
2:30 - 2:45	Closing remarks