In the years to come, the roles of the Canadian Forces will continue to be to defend the country and its vital interests, and to participate actively in peacekeeping and peace restoration missions. To carry out these tasks in an appropriate and effective way, the Forces must keep abreast of technological advances and needs if they are to adopt and bring into service the best available ones. Moreover, effective collaboration with our allies, especially the Americans, will clearly demand the best in equipment and training. Last year, the Defence Research and Development Branch of DND published a document explaining the policies, opportunities and desired outcomes for the near future. ‘Smart materials’ and ‘smart structures’ are listed among the technological opportunities and the proposed Research and Development (R&D) activities of the future defence program. The race is on to explore, develop and exploit the newest products of smart technology, and this is needed to keep our Forces competitive with potential adversaries. So, what are ‘smart systems’?

**DEFINITION**

Smart systems trace their origin to a field of research that envisioned devices and materials that could mimic human muscular and nervous systems. The essential idea is to produce non-biological systems that will achieve the optimum functionality observed in biological systems through emulation of their adaptive capabilities and integrated design. By definition, smart materials and smart structures — and by extension smart systems — consist of systems with sensors and actuators that are either embedded in or attached to the system to form an integral part of it\(^1\). The system and its related components form an entity that will act and react in a predicted manner, and ultimately behave in a pattern that emulates a biological function. The human body is the ideal or ultimate smart system.

One of the first attempts to use the smart materials technology involved materials constructed to do the work of electromechanical devices. Since then, many types of sensors\(^2\) and actuators\(^3\) have been developed to measure or excite a system. This technology is still in its infancy and the scientific community is just beginning to scratch the surface of its potential. With a bit of imagination one can see enormous benefits to society.

This paper presents a simple overview of the technology. After defining what is meant by ‘smart materials’, it describes a smart structure and its components, and provides a few examples. This is part of an ongoing work on the use of smart materials for applications in engineering. A more detailed insight into smart structures and their applications is given elsewhere\(^4\).

Today the drive to innovation is stronger than ever. Novel technologies and applications are spreading in all fields of science. Consequently, expectations and needs for engineering applications have increased tremendously, and the prospects of smart technologies to achieve them are very promising. Figure 1 summarizes these inter-relationships.

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**Table 1: General Requirements and Expectations**

<table>
<thead>
<tr>
<th>Requirement</th>
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<tbody>
<tr>
<td>1. High degree of reliability, efficiency and sustainability not only of</td>
</tr>
<tr>
<td>the structure but also of the whole system.</td>
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<tr>
<td>2. High security of the infrastructures particularly when subjected to</td>
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<tr>
<td>extreme and unconventional conditions.</td>
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<tr>
<td>3. Full integration of all the functions of the system.</td>
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<tr>
<td>4. Continuous health and integrity monitoring.</td>
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<td>5. Damage detection and self-recovery.</td>
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<td>6. Intelligent operational management system.</td>
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</table>

**Table 2: Smart Technologies Prospects**

<table>
<thead>
<tr>
<th>Prospect</th>
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<tr>
<td>1. New sensing materials and devices.</td>
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<tr>
<td>2. New actuation materials and devices.</td>
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<tr>
<td>3. New control devices and techniques.</td>
</tr>
<tr>
<td>4. Self-detection, self-diagnostic, self-corrective and self-controlled</td>
</tr>
<tr>
<td>functions of smart materials/systems.</td>
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**Figure 1: Smart Systems for Engineering Applications**

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**SMART MATERIALS**

Smart or intelligent materials are materials that have the intrinsic and extrinsic capabilities, first, to

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respond to stimuli and environmental changes and, second, to activate their functions according to these changes. The stimuli could originate internally or externally. Since its beginnings, materials science has undergone a distinct evolution: from the use of inert structural materials to materials built for a particular function, to active or adaptive materials, and finally to smart materials with more acute recognition, discrimination and reaction capabilities. To encompass this last transformation, new materials and alloys have to satisfy a number of fundamental specifications.

New Material Requirements

To achieve a specific objective for a particular function or application, a new material or alloy has to satisfy specific qualifications related to the following properties:

- technical properties, including mechanical characteristics such as plastic flow, fatigue and yield strength; and behavioural characteristics such as damage tolerance and electrical, heat and fire resistance;
- technological properties, encompassing manufacturing, forming, welding abilities, thermal processing, waste level, workability, automation and repair capacities;
- economic criteria, related to raw material and production costs, supply expenses and availability;
- environmental characteristics, including features such as toxicity and pollution; and
- sustainable development criteria, implying reuse and recycling capacities.

If the functions of sensing and actuation are added to the list, then the new material/alloy is considered a smart material.

Classification of Smart Materials

Smart materials can be grouped into the following categories:

- **Piezoelectric.** When subjected to an electric charge or a variation in voltage, piezoelectric material will undergo some mechanical change, and vice versa. These events are called the direct and converse effects.
- **Electrostrictive.** This material has the same properties as piezoelectric material, but the mechanical change is proportional to the square of the electric field. This characteristic will always produce displacements in the same direction.
- **Magnetostrictive.** When subjected to a magnetic field, and vice versa (direct and converse effects), this material will undergo an induced mechanical strain. Consequently, it can be used as sensors and/or actuators. (Example: Terfenol-D.)
- **Shape Memory Alloys.** When subjected to a thermal field, this material will undergo phase transformations which will produce shape changes. It deforms to its ‘martensitic’ condition with low temperature, and regains its original shape in its ‘austenite’ condition when heated (high temperature). (Example: Nitinol TiNi.)
- **Optical Fibres.** Fibres that use intensity, phase, frequency or polarization of modulation to measure strain, temperature, electrical/magnetic fields, pressure and other measurable quantities. They are excellent sensors.
- **Materials with Added Functions.**
  - All around sensor material that can detect certain signals, adjust sensitivity according to environmental changes, or restore degraded sensitivity.
  - Catalytic material that can detect the progress of a reaction or distinguish the reaction of a product.
  - Textile material that can detect a variety of signals from the human body and weather conditions so as to allow for greater comfort. (Example: the smart T-shirt.)

Smart Composites

Combining two or more single smart materials to utilize synergistically the best properties of their individual constituents is the ultimate objective of any new composite smart material. That is why ‘smart composite materials’ are very close to satisfying all of the above specifications. Their advantages and adaptability to the design requirements mentioned above have led to a profusion of new products. There are essentially two types:

- A completely tailored man-made composite material. The purpose of this material is to improve or add strength or stiffness. The following examples will provide insight into the field. One product is made by incorporating a strong fibrous material with boron or silicon into a matrix of aluminium or titanium, another by mixing a solid with minute spheres of glass, ceramic, or polymer, and a third by turning polymer, glass and some metals into sturdy foams. Syntactic foams use bubbles that are mechanically combined with a resin to form a composite material. These foams can be combined with thin panels or outer skins to create laminated composite or sandwich construction. Another example
consists of a non-metallic material introduced into a powder alloy to form a metal matrix composite.

- An amalgamation of single/composite materials with Fibref/Reinforced Polymers (FRPs). In the last two decades, FRPs have been used as reinforcement for concrete, steel or other construction materials. The selection of FRP as an alternative to other materials, particularly steel, is possible because the tradeoffs between cost, weight, handling and transportation are very attractive and economical. Another significant advantage is the flexibility of the various design configurations. If the FRP is combined with fibre optic sensors, the resulting product will be an attractive and particularly cost effective smart composite.

SMART STRUCTURES

As described earlier, a smart structure is a system that incorporates particular functions of sensing and actuation to perform smart actions in an ingenious way. The basic five components of a smart structure are summarized as follows (Figure 2):

- **Data Acquisition** (tactile sensing): the aim of this component is to collect the required raw data needed for an appropriate sensing and monitoring of the structure.
- **Data Transmission** (sensory nerves): the purpose of this part is to forward the raw data to the local and/or central command and control units.
- **Command and Control Unit** (brain): the role of this unit is to manage and control the whole system by analyzing the data, reaching the appropriate conclusion, and determining the actions required.
- **Data Instructions** (motor nerves): the function of this part is to transmit the decisions and the associated instructions back to the members of the structure.
- **Action Devices** (muscles): the purpose of this part is to take action by triggering the controlling devices/units.

DATA ACQUISITION

The sensing components of a smart structure are designed according to the nature of the event to be sensed — radiation, magnetic, thermal, mechanical or chemical — as well as according to the nature of the output required, such as thermal, magnetic, electrical, optical or mechanical. Other features considered are the size, geometry and mechanical properties of the required interface; the type of the environmental conditions, such as corrosion, thermal, magnetic or electrical and, finally, the operational properties of the collected data such as sensitivity, bandwidth, linearity, gauge length, range. Fibre optics are an excellent example of sensors.

Fibre Optic Sensing

Fibre optics are used as sensors that duplicate the action of conventional strain gauges. They respond to a change in transmitted light. This change could be in intensity, phase, frequency, polarization, wavelength or mode. They are highly sensitive, can detect minuscule

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![Smart Structure Diagram](image-url)
variations and thus work very well. Three types of sensors are available:

- The Intensiometric type responds to any perturbation such as bending or twisting that changes the intensity of the transmitted light. (Advantage: relatively simple.)

- The Interferometric type that responds to changes in phase and spectrometry. These phase sensors come in a number of configurations and are highly sensitive to strains. The Michelson and Mach-Zehnder types use two fibres, one to sense and one as reference. They can measure strain over lengths in the order of metres. The Fabry-Perot type, which employs a single fibre and reflectors, is based on the interference of light between two closely spaced surfaces.

- The Bragg grating type exploits spectroscopy, which is based on the modulation in the index of refraction along a short length of the fibres. The advantage of this type lays on the sensed information encoded directly into the wavelength which is an absolute parameter, independent of any variation. The wavelength division multiplexing is realized by fabricating each grating (mask) at a slightly different frequency. This create a large number of gratings each with a slightly different resonant frequency along one fibre.

Bragg grating sensors work very well but are expensive, while Fabry-Perot sensors are cheaper to build. This technology is already used in a few civil engineering applications. For example, deformation and vibration are being measured in a cracked bridge in Berlin, Germany. Displacement of joints between concrete panels is being observed in dams in Germany and Switzerland. Vibration and corrosion are being monitored in a few bridges in the US and Canada. Rock slides are being diagnosed in anchoring cables in pilings and tunnels in Switzerland. Finally, many bridges and buildings are being monitored in Japan.

Figure 3 presents, in a schematic way, a section of a smart bridge.

**ACTUATING COMPONENT**

Like the sensing component, the actuating components are designed according to the nature of the required actuation — optical, magnetic, thermal, mechanical or chemical — as well as according to the nature of the driving energy, such as thermal, magnetic, electrical or chemical. Here also, environmental considerations such as thermal, magnetic or electrical properties and corrosion, as well as the size, geometry and mechanical properties of the interface have to be considered. Finally, the properties of the actuators such as displacement, force generation, hysteresis, response time and bandwidth are also specified appropriately.
Actuation can be produced by controlling devices such as actuators, pumps, heaters and dampers, and by a number of new materials such as those described previously.

**SENSORS AND ACTUATORS**

For active noise control applications, microphones are used as acoustic sensors and loudspeakers as acoustic actuators. For displacement and velocity control, two types of transducers are convenient: Linear Variable Differential Transformers (LVDT) and Linear Variable Inductance Transformers (LVIT). Other devices are also available—accelerometers and two basic types of actuators. Hydraulic and pneumatic actuators are employed when low frequency, large force and displacements are required, while the electromagnetic/shaker types are utilized to react against an inertial electrodynamic mass.

**COMMAND AND CONTROL UNIT**

The command and control unit is the manager of day-to-day operations, responsible for monitoring the health and integrity of the system by means of a communication network which works in real time. The unit operates by controlling a compendium of integrated non-destructive evaluation instruments, by managing optical fibre sensors and actuators, or by overseeing operational and control devices. This is the brain of the smart structure and has two basic and distinct functions.

- **The Processing Function.** This function receives information; analyses it; sorts, arranges and classifies it; and stores and/or processes it depending on the nature, frequency and quality of the data and its origins. All these previous operations are dealt with by intelligent or smart processing, with or without human intervention, and with little or no human interaction. Special algorithms can be used to control the behaviour or detect damage. Pattern recognition algorithms, as well as neural networks with fuzzy logic can be efficiently employed to process the raw data. Finally, expert systems can handle the retrieval, management, classification, and storage of the data.

- **The Analysis Function.** This function deals with the detailed examining of the raw data in an intelligent way. Using the analysis outlined above, it will exploit the results to assess the condition of the structure. This analysis consists of localizing and identifying specific variables, items or features as compared to threshold levels defined in advance, or specified in codes, rules, regulations or standards. When an adverse condition is detected and the appropriate corresponding conclusion is reached, decisions for action are sent to the action controlling devices, which will be triggered to react. Special algorithms are developed to operate these functions.

**A FEW EXAMPLES**

- **Vibration reduction in sporting goods.** A new generation of tennis rackets, golf clubs, baseball bats (Figure 4) and ski boards have been introduced to
reduce the vibration in these sporting goods, increasing the user’s comfort and reducing injuries.

- **Noise reduction in vehicles.** Filaments of piezoelectric ceramic fibre shaped into various geometries are used in conventional fabric or material processing to counter noise in vehicles, neutralize shaking in helicopter rotor blades, or nullify or at least diminish vibrations in air conditioner fans and automobile dashboards.

- **Spatial High Accuracy Position Encoding and Control System (SHAPECONS)** incorporates smart components that were developed for the STEAR-9 Program (Figure 5).

- **Frangibolt,** a system flown on the 1994 *Clementine* mission to the moon, is used to deploy solar arrays, antennae and satellite from a launch vehicle.

**MILITARY APPLICATIONS**

A number of distinctly military applications for the use of smart materials and smart systems can be delineated, among them:

- **Smart Skin.** In battle soldiers could wear a T-shirt made of special tactile material that can detect a variety of signals from the human body, such as detection of hits by bullets. It can then signal the nature of the wound or injury, analyze their extent, decide on the urgency to react, and even takes some action to stabilize the injury.

- **Smart Aircraft.** Figure 6 presents a few potential locations for the use of smart materials and structures in aircraft.

- **Autonomous Smart systems.** Ground, marine or space smart vehicles will be a feature of future battles. These carriage systems, whether manned or unmanned, and equipped with sensors, actuators and sophisticated controls, will improve surveillance and target identification and improve battlefield awareness.

- **Stealth Applications.** The smart vehicles mentioned above could be constructed using stealth technologies for their own protection: the B-2 stealth bomber or the F-117 stealth fighter are good examples of this technology. And, just as important, smart systems are needed for rapid and reliable identification of space or underwater stealth targets. The identification and detection of such targets, as well as the subsequent decision to take action with or without operator intervention, is another potential application of smart systems.

**THE POTENTIAL BENEFITS**

The potential future benefits of smart materials, structures and systems are amazing in their scope. This technology gives promise of optimum responses to highly complex problem areas by, for example, providing early warning of the problems or adapting the response to cope with unforeseen conditions, thus enhancing the survivability of the system and improving its life cycle. Moreover, enhancements to many products could provide better control by minimizing distortion and increasing precision. Another possible benefit is enhanced preventative maintenance of systems and thus better performance of their functions.

By its nature, the technology of smart materials and structures is a highly interdisciplinary field, encompassing the basic sciences — physics, chemistry, mechanics, computing and electronics — as well as the applied sciences and engineering such as aeronautics and mechanical engineering. This may explain the slow progress of the application of smart structures in engineering systems, even if the science of smart materials is moving very fast.
CONCLUSION

Today, the most promising technologies for lifetime efficiency and improved reliability include the use of smart materials and structures. Understanding and controlling the composition and microstructure of any new materials are the ultimate objectives of research in this field, and is crucial to the production of good smart materials. The insights gained by gathering data on the behaviour of a material’s crystal inner structure as it heats and cools, deforms and changes, will speed the development of new materials for use in different applications. Structural ceramics, superconducting wires and nanostructural materials are good examples of the complex materials that will fashion nanotechnology. New or advanced materials to reduce weight, eliminate sound, reflect more light, dampen vibration and handle more heat will lead to smart structures and systems which will definitively enhance our quality of life.

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NOTES
