

January 01, 2004

## Product take-back: sensors-based approach

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### Recommended Citation

Kamarthi, Sagar V.; Gupta, Surendra M.; and Ibrahim, Zeid, "Product take-back: sensors-based approach" (2004).. Paper 96.  
<http://hdl.handle.net/2047/d10003435>

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Laboratory for Responsible Manufacturing

## Bibliographic Information

Zeid, I., Kamarthi, S. V. and Gupta, S. M., "Product Take-Back: Sensors-Based Approach", ***Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing IV***, Philadelphia, Pennsylvania, pp. 200-206, October 26-27, 2004.

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# Product Take-Back: Sensors-Based Approach

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## ABSTRACT

The driving forces behind product take-back and green manufacturing are well established. The two main product end-of-life options are reuse/remanufacturing and recycling. For either option, all take-back units are treated equally because no information that tracks the conditions of a product during its useful life is available. For example, all expired PCs are treated equally; no distinction can be made about which units still have healthy hard disks. This paper discusses sensor-based monitoring and prognostic methodologies for tracking the condition of products while being used by customers and timely and targeted servicing, smart and selective disassembling and refurbishing of products with known (long) remaining lives. The paper also discusses the added benefits to product manufacturers when the time comes to redesign their products. The real-time field data on service and utilization of products are communicated to manufacturers' headquarters for further analysis.

**Keywords:** Product take-back, Green manufacturing, Design for disassembly, Smart Sensors, Sensors Networks, Computational models

## 1. INTRODUCTION

The National Research Council's recent report [2] on embedded computers states that *“As the cost of these and related technologies continues to decrease, computing and communications technologies will be embedded into everyday objects of all kinds to allow objects to sense and react to their changing environments. Networks comprising thousands or millions of sensors could monitor the environment, the battlefield, or the factory floor; ... [EmNets] have the potential to change radically the way people interact with their environment by linking together a range of devices and sensors that will allow information to be collected, shared, and processed in unprecedented ways. The range of applications continues to expand with continued research and development.”*

Keeping this vision in mind, the authors foresee that Smart Sensor Embedded Products (SEPs), in the very near future, are going to become an inevitable part of people's every day lives. SEPS will have significant positive impact on product lifecycle management. SEPs can improve product performance, effectiveness, reliability, maintainability, serviceability, recyclability, and cost. In addition, SEPs can reduce costs associated with product design, product operations, and product retirement. SEPs will provide the following major advantages.

**Marketing:** data on patterns of product usage can be used to design products that satisfy customer needs better.

**Design for Reliability:** data on failure modes and frequencies can take designs beyond what can be achievable using laboratory tests or field trials.

**Servicing:** repair/service personnel can readily obtain data on likely causes of failure, which they can use to make diagnosis and servicing decisions and plan for obtaining spare parts in advance.

**Predictive Maintenance:** product condition monitoring can avert product breakdowns and facilitate convenient and cost-saving repairs instead. The pitfalls of standard scheduled maintenance plans can be addressed.

**End-of-Life Take-Back:** products' full life histories, including servicing data, can be accessed and used to optimize their end-of-life processing operations. Parts removed can be classified for treatment according to their life history.

## 2. SENSOR TECHNOLOGY

The unabated advances in silicon-based technology is making possible the design and deployment of extremely inexpensive, highly capable, low-power sensors in many day to day applications starting from home appliances, TVs, computers, to automobiles. High-speed and low-cost electronic circuits, novel signal processing methods, and sophisticated microsystem manufacturing technologies are advancing sensor technologies at a rapid pace. Innovative smart sensors have been designed with many useful features. Smart sensors can have many useful features such as high reliability and sensitivity, self-calibration, automatic compensation of non-linearity, low-power operation, digital pre-processed output, self-checking and diagnostic modes, wireless communication, and compatibility with computers. Further, multi-sensor systems and data fusion techniques are employed to make accurate measurements and correct decisions. Already there exist MEMS-based technologies that allow one to sense odors, vibration, acceleration, pressure, temperature, and many other physical phenomena in ways that is extraordinarily useful across a wide range product monitoring applications. New sensors for sound, visible light, infrared, and extremely low light, combined with ever faster and cheaper digital signal processors, will make product condition monitoring practical and commonplace. The implications of these improving sensor technologies to SEPs are profound.

Smart sensor and networking technologies when applied to product condition monitoring could drastically change the way products are repaired and refurbished. Emergence of wireless communication technologies, satellite links, and Internet will enable one to monitor geographically remote devices from a centralized location. The utility of wireless sensor technology is expected to affect many aspects of product condition monitoring, most notably when products are distributed geographically and data has to be collected at a central location. It is possible to remotely perform product condition monitoring and recommend context-dependent anticipatory repairs.

### 2.1 Essential Elements of SEPs

- Smart sensors to register environmental parameters (such as temperature or vibration) and convert them into a suitable signal form, e.g., analog voltage or digital signal.
- A processor and clock, to receive control signals, manipulate the data and store results.
- Non-volatile memory (EEPROM)
- Data transmission from the smart sensor to communication network.
- Power supply from the product power source or a separate battery to run a real-time clock if the product is expected to operate without power or subjected to long power breaks.

### 2.2 Types of Data

**Static Data:** It consists of specification of the product, details of materials, information regarding components and suppliers, configuration and options, servicing instructions and end-of-life information such as disassembly sequence, mean time between failures, and battery specs. The storage of such data is common in motor vehicles and also found in business machines such as copiers. However much of this data does not

need to be stored in the product itself but can be held in a remote database, as long as the product has a unique identification code.

**Dynamic Data:** It refers to any data and information that is generated over time such as patterns of use, number of use cycles, runtime in each use cycle, environmental condition, temperature, humidity, voltage, current, power service data, and servicing actions such as data on service inspections, parts replaced and repaired. It is normally stored in non-volatile memory attached to the product and is transmitted intermittently to a central data processing center through a communication network.

**Product Condition Data:** It consists of measurement of parameters such as temperature, humidity, vibration, and acoustic emission that are correlated to component/product condition and remaining life. An on-board processor uses this data to assess the condition of components and/or the product. Either the raw sensor data or the condition assessment results or both are transmitted to the central data processing center via communication network.

### **Product Condition Monitoring (PCM)**

Product condition monitoring (PCM) is the process of collecting sensor data from the product components in order to assess the health of the components and also estimate the remaining life of the components. The information generated during product use can be used for scheduling repairs and also for making product end-of-life decisions.

Many product components exhibit degradation signals of one type or other. A degradation signal characterizes the evolving changes in the physical and function quality of components with respect to the operating time of the components. In other words a degradation signal captures the deterioration pattern of the components. For example, the degradation signals generated by individual sensors attached to product components can be processed to continually assess their health and estimate their remaining-life. There are many computational methods that link degradation signals given by the individual units to their condition and ultimate life expectancy in a probabilistic sense.

Traditional reliability engineering methods provide failure characteristics of average components, which are taken into consideration during the product manufacturing stage. But those characteristics are of little use beyond the manufacturing stage. Once products are manufactured and delivered to customers, different product units are exposed to different working conditions and different usage patterns. That makes the traditional reliability estimates provided by the product manufactures invalid. Consider a the transmission system of an automobile with 200k mile manufacturer specified mean time to failure. If the transmission fails at 40k miles, it doesn't provide much comfort to the customer. Even worse is experiencing a hard disk crash much before its expected life. In contrast, some components of products may remain in good working condition beyond their expected life. To deal with these scenarios the authors develop the framework and concepts of Sensor-Embedded Products (SEPs) which have provision for monitoring the health of their components at any desired point in time. Advances in the field of sensors, microprocessors, and communications technologies offer tools necessary to transform the traditional reliability approach to on-line condition assessment.

Many automobile manufacturers want to move away from the current model of diagnostics to a model of prognostics, which allows them to monitor their products to avert sudden and unexpected failures and to perform maintenance activities only when it is really required rather than as a matter of routine scheduled maintenance.

### 2.3 Computational Methods for Product Condition Monitoring

Product condition monitoring methods may fall into one of the three categories: model-based, feature based, or hybrid of model-and-feature-based approaches. In a model-based approach, a model linking the sensor outputs to the mechanics of behavior of the component is first formulated. Then, during the normal monitoring stage, the sensor outputs are fed to the model to detect or predict the change in the component condition. Feature-based monitoring consists of two steps. The first step, "sensor data representation (also known as feature extraction)," provides the most compact signal representation possible while preserving the structural features of interest in the sensor signals. The second step, "system condition assessment," involves identifying system conditions based the sensor-signal feature extracted in the previous step using one of several techniques such as analytical functions, pattern recognition methods, fuzzy system, decision trees, neural networks, and expert systems. Depending on the nature of the application, a model- or a feature-based method is used for product condition monitoring. In an application where a fairly accurate model of the component behavior can be developed, the model-based monitoring is desired over a feature-based approach. The following are two commonly used approaches for condition-based maintenance.

**Approach 1:** In this approach the condition assessment methodologies will have three essential components: (1) a physical model, (2) an intelligent nonparametric model, and (3) an on-line condition assessment method. A physical model would capture understanding of the failure physics of the component to the extent possible, defining how the failure modes and mechanisms are in action given the operating environment. Intelligent nonparametric model that is continuously revised based on the degradation measures generated by the individual components would account for the limitations and incompleteness of physical models. Together, the physical models and the nonparametric model would allow real-time assessment of the physical and performance condition of the individual components. Utilizing the information from the two models, the on-line condition assessment method would determine the probability associated with prospects of a failure-free remaining life for the component.

**Approach 2:** In this approach a multi-layer neural network is trained on the observed degradation signal of a set of test components. The real-time degradation signal of an operating component is input to the neural network to predict its remaining life. An empirical distribution for the error inherent in this approach is computed by using his approach to predict the remaining lives of test components for which the actual remaining lives are known. The predicted life and empirical error distribution are then used to compute a confidence interval on a component's remaining life.

### 3. DECISION SUPPORT MODELS

This section presents the development of decision support models that minimize the cost and maximize the efficiency of repair, disassembly, and refurbishing operations by smartly using the information provided by product condition monitoring.

New products are introduced to the market almost everyday. Take computers, for example. The average computer life has decreased from 4-5 years at the beginning of 1990s to 1-2 years currently. This means that the computers will enter the waste stream much faster than before [8]. According to a forecast, by the year 2005, there will be almost 50 million computers becoming obsolete every year in the U.S. alone. The life cycles of other products will also have a similar fate. All these will have an effect on the waste management infrastructure.

During the last decade or so, product recovery has become an obligation to the environment and to the society itself; it is also nourished primarily by governmental regulations and customer perspective on environmental issues [5]. Product recovery aims at minimizing the amount of waste sent to landfills by recovering parts and materials from old or outdated products by means of disassembly, remanufacturing (including reuse of parts

and products) and recycling. Remanufacturing preserves the product's identity and performs the required disassembly, sorting, refurbishing and assembly operations in order to bring the product to a desired level of quality. Recycling, however, recovers the material content of retired products by performing the necessary disassembly, sorting, and physical and/or chemical separation. Several studies have recently emerged that address various aspects of disassembly and product recovery [1, 3, 4, 5, 6, 7, 8, 10].

The facilities that process end-of-life (EOL) products seldom know exactly when those products were deployed and why were they discarded. In addition, there is normally no indication of the remaining life periods of such products. So, it is difficult to decide if it is "sensible" to repair (if necessary) a particular product for subsequent reuse or sale on the second-hand market or to disassemble it partially or completely for subsequent remanufacture, recycle and/or disposal. Often, they undergo partial or complete disassembly for subsequent remanufacture or recycle. However, it might make more "sense" to make necessary repairs to the products and sell them on the second-hand market than to disassemble them for subsequent remanufacture and/or resale. There are no existing models that help make such decisions. The only known model is by Pochampally and Gupta [9] who have described how to build an expert system using Bayesian updating process and fuzzy set theory, to decide if it is "sensible" or not to repair the product of interest for subsequent sale on the second-hand market. However, such a model would have to be rethought anew because additional information from sensor-based monitoring may would steer us in a totally different direction. It is as if one moves from mass production to customized job shop!

Let us assume that, with the help of embedded sensors, we are able to obtain the following additional information that is considered reasonably accurate: (1) Remaining life of the end-of-use product. (2) Composition of the end-of-use product. For example the additional information may indicate what components are still inside the product, whether or not a particular component is functioning properly, stress/strain undergone by each component.

Availability of new information raises new questions such as:

1. How difficult is it to repair the product?
2. How much does it cost to repair the product?
3. How saleable is the product?
4. Has the product met with an accident (fall, collision, etc) before (check the information with respect to stress/strain/cracks of the components)?
5. Has the product been the subject of a safety recall in the past?
6. Does the product have all the relevant accessories (connecting cables, remote control, etc)?
7. Can the product be sold at a price that is substantially lower than that of a new product?
8. Can the product be sold with the same (or almost the same) guarantee as the new product?
9. Are spare components easily available to the buyer if they need them?
10. What is the attitude of the consumers towards the risk involved in buying the product?
11. Are there enough products (of the same type) so that one can simultaneously run a leasing/renting business?

#### 4. COMMUNICATION MODELS

This section deals with the development of models of communication for sensor data/information collection from the products that are located at geographically distributed centers.

To monitor the products health, we deploy smart sensors in a sensor network. Sensors collect data. The effective use of this data in decision-making requires processing it, displaying it, and storing it. Both real-

time data (current sensing readings) and historical data (previously stored sensing data) must be available and accessible online in a Web browser, for use by different personnel and applications in different locations.

The growing volume of archived data must be stored in a database system with good file management and retrieval facilities. It is not unusual for the size of real-time data to reach gigabytes and the size of historical data to reach terabytes. The database system must be able to deal with the three types of data encountered in this research: static data, dynamic data, and product condition data.

The data processing algorithms must also process and display the data in the most convenient fashion for different groups with different interests to enable them to analyze the data and make decisions. They should consider the various aspects of product lifecycle management including marketing, design for reliability, servicing, predictive maintenance, warranty take-back or repair, and end-of-life take-back.

## **5. PUBLIC POLICY ISSUES**

There are few, if any, ethically neutral technologies. Powerful technologies such as computing, especially on the scale addressed in this paper, have the potential to be utterly pervasive in people's lives. These technologies will be deployed with the best of intentions, but as with all previous technologies, an array of forces will come to bear on them that can be only partially anticipated. These forces will bring a corresponding array of ethical, legal, and policy issues that are profound and important.

They will require consideration at all levels during the conception, design, deployment, and use of large SEPs. It is hard to come up with easy prescription for the ethical, legal, and policy questions posed by SEPs. Other issues that will undoubtedly arise concern intellectual property (to whom does the data collected by SEPs belong?), liability (who is responsible when systems fail?), and the "digital divide" (who will have access to what kinds of systems?).

Embedding sensors in products is unavoidably going to pose some challenges in both technology and economics. The technology must be inexpensive enough for large numbers of people to be able to afford it, yet it must be powerful enough to solve some need. And ultimately, there must be enough profit in the venture for the purveyor of the technology to develop products and support them. It is by no means taken for granted that the best technology will prevail, and if there is no economic benefit (or too high a perceived risk, particularly of consequential damages), no vendors may wish to participate. The technology will be associated with large markets but that part of the research and development challenge may relate to lowering costs for a given level of performance or quality. For public-benefit SEPs that constitute new applications domains, the way forward may be less clear and market development more uncertain. By contrast, for SEPs with inherent commercial value (such as smart office and home appliances), one could expect significant markets to develop.

## **6. CONCLUSION**

The SEPs concept harnesses the combined power of sensors, wireless communication, and information technologies to radically change the way the consumer products such as refrigerators, washing machines, televisions, and computers are built, repaired, disassembled and refurbished in order to minimize the environmental burden through extended utilization of material resources and reduction of waste. The authors believe that one can achieve this by building products with inexpensive embedded sensors, and by assessing the condition and remaining-life of products to plan service/repair operations proactively and cost-effectively, and to come up with efficient disassembly plans, and to build refurbished products by assembling components that have uniform spans of remaining lives.

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