Cost-effective approach to automated resource management using real time sensing and networking

by

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Abstract

Approximately 50% of the operating funds in heavy manufacturing are tied up in inventory. Reducing this cost can be achieved by automating the inventory management. This thesis develops a cost-effective approach to automated resource management using real time sensing and networking. The enabling technology for automated inventory management is based primarily on real time sensing and standard network protocols and languages. With techniques developed in this thesis, all classes of resources, including discrete and continuous objects, can be managed with less labor than the traditional approaches.

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This thesis develops a cost-effective approach to automated resource management using real time sensing and networking. The enabling technology for automated inventory management is based primarily on real time sensing and standard network protocols and languages. With techniques developed in this thesis, all classes of resources, including discrete and continuous objects, can be managed with less labor than the traditional approaches.

1.1 Motivation

Inventory management has always been a critical component of an efficient supply chain. Today's new business practices are forcing firms to operate with even leaner inventories and staff while providing higher supply availability and speed of delivery. The inventory of finished items awaiting final sale, or in process between stages of manufacture, or in raw materials, etc., accounts for a large amount of the money required to run the economy. For example, approximately 50% of the operating funds in heavy manufacturing are tied up in inventory which is why so much effort is being put into reducing this investment.

1.2 Enabling Technology

Currently, the real time sensing can be achieved by a typical Radio Frequency Identification (RFID) system shown in the Figure 1.1. It consists of a tag, a reader, and some sort of data processing equipment, such as a computer. The reader sends a request for identification information to the tag. The tag responds with the respective information, which the reader then forwards to the data processing device. The tag and reader communicate with one another over a radio frequency (RF) channel. In some systems, the link between the reader and the computer is wireless. This technology
together with other existing technologies allow for every consumer object that has a tag to distribute information about itself over the World Wide Web (WWW). That information can be communicated to all other objects or devices connected to the WWW.

This integrated technology allows us to track inventory automatically. Information about objects flows seamlessly across different platforms and industries. All the objects we are using in the daily life could be connected through the WWW. One common standard could be used for description of all manufactured items from coke cans to the airplanes. We are developing a special language, the Object Description Language (ODL), for this purpose. Information about all kinds of products would be available to users. These include manuals, instructions or product labels, just to name few.

In manufacturing, for example, the inventory problem could be analyzed in terms of a batch size to be produced. Some of the names used in scientific literature and industry that formulate this problem would be the Christmas tree problem, or the
newsboy problem, or formally, the single period inventory control problem. When selling Christmas trees, the businessman has to decide in advance how many trees to order because he can not replenish the supply. Furthermore, she can not make money on any unsold trees. The approach to solving a typical problem like this one is to model a demand, D, as a random process since the size of a batch, M, clearly depends on the demand.

1.3 Classes of Inventory

Automated inventory management would not be sufficient for some classes of inventory such as fluids or particles, because they are measured in continuous rather than discrete values. In order to keep track of these types of inventory, precise and cost effective measurements are required. These measurements would relate to the state of a process, machine or a particular component in a larger system. Today, high-resolution sensors are expensive for some simple applications such as keeping track of quantity of a matter. For example, it probably would not be cost effective to use high-resolution, sensors to keep track of the amount of milk in a milk container. It would be really convenient to be able to measure quantities of some food items, but because the cost is important constraint in such attempts, the ideas fail to become reality in every day's life.

1.4 The Problem

Today's practice of managing inventory is a mixture of manual and automated systems. Electronic Data Interchange (EDI) and Universal Product Codes (UPC) code are examples of standards used to track inventory [14, 15]. Bar code scanners are used to get information from objects and commonly seen in retail stores and distribution centers. Although software and electronics for inventory management is becoming more sophisticated, the main deficit is wide variety of standards and formats used in inventory control, as well as, the manual labor needed to keep the track of the inventory. For
example, inventory can be tracked automatically provided all the data about the products is available. However, currently there is no efficient and cost effective way to the following:

**Data Collection** - collect the data about inventory without using human labor and

**Communication** - communicate the data with other distributors, manufacturers or consumers without converting to different data formats across different platforms and protocols.

Industry and academia are primarily focused on making software for inventory control more efficient, but not on fundamentally improving the way inventory management is performed or the format of inventory data is presented.

Tracking inventory such as milk, oil, or other liquids require precision sensors. Precision sensors are usually sensitive to changes in the environment and could be damaged due to unpredictably changing conditions. The size of high-resolution sensors often presents a difficulty when attaching them to various configurations. Using high resolution, high-cost sensors to keep track of quantity of such items such as milk, salad dressing, bread, etc., is not practical for the following reasons:

**Cost** - the cost of such attempt is too high (e.g. using a sensor of sufficient accuracy may cost more than the product itself. Furthermore, the cost of the lost information would not be significant compared to the cost of the sensor)

**Geometry** – the mounting and size of such sensors is impractical.

**Computation** - actual use of sensor would require additional data processing and data storage equipment not readily available in shape and form that would suit non-engineering requirements.
1.5 Research Contribution

This thesis improves management of physical inventory by implementing cost-effective techniques, which use the real-time measurement and standard networking protocols and languages. Already existing miniature and inexpensive tags attached to inventory provide a way to locate, identify and count objects, eliminating the need for manual labor and shortening the time to gather data. Making this set of operations more effective would incur large savings of time and labor.

One of the most important contributions of this thesis is a mathematical model for automatic Web ordering, which provides a more efficient and precise way of managing inventory. The demand of inventory is treated as a dynamic variable, which allows for better estimates of the reorder point. Another significant contribution is the determination of the number of sensors for measuring continuous classes of inventory.

The methods and tools that are developed and presented in this thesis have the following characteristics:

**Modeling Ease** - The theoretical principles underlying each of the approaches used in this thesis are relatively simple and would be very easy to model for a particular inventory control problem.

**Encompassing Many Problems** – Use of RFID-based technology could be done in many different ways. This technology is more efficient in data retrieval, data storage and data exchange than current technologies. Although today's technology and RFID-based technology use the same hardware, the latter is more ubiquitous because it offers the implementation of a new standard. Some of the fields that could benefit from tag technology are preventive maintenance, product design, telerobotics and service industries, to name few.
Compatible with existing technologies - One of the main advantages of the tag technology is its compatibility with existing technologies. To start using this technology, there is no need for any dramatic engineering advances, but only specific implementations using existing technology.

Automatic inventory control developed in this thesis integrates some of the common techniques used for inventory control today such as stochastic demand estimates [12]. In automatic inventory, a model of future demand is first developed and used to calculate the probable supply quantity needed to meet this demand, as well as the way to determine the reorder point (the point at which the new order is placed). The information about objects resides on the Web. The access restrictions should be implemented to ensure that confidential information is accessed by only authorized users.

For non-discrete inventory tags are not a good way of tracking. Sensory tags measure continuous quantities and communicate this information over the network. Once the quantity is known, the same mathematical model for automatic inventory could be used. Another result in this thesis is optimization of low-cost placement. The common denominator for comparing the measurements of single bit sensors and higher resolution sensors was the reliability of measurements for each type of sensors. Results show that it makes sense to replace expensive sensors with cheaper ones, which maintain the same functionality and reliability.

1.6 Scope of Thesis

Chapter 2 presents a new technology that integrates RFID technology with other technologies into WWW. This technology was evaluated through comparison with other similar technologies. Object Description Language and Universal Identifier are defined as integral components of tag technology. Chapter 3 develops a mathematical and practical model to be used for automatic inventory control via WWW. Chapter 4
addresses the potential of using cheap, single-bit sensors to replace high cost high-resolution sensors. Not only discrete objects, but also quantities such as liquid levels could be tracked using this new technology. Reliability was the same for both types of sensors. Chapter 5 shows an implementation of the theory on two examples. Chapter 6 summarizes the significant results and presents future work.
Chapter 2  
Background - Enabling Technologies

This thesis brings together a number of powerful, emerging technologies and extends these technologies for the purposes of resource management. The enabling technologies presented in this thesis rely heavily on the use of World Wide Web (WWW). However, in the future there might be another communication medium that would be as applicable to enabling technologies as it is WWW today. The most important contribution of this thesis is theoretical work. World Wide Web and enabling technologies are contemporary means for applying the ideas developed here.

2.1 The Internet

The Internet is truly revolution in communication. Today, people can instantly access and distribute information – text, picture, sound, and video – through a simple, intuitive interface. The World Wide Web (WWW) is both source and storage for vast quantities of human knowledge. The Web allows direct communication with other people and broadcast messages to millions. As advanced as the Internet is, however, it has left out the largest area of human endeavor – the physical world.

Physical objects could be described using a general markup language readable by a Web browser. Currently, there were numerous standards for communicating object descriptions such as File Transfer Protocol (ftp), gopher, Hypertext Markup Language (HTML), and the Extensible Markup Language and most recently, the Extensible Query Language. Currently, our technology uses Extensible Markup Language and the most popular Web markup language is Hypertext Markup Language (HTML) [17]. The HTML language has been powerful asset to Web development, but it lacks the capability for specialization, which restricts its growth. The entire HTML is already defined and in the case a user has a specialized task, such as transmitting the hospital records via Web in an easily readable way, HTML is not a good choice. HTML formats how you present a Web page’s data, and it is not designed to work with what that data represents.
The extensible Markup Language (XML) is used to support development of our technology by offering an open and flexible structure for creating and storing the information about the objects in various formats. This is contrary to HTML and its rigid format [17]. By letting users define their own elements, XML enables them to structure a document, as they want it, without having to restructure their data to fit a predefined markup language. In order to advance the development of a unique standard for identifying, manipulating and integrating objects, devices and information on the Internet, a new language and a protocol are being developed at the time of this thesis.

One of the advantages of this new technology is its ubiquity and application to numerous industries. There are some technologies that are based on use of tags already. It is fair to assume that these technologies would use the standard in the future in order to become integrated.

2.2 Emerging Communications Technologies

Although not fully developed, there are some technologies that integrate the physical world to the Internet. Web controlled cameras, the NASA Sojurner robot, and Internet traffic control software are some common examples. However, this current technology does not have vision nor a broad and flexible technical base to fully take an advantage of opportunities that Internet offers. Some of the newer technologies that move closer to our vision are miniature data tracking and collecting devices from iButton and wireless Internet connection such as Bluetooth. These technologies are considered as some of the most related and by exploring their technical base and their reach it would be clear what are their limitations that could be surpasses with use of tag technology.
2.2.1 Wireless Internet Connection - Bluetooth

Bluetooth is the codename for a technology specification for small form factor, low-cost, short range radio link between mobile PCs, mobile phones and other portable devices. The Bluetooth Special Interest Group is an industry group consisting of leaders in the telecommunications and computing industries that are driving development of the technology and bringing it to market.

Bluetooth technology will enable users to connect a wide range of computing and telecommunications devices easily and simply, without the need to buy, carry, or connect cables. It delivers opportunities for rapid ad hoc connections, and the possibility of automatic, unconscious, connections between devices. It will virtually eliminate the need to purchase additional or proprietary cabling to connect individual devices. Because Bluetooth can be used for a variety of purposes, it will also potentially replace multiple cable connections via a single radio link.

This new technology is fabulous on the hardware side but it does not offer much on the protocol side that would integrate various devices with ease. The technology also concentrates only on the information transmitted but not on the format of information nor the source and the destination of the information flow. It can not, for example, allow other devices that are not Bluetooth software and hardware compatible to transmit and receive information. This technology can not provide for tracking an inventory remotely unless each piece of the inventory is supplied with Bluetooth-like device, which is impractical to do because of the cost.

The tag technology will bridge the gap between fancy devices and very simple objects, such as inventory in storage or food products. Anything ranging from the ball bearings to the airplanes can be "tagged" and tracked down remotely.
2.2.2 Miniature Data Tracking Devices-iButton

The iButton is a 16mm computer chip housed in a stainless steel can. The iButton can be worn by a person or attached to an object for up-to-date information at the point of use. The steel button is rugged enough to withstand harsh outdoor environments; it is durable enough for a person to wear everyday on a digital accessory like a ring, key fob, wallet, watch, or badge.

There are a variety of buttons with different features. Each starts with a guaranteed-unique registration number engraved in the silicon. Some buttons add computer memory to store typed text or digitized photos; information can be updated as often as needed with a simple, momentary contact. Other buttons contain a real-time clock to track the number of hours a system is turned on for maintenance and warranty purposes; a temperature sensor for applications where spoilage is a concern, such as food transport; a transaction counter that allows the button to be used as a small change purse; or complete cryptographic circuitry to secure Internet transactions.

The fact that iButtons can be used to store data raises questions of possible security violation or data loss to the loss or destruction of the actual iButton device. One of the reasons the new tag technology would be so robust is that the information is not necessarily stored on the actual tracking device, such as in the case of iButton, but rather distributed on the World Wide Web. WWW offers multiple layers of security and probability that the information can be lost is very small considering existence of mirror sites with duplicate of the same data. iButtons use software built by many different companies, using different standards. For this reason, the interchange of information can not be seamless.

2.3 Radio Frequency Identification (RFID) Technology

This thesis presents an existing novel language and protocol for describing physical objects [13]. The intention of this language is to facilitate the integration of physical
things - both natural and man-made - into the World Wide Web. This integration will be accomplished twofold: through telesensing and teleoperation, and through tagged information on the objects.

The importance of this standard is clear when considering the diversity and magnitude of industries that may be effected. Although Universal Product Codes (UPC) and Electronic Data Interchange (EDI) currently exist, they are relatively industry specific, and are geared primarily for the manufacturers, distributors, and retailers. The information that they provide is not inclusive because they do not, for example, include material safety data sheets (MSDS), service manuals, operating instructions, replacement parts, packaging geometry, mechanical characteristics, advertisements, expiration dates, shipping requirements, parts lists, service centers, manufacturing methods, etc.

2.4 Object Description Language (ODL)

A universal Object Description Language (ODL), which effectively bridges industries and which is used by manufacturers, retailers, and customers, would be of great benefit for everyone [13]. The basic idea would be to mark objects with a Universal Identifier (UI), which references an ODL Web page. The ODL format would most likely be a derivative of the Extensible Markup Language (XML), or, perhaps, an implementation of the Resource Description Framework (RDF).

It would be appropriate to have a language that can be sanctioned by a standards body (W3C, ISO). This is because ODL would have important for commerce, manufacturing, retailers and customers. Although the actual implementation seems to be difficult to achieve, the commonality of physical entities and their general method of creation, distribution, and consumption, imply the possibility of a universal standard.
2.4.1 Simplicity and Ease of Use

New Object Description Language (ODL) should be very general, easily extensible and widely used. ODL should be a base line for creating a rich standard that allows use by humans and machines. Making sure that both machines and humans can make use of the language, many different databases should be utilized to create a single ODL file, the idea that is very far reaching. Although it would be nice to have first ODL version very general, it is not as practical to do so. Much as the original Hypertext Markup Language (HTML) was simple but limited, the same is expected for the first implementation of the Object Description Language (ODL). This later approach will help generate interest and motivate users to recognize the language as a standard.

2.4.2 Physically Based Object Descriptions

The general approach for describing objects may be from a truly physical perspective; in other words, a description of the type and arrangement of atoms. One could describe object based on geometry, composite geometry, molecular composition and mechanical properties. Object descriptions of this type would be similar to the Virtual Reality Modeling Language (VRML), in which objects are represented as Boolean combinations of basic and polyhedral solids. Surface properties, textures, lights, links, sounds, animation, and viewpoint, are added to these fundamental descriptions to enrich the visual appearance. Similarly, ODL would have rich information content.

2.4.3 User Based Object Descriptions

From a completely different perspective, object may be modeled as the manufactures, retailers, and customers see them; that is, as product name, lot number, quantity, invoice, price, sales tax, weight, volume, size, related products, expiration data,
product usage, nutritional information, safety data, etc. This later description is more immediately useful to the makers and users of objects. The physically based object descriptions, however, may be needed for visualization and, perhaps, for use with automated equipment (automated inventory equipment and robotics, for example). The advantage of this physical object description is in its inherently clever way of object manipulation. If an object could "tell" a machine what to do with it, the efforts to produce better results in fields of synthetic vision and object recognition would be challenged.

2.4.4 Object Information Maintenance

Whatever approach is adopted, however, should be accessory to people who work with the information. The makers of shampoo should not be expected to produce description data for their bottles. That job should be left to bottle manufacturer. On the other side, information on related products should be expected from the same manufacturer (such as conditioners, hair sprays, dyes, baby shampoo, etc.), advertisements, usage, ingredients, safety data, liquid volume, suggested retail price, local retailers, and, perhaps, pointers to the bottle manufacturer, which then contains geometry information on the bottle itself. Makers of food products may have ingredient lists, such as "salt, corn syrup solids, sugar, monosodium glutamate, ...,". These ingredients would point to generic information sites that describe them. These manufactures would further be motivated to create links to recipe sites, which use their product, and, in turn, these would link to other food products.

2.4.5 Object Models

In addition to static information, objects may also have dynamic information or simulation models. The bacterial content of milk, moisture content of a plant, or surface wear on a machine, all depend on the characteristics of the object, as well as the operating
environment. These object models are critical for many classes of physical systems, and should be included in any object description language.

These simulation algorithms should be defined with sufficient detail to allow compatibility and consistency between disparate algorithms. For example, there should be clear distinction between models, which are continuous or discrete, statistical or analytic, periodic, or event based, and elemental or aggregate. In addition to the general nature of the algorithm, significant detail for the input and output variables, value limits, stability, reliability, accuracy, etc. should also be provided. Further, providing administrative data, such as author, date, organization, purpose, description, etc. should be possible. The object models should facilitate manual construction of simulation systems, while at the same time accommodating automated search engines. Eventually, that automatic construction of synthetic environment though intelligent acquisition and assembly of simulation components from the Internet is expected.

2.4.6 Active Objects

In the near future, Internet Devices, that is machines monitored and controlled from the Internet, may be the largest users of ODL files. ODL files would contain instructions on how the objects should be operated on by an automatic device. For example, an instant dinner may encode cooking instructions for microwave or convection oven. Automobile subassemblies could encode handling instructions for both gantry and serial link robots. Providing these operating instructions for both human and machine could result in simpler and more efficient machines.

2.5 Electronic ID (EID)

The Universal Product Code (UPC) has for years provided a standard for identifying objects by manufacturer and product type. More advanced technologies (such
as embedded processors, radio frequency identification, infrared sensing, acoustic recognition and direct imaging) now allow more information to be stored with each item. However, rather than storing extensive information with each object, it is more efficient to simply store a reference to an information resource. In other words, the Electronic Identification (EID) would contain a pointer to a Web page, which contains a complete object description. In this way, large amounts of data, from multiple, disparate sources, could be linked to an object.

Although the full object description would be stored remotely, it is still important to contain some information directly on the object. This information may include the legacy UPC codes, product classification information, privacy and security data, individual object references, health and safety data, etc.

2.5.1 Bit count

The Universal Identifier must, at a minimum, uniquely identify every individual object. As a reference, the UPC code contains 12 digits: 6 for the manufacturer, 5 for the product, and 1 for parity. Since the UPC is a base 10 code, this implies a maximum of $10^6$ manufacturers and $10^5$ products -- certainly not enough to represent every object. As another reference, typical RFID systems encode more than 64 bits of data (of order $10^{19}$ possible identifiers) and 96 bits (O(28)) and 128 bits (O(38)) are common. This would certainly be sufficient to identify every manufactured object. Consider if we were to uniquely identify every square centimeter on the surface of the earth (including oceans), that we would need only $10^{19}$ identifiers.

In addition to uniquely identifying objects, the EID should include some information about the object -- particularly privacy and security data. It would also be extremely helpful to store some classification information, through which bit masking operations could quickly determine some object characteristics. If this were the only consideration, the EID I would store the maximum number of bits possible. While this may be
technically feasible, increasing the number of bits on the object generally increases the cost and reduces the bandwidth in which the tag can be read.

2.6 Internet Machines

The Internet machines would be characterized by their intelligence being uploaded from the Internet. This uploading capability would make machines more flexible and easy to reconfigure. The Internet is becoming a host to many physical entities that use the Internet to communicate to other entities. A far reaching idea it is not, because there is already a movement at MIT to develop a new standard protocol and language for object description and communication. Research that led to the idea of unique object identification using tags originated through work on robotics. Virtual reality environment for robots should allow for the robots to manipulate objects through remotely controlled interfaces. The problem with the approach is the cost and level of sophistication of current technology used to help in performing manipulation task. Vision algorithms and stereo vision techniques are both expensive and experimental and prove to put too much overhead to obtaining the cost effective solution for putting plain machinery to the Internet in massive quantities. If every 3 DOF robot would be required to have expensive object recognition tools for performing the simplest tasks such as moving objects in the space with ability to orient them successfully, than the cost of the manufacturing facility that would implement such a technology would be to great to allow implementation.

Imagine a microwave that cooks your dinner automatically. Microwave would use the tag to look up for dinner's ODL file on the web site of the company that produces it, extract from the file the instructions about the time to cook and the power level to use (low/medium/high) during the time interval, and finally set itself based on the instructions. This application would be one of the simplest ones yet conveying a very powerful idea that passive objects could navigate devices and "tell" them what to do a concept not explored in depth in robotics research today. Tag technology could be
further combined with sensory technology to facilitate automatic ordering via web as well as preventive maintenance of various systems and devices. This thesis proposes the alternative to using expensive sensors to be cheap and miniature single bit-sensors. The reason is two-fold: reduced cost for sensors and increased measurement ability. This thesis quantifies the difference when using single-bit sensors as an alternative to high resolution sensors.

Some of the most immediate commercial applications that are being developed based on tag technology are Web kitchen of the future under DISC at MIT and automatic inventory control of beverages. The Web kitchen project proposes to build a kitchen where almost all the electrical appliances would be connected to the Internet and also to use tag readers for tracking kitchen inventory. All objects in the kitchen would have a tag attached to track their quantity, location and their quality. Tag readers and cheap force sensors would be distributed all around the kitchen. If instant meal was placed in the oven or microwave, tag attached to a meal box would point to ODL file that contains cooking instructions for microwave. Figure 2.1 shows how the basic components of the tag technology would work together. Frozen dinner could simply “tell” microwave how to cook it. Cooking instructions would come from the Web after the microwave has read the tag and use that tag to locate these instructions on the Web. The cooking instructions would be placed in object specific file that contains a rich information about an object.
Figure 2.1: Instant dinner cooked by the microwave. Microwave uses cooking instructions from the World Wide Web.

Figure 2.2: Detailed information flow in the microwave.
This chapter presents a cost effective and engineering approach to automated inventory management. One of the results of this chapter is an automatic inventory model based on the calculated dynamic demand. Calculating dynamic demand helps the actual estimate of reorder point to be more accurate. Two existing mathematical components were implemented in this cost effective engineering approach. One is the Poisson or random process distribution analysis and other is profit analysis based on the size of the order and the demand.

The motivation for developing the cost effective approach to inventory management in this thesis was to reduce the inventory costs associated with holding cost and the cost of penalty of stockout [12]. Holding cost consists of such things as paying interest on the money invested in the goods in inventory, paying for housing the items and insuring them against fire and theft, the cost of obsolescence when the goods are in inventory are superseded by improved designs or they spoil or go out of style, etc. Although figures differ from one case to another, the average holding cost is in the range of 30-40% per year of the cost of the item. The cost of the stockout is associated with money lost due to the customer dissatisfaction or with the extra work needed to special order or backorder to try to keep customers satisfied. There are other costs associated with monetary penalties when a production must come to a halt because there is a shortage of a critical component.

The direct approach of balancing costs associated with inventory is cumbersome. Fortunately, there is another approach that does not depend on this potentially complicated cost analysis and that is the engineering approach. Engineering approach looks at the inventory problem based on a feel for the problem. The approach involves a scientific reasoning independent of trends in the market, personal bias, various financial
interests from parties involved with the inventory management process, etc. In short, the engineering solution is robust and resilient to the human influence.

This chapter starts with introduction of demand as a random variable that can be modeled using Poisson process. Other variables of interest are the reorder point, \( \tau \), and the quantity of items ordered, \( N \). The expected profit is then calculated based on the given probability of demand not exceeding the supply as well as the expected demand (obtained from the previous experience). This economic analysis is used to determine the supply quantity every time the new order is placed. Further findings concentrate on determining the reorder point by calculating the probability of no stockout while using the dynamic or variable demand approach. The chapter than concludes with an algorithm that describes the entire automatic inventory process.

3.1 Assumptions and Constraints

In order to make the automated inventory management an attractive alternative to current methods of inventory control, the implementation cost has to be reasonably low, and the savings in implementing new technology should be much larger than the cost. The time savings obtained using this new approach should be greater compared to time savings using current technology. The tags that exist today are easy to attach, relatively low-cost compared to the objects they are attached to, easily readable remotely, durable, etc. The following are some assumptions to help in understanding of the results.

**Assumptions**

- The demand was assumed to be a random variable with a Poisson's distribution.

- The price for the item is always greater than the cost of the item (very important for implementing the cost model)
• The expected profit from the sales could be calculated using the expected value theorem

• The actual count of the inventory is known instantaneously (real-time sensing)

• Order for new supply is processed instantaneously after it is received (no time delay)

• Orders can be placed at any time (this does not guarantee that the supplier is going to be responsive at any time as well)

• Profit (S), Cost (C) and Salvage Value (V) are constant variables that are set by outside considerations (these values depend on particular business or industry)

• Probability of no stockout is kept constant and other variables are calculated based on this value

3.1.1 Economic Analysis and Dynamic Demand

Economic analysis underlying the decision about the size of the order to be made is known as a single period inventory control problem [12]. For example, an entrepreneur selling Christmas trees has to decide in advance how many trees to stock so that she maximizes the profit in case that some of the trees remain unsold. The size of the order, N, is clearly dependent on the actual demand, D. The demand is obviously a random variable. The probability distribution of random variable D is by definition Poisson and calculated as

\[ p_D(d) = \frac{\lambda^d e^{-\lambda}}{d!} \quad d = 0, 1, 2, \ldots ; \]

(3.1)
where
\[ \lambda = \text{expected demand, } \lambda = E(D) \]
\[ d = \text{demand} \]

There is a good reason, both empirical and theoretical, for assuming the distribution is Poisson.

The economic analysis depends on the factors such as: cost per item for the entrepreneur, \( C \), the price for the item, \( S \), and the salvage value, \( V \). These three constants are set by outside considerations. The profit for given demand \( D = d \) is calculated as

\[
h(d) = \begin{cases} Sd - CN + (N - d)V, & 0 \leq d \leq N, \\ (S - C)N, & d > N. \end{cases}
\]

(3.2)

The expected value of the function \( h(X) \) of the random variable is by definition

\[
E[h(X)] = \begin{cases} \sum_{x} h(x_i) p_x(x_i), & \text{discrete,} \\ \int_{-\infty}^{\infty} h(x) f_x(x) dx, & \text{continuous.} \end{cases}
\]

 dependent on whether \( X \) is discrete or continuous. Here \( h(x) \) is an arbitrary function; the only requirements are that it be a real function of a real variable and that the sum or integral converge absolutely.

Now, the expected profit is calculated using expected value theorem as follows

\[
E[h(D)] = Q(N) = (S - V) \sum_{d=0}^{N} p_D(d) - N(C - V) \sum_{d=0}^{N} p_D(d) + N(S - C) \sum_{d=N+1}^{\infty} p_D(d)
\]

(3.3)
and \( Q(N) \) was used to emphasize the dependence on \( N \), the order size, that is the parameter to be optimized. The optimum \( N \) is one that maximizes \( Q(N) \). To find the optimum we can, starting with \( N=0 \), increase \( N \) to \( N+1 \) to see if \( Q(N) \) is increased and continue to do so until there is no improvement.

\[
\Delta Q(N) = Q(N+1) - Q(N),
\]

\[
= (S - V)(N + 1)p_D(N + 1) + V[(N + 1)p_D(N + 1)
+ \Pr(D \leq N)] + S[-Np_D(N + 1) + \Pr(D > N + 1)] - C,
\]

\[
= (S - C) - (S - V)\Pr(D \leq N).
\]

The result is the following expression which suggests that \( N \) is to be increased as long as

\[
\Pr(D \leq N) = \sum_{d=0}^{N} p_D(d) < \frac{S - C}{S - V}
\]

(3.4)

This inequality tells us that \( N \) should be picked as the smallest integer for which the inequality is not true anymore. Let’s illustrate the use of this expression through an example. Let’s assume that the demand, \( \lambda \), is \( \lambda = 5 \). Table 2.1 shows the distribution function for this particular case and was extracted from the table for the Poisson distribution in Appendix 1. Starting with \( C = $100 \) and \( S = $1000 \) assume that salvage value is \( V = 0 \). Than, \( (S-C)/(S-V) = 0.9 \); from the table it can be seen that the profit will be maximized if \( N = 8 \) of the items are in the inventory.
If there is an alternative market where $V=50$ than $(S-C)/(S-V)=0.9474$ and $N=9$ is the optimum inventory.

### 3.1.2 Determining the Reorder Point

It is common practice in economics to model a problem of random demand using so-called two-bin system [18,19]. The two-bin system is characteristic for two distinct bins, bin $P$ and bin $S$. Bin $P$ is used to supply the customers until the last item from this bin is taken. After the last item was taken there are two things that happen: 1) shift to the secondary bin, bin $S$, to respond to demand, and 2) order a new supply of the goods. The idea of the two-bin system is ubiquitous because it is so natural. The two-bin system here is modified in this thesis to fit a to a single-bin system that is treated as the secondary bin, bin $S$. The reorder point is calculated as each item is taken from a single bin system taking into consideration the risk associated with the probability of the stockout. The probability of the stockout is set voluntarily by a manager. The moment that this probability falls below the threshold value determines the reorder point and at that point the new order is placed.
The elapsed time $\tau$ between when the order is placed and when it is received is called the lead-time. If the demand during the lead-time is exactly $\mu$ per unit time than the amount of stock $m$ is calculated as $m = \mu \tau$. This stock is used up entirely during the lead-time. In real life, $\mu$ is a random variable and the demand is modeled as Poisson process. Consider keeping gasoline in your automobile: the gas gauge showing fuel on “low” is reasonable operating rule to start looking to replenish the supply. Early models of one of the popular imported cars actually had two gas tanks, a main tank (bin P) and a reserve tank (bin S), and no gas gauge. The driver was expected to drive the car using its main tank until it ran out and then switch to the reserve tank; then, knowing that only a limited amount of gasoline remained in the reserve tank, the driver should think of replenishing the supply. Another example of using a two-bin concept is buying groceries and deciding if there is enough groceries of type $A$ to last until the next time you decide to go shopping. The name for the point when the action is taken is called the reorder point.

A very important protection against stockout is called the safety stock. The safety stock is the amount by which the $m$ ($m = \mu \tau$) exceeds the average demand

$$\text{safety stock} = ss = m - \mu \tau.$$  \hspace{1cm} (3.5)

There are two possibilities to consider in choosing $m$. One, if $m$ smaller than the average demand, $\mu \tau$, the safety stock will vanish before the lead-time has elapsed. The penalty of running out of items during a lead-time ranges from a minor problem to a major one. The affect of stock out should be reduced to money terms in order to compare it with the situation when there is left over product in stock. Left over products can induce inventory carrying costs. The cost associated with the stock out can come from the monetary value placed on the disappointment of a customer, cost of special order or backorder to try to keep the customer happy and/or monetary penalties associated with halting the production facility because there was a shortage of some critical part.
It is evident that the cost analysis can be very complicated and overbearing. Another approach to finding the right quantity of goods for protection against stockout is the engineering approach. This approach assumes that given the initial number of items in stock, \( N \), the next thing to do is to calculate the reorder point, \( \tau \), at which the new quantity of items is ordered. The assumption made before should be emphasized again: the entire bin is modeled the same way as the secondary bin, bin \( S \). The probability of using up bin \( S \) \( \text{Po}(\tau) \) is calculated as in equation 3.6 [12].

\[
P_S(\tau) = \sum_{j=m}^{\infty} \frac{(\mu \tau)^j e^{-\mu \tau}}{j!}
\]

(3.6)

where \( j \) = the number of items removed from the inventory
\( m \) = the safety stock, or equivalently, \( m = N \) and \( j \geq m \)

Equation 3.6 says that the probability of the stockout is equal to the probability that the demand, \( j \), is greater or equal the number of items in stock, \( m \). The demand in this case could be any number greater than or equal to \( m \), which is shown as a sum in equation 3.6.

If the demand during the lead time is satisfied, than technically there is no unsatisfied demand. The actual probability of the stockout would therefore be calculated as

\[
P_s(\tau) = \sum_{j=m+1}^{\infty} \frac{(\mu \tau)^j e^{-\mu \tau}}{j!}
\]
It is easy now to calculate the probability of no stockout as

\[
\Pr(\text{no stockout}) = 1 - P_\lambda(\tau) = P_\tau(\tau) = \sum_{j=0}^{m} \frac{(\mu \tau)^j e^{-\mu \tau}}{j!}
\]

(3.7)

where

\( \mu = \text{average demand in items per time unit} \)

\( \tau = \text{reorder point in time units} \)

\( m = \text{number of items at the reorder point} \)

It would be useful if the probability of no stock out is chosen in advance so lets assume further that this is known. Now that the \( \Pr(\text{no stock out}) \) is known, the average demand can be calculated as inventory is decreasing. The lead time is usually fixed since it measures the time it takes to send and receive message and the time needed to transport the merchandise to the desired location and both of these intervals can be assumed to be constant over time. The initial demand, or so called expected demand \( \lambda = E(D) \) is used for initial value of average demand, \( \mu \). Later demands are calculated dynamically. For all practical purposes, \( \tau \) is usually given in some integer units of time such as hours or days and less often in minutes or seconds, but theoretically any time unit could be used.

Equation 3.6 can be written as

\[
\Pr(\text{no stock out}) = e^{-\mu} \left[ \frac{\mu^1}{1} + \frac{(\mu \tau)^2}{2!} + \frac{(\mu \tau)^3}{3!} + \ldots + \frac{(\mu \tau)^m}{m!} \right]
\]

(3.8)

Iterating \( \mu \) to satisfy the equation 3.7 is done each time the inventory count decreases by one, or in some cases by more than one if one customer purchases more than one item, or different customers purchase items at the same time. Once the right hand side of equation 3.7 falls below the value on the left-hand side, than the new order is placed.
This assures that the probability of no stock out is kept constant as one of the important objectives.

### 3.1.3 Calculation of the Dynamic Demand Rate

The reason for using dynamic demand rate is the fact that demand rate changes unpredictably in most of the situations and therefore it is not always correct to assume that the demand is constant. A good example is selling newspapers. Demand for news is higher when there is a very interesting issue publicized but other than that the quantity of newspaper produced is estimated based on statistical analysis of average demand for newspaper per day. The inventory model based on an average demand would not be capable to adjust to a change in the demand quickly. This is true because the model for the demand should be developed based on another statistical analysis and that analysis would by nature take more time to produce a new demand rate since involves data collecting process from various newspaper distributors. However, the inventory model based on assumption of a dynamic demand is well prepared to address the changes in demand and order bigger supply if the demand suddenly increases with already predetermined probability of no stockout.

The dynamic demand rate is calculated as follows:

\[
\mu(m-1) = \frac{(j-1)\mu(m) + \frac{1}{\Delta t_j}}{j}
\]

where \( j = 1, 2, \ldots, m \).

The demand rate at the time when the first item is removed from the inventory is
\[ \mu(m) = \frac{1}{\Delta t_i} \]

where \( \mu(m) \) = demand rate at the time when the m-th item was removed from the inventory

\( \Delta t_i = \) the time passed prior to first element being removed

From equation 3.8 demand rate is independent of reorder point, \( \tau \). The variable \( j \) has a random distribution and represents the items withdrawn from the inventory at time \( t_j \). The inventory starts with \( m \) items. Each time an item is taken out the inventory, the time interval \( \Delta t_j \) is measured using the equation = \( t_j - t_{j-1} \). Figure 3.1 shows how the actual demand is calculated.

![Figure 3.1: Time intervals used in calculating the dynamic demand](image)

Averaging demand is a natural way to go about this because averaging helps reduce the probability of ordering items prematurely. Premature ordering could be caused by the sudden increase in demand in a short period of time. If not averaged over a long period...
of time, this increase in the demand would appear to be the actual demand. An example to support this idea could be found in situation where a user buys a large quantity in a short period of time (bulk). If the inventory ordering system is too sensitive to this sudden impulse of demand and it is not taking the overall demand frequency into consideration, it could start ordering new items long before the old supply got off the shelves. In the best case scenario, at the time the new order comes in there will be shortage of storage space to place the items and that could make a part of the order to be returned and penalties to be paid.

The plot for demand rate, ℹ, is shown on Figure 3.2. Unit for demand is [items/time] = (1/time unit). Note sharp changes in demand. These changes are actual corrections due to the averaging mode of estimating the demand. The curve for the demand really depends on the actual situation and Figure 3.2 is not a typical curve.

Figure 3.2: Demand rate calculated as the inventory changes.

The following figure uses m=20 and τ = 2 (star), τ = 5 (circle) and τ = 8 (square).
3.1.4 Automatic Inventory Process via World Wide Web

After laying out the necessary theoretical framework, the automatic inventory management can be implemented. The overall process can be represented using figure 2.1. Note that placing the new order must be done using the Internet.
The process starts with setting the expected demand to be the current demand. The current demand is used to calculate the number of items, m, needed to make the greatest profit. Once m is found, a new order is placed (via the Internet). The process loops in place until the new order arrives. After the order is in, the probability of no stockout is chosen and set as a constant. The actual probability of no stockout, based on m, τ and μ, is than calculated and compared to the constant value set earlier. If the actual probability is smaller than the constant value, than the expected demand is calculated based on the current demand and the model of demand that includes demand history. Than the cycle is repeated. If the actual probability is greater or equal than the constant value, than the number of items in stock is updated. Given the updated number of items in stock, the dynamic demand is calculated. With new value for the dynamic demand, the process is returned to the point of calculating probability of no stockout. This concludes the entire process.
Model of demand that includes demand history used for estimating the expected demand $\lambda = E(D) = \mu(m)$

Expected demand $\lambda = E(D) = \mu(m)$

$\sum_{d=0}^{N} p_D(d) \leq \frac{S - C}{S - V}$

New order placed

New order arrived?

yes

Stock count starts at $m$ items

Calculate $\Pr(\text{no stockout})$ given current demand

$\Pr(\text{no stockout}) = \sum_{j \leq m} \frac{\left( \frac{\mu(m-1)}{\tau} \right)^j e^{-\mu(m-1)\tau}}{j!}$

Pr(const) $<$ Pr(no stockout)

$\Pr(\text{const}) = \Pr(\text{no stockout})$

no

yes

Number of items in stock decreased?

no

yes

$\mu(m-1) = \frac{(j-1)\mu(m) + \frac{1}{\Delta t}}{j}$

Figure 3.4: Automatic Inventory Management Process description
3.2 Chapter Summary

This chapter developed a cost effective engineering approach to inventory management. In doing so, the probability of no stockout was set by a user and used as a constant to calculate the reorder point. The demand was assumed to be dynamic. Once the reorder point was determined, the actual quantity to order was calculated based on the optimal profit model. At the conclusion of this chapter, some graphical data were shown and also the algorithm used to implement the process is demonstrated.
The result of this chapter shows explicitly how many single-bit sensors are needed to replace the higher-resolution sensor achieving the same or better reliability. The common denominator used to compare the single-bit sensors with the higher resolution sensors was the reliability of the sensory measurement.

Automating the inventory management system using only tags attached to objects would not suffice for some classes of inventory such as fluids and particles because fluids and particles are measured in continuous values. For example, a milk carton with a tag could be useful when the empty gallon is thrown out so that the automatic inventory system detects that milk is missing from a refrigerator and orders a new supply. The problem with this approach is that it takes time to replenish the milk supply and in the meantime milk is still needed. One way of solving this problem is to have a sensor that could tell the amount of milk left in a gallon and send that data to the automatic inventory management system. This way the order of milk could be placed while there is still some milk left in that gallon. By the time the entire gallon of milk is used, the new gallon comes in. The sensor that measures the quantity of milk should be very cheap relative to the price of milk. This brings a new way of thinking about sensors. The trade off to producing a very low cost sensor would be very low resolution because resolution is proportional to the price.

Besides low resolution, cheap sensors should be fairly small and light to attach it to the milk gallon or other consumer products. Smaller components are more expensive because they require more precision. Should the resolution remain the same while shrinking the size of a sensor its price would automatically jump up. An example of extremely cheap and small sensor would have only one bit of resolution and would be easily attachable to many different surfaces due to its size and design.
4.1 Sensor Substitution

The results of this chapter convey that when the high resolution sensors have a low reliability it would be better to replace them with low resolution sensors. That can improve their reliability and decrease the cost. For higher reliability, high resolution sensors the replacement is not the best solution. The following assumptions were made in solving this problem:

- Sensor measurements are independent
- Reliability of two bit sensor is \( R \)
- All the single bit sensors are equally reliable, \( r = r_1 = r_2 = r_3 \)
- There is always greater number of good sensors than the bad ones

The relation between reliability and number of sensors is developed based on comparisons made to determine advantages and disadvantages of having one high-resolution sensor versus many low-resolution sensors. Sensor substitution was applied to measure fuel level in a tank.

**Example: Fuel Measurement**

Suppose in Figure 5.1 we had a 2-bit sensor, which measures four different fuel levels.

![Sensor and fuel levels](image)

*Figure 4.1: Fuel tank and sensor measuring four different fuel levels*
The sensor needs to have at most two bits of resolution because it can show four different levels of fuel so we could write

\[ 2^n = 4 \]

where \( n \) = number of bits = 2 and \( n \) is an integer.

Four different fuel levels are

- Level 1: 75% full < level < 100% full
- Level 2: 50% full < level < 75% full
- Level 3: 25% full < level < 50% full
- Level 4: 0% full < level < 25% full

The sensor reliability in representing the actual state of the world can be anything in the interval \([0,1]\) where 0 means that sensor is not working, and 1 means that sensor always shows the correct value. However, it is difficult to find sensor in the real world that has reliability very close to 1. The probability that a sensor gives a true estimate of the measured value is given as the sum of the following expressions

\[ p(\text{sensor shows true } | \text{measure is true}) \text{ and } p(\text{sensor shows false } | \text{measure is false}) \]

A manufacturer provides data about the probability that sensor is measuring correct or incorrect value so that this piece of information was assumed to be known.

4.2 Single bit sensor Analysis

Two variables of interest shall be used to compare the reliability of a single bit sensor to a two-bit sensor.
1. Number of sensors, \( N_{si} \), where \( i \) is the number of bits and \( s \) is a particular sensor

2. Reliability of the measurement, \( R_m \), where \( m \) is the measurement number

Following the example with fuel tank from previous paragraph will help clarify the point. In order to measure four different fuel levels using single-bit sensors, at least three single-bit sensors are needed. One could be placed at the border between two levels so that it can “tell” if the upper level is full or empty as well as if the lower level is full. Let's suppose that the placement of these sensors on the fuel tank is shown in Figure 5.2. Each sensor can tell whether or not there is a fuel at the measured level. If there is a fuel, the value of the sensor is high or logical 1. If there is no fuel, the value of the sensor is low or logical 0.

![Figure 4.2: Multi-sensor array can replace a single two-bit sensor](image)

Let's assume there are \( L \) different levels to detect, then the number of single bit sensors is given as follows:

\[
N_{s1} = \begin{cases} 
L - 1 & \text{for } L > 1 \\
1 & \text{for } L = 1 
\end{cases}
\]
The combination of logical 1 and 0 obtained from the sensors determines the fuel level. However, there will be cases where the actual logical combination will not make sense. For example, the following case is not realistic:

Sensor1 = 1, Sensor2 = 1 and Sensor3 = 0

This combination makes no sense in reality unless the tank sits upside down, which is not the case because Sensor3 is the one at the bottom of the tank and other two sensors are positioned above Sensor3. In this particular case, Sensor3 has a high probability of being faulty.

One advantage of using an array of single-bit sensors versus a single 2-bit sensor is the ease of failure detection. In the case above, state of sensors one and two could be an indication that the sensor three may be broken. However, it could be that sensor three is working properly and sensors one and two are bad but that situation has less likelihood because there is always greater number of single-bit sensors that perform well than those who do not. This is true because the bad sensors are very likely to be replaced immediately. In general, the states that are physically impossible help uncover sensor failure with a quantifiable measure of probability.

Another way to improve this situation is to increase the number of sensors that measure each fuel level. Then, the majority of the sensors that show the same output are assumed to be correct. The truth table for the single-bit sensor array gathering data from the fuel tank shown above is as follows:

<table>
<thead>
<tr>
<th>sensor 1</th>
<th>sensor 2</th>
<th>sensor 3</th>
<th>level 75-100%</th>
<th>level 50-75%</th>
<th>level 25-50%</th>
<th>level 0-25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>
The joint probability distribution for three sensors at four different levels of fuel is calculated as follows:

\[
\begin{align*}
\text{p}(0<\text{level}<25\%) &= p(s_1=s_2=s_3=0) = p(s_1=0)p(s_2=0)p(s_3=0) \\
\text{p}(25<\text{level}<50\%) &= p(s_1=s_2=0,s_3=1) = p(s_1=0)p(s_2=0)p(s_3=1) \\
\text{p}(50<\text{level}<75\%) &= p(s_1=0,s_2=s_3=1) = p(s_1=0)p(s_2=1)p(s_3=1) \\
\text{p}(75<\text{level}<100\%) &= p(s_1=s_2=s_3=1) = p(s_1=1)p(s_2=1)p(s_3=1)
\end{align*}
\]

These expressions are compliant with the assumption that sensor measurements are independent of each other. Another compliant assumption is that each level measured by a 2-bit sensor has inherited reliability of measure \( R \). This reliability is equal to the probability that measurement is correct. In order to make multi-sensor array equally or more reliable as 2-bit sensor, the combined reliability of one-bit sensors must equal or exceed \( R \). Let's assume that \( R \) is the probability of correctly measuring that fuel level in the interval \( 0 < \text{level} < 25\% \). Then the following holds

\[
R = p(s_1=s_2=s_3=0) = p(s_1)p(s_2)p(s_3) = r_1r_2r_3
\]

where \( r_1, r_2 \) and \( r_3 \) are the reliability of measurement by sensors one, two and three of multi-sensor array and \( R \) is the reliability of the 2-bit sensor given by the sensor manufacturer. It was assumed that all the sensors are equally reliable, \( r = r_1 = r_2 = r_3 \) and therefore

\[
R = r^3
\]

From this equation \( r \) can be calculated to be:

\[
r = \sqrt[3]{R}
\]

Equation 5.1 allows for calculation of the maximum reliability \( r \) for a one-bit sensor in a multi-sensor array whereby this array provides equally reliable measurement, as would the single two-bit sensor.
4.3 General Approach to Sensory Substitution

Assumptions:

- Single bit sensors are positioned at equal distances uniformly covering the entire height of the reservoir.
- The resolution of the measurement increases proportionally to the increase in the number of single bit sensors along the height of the fuel tank.

Measuring fuel level with \( n \) one-bit sensors is shown in Figure 5.3. As in the case with three sensors, the objective here is to calculate \( r \) for one-bit sensors so that the measurement of the one-bit multi-sensor array is as reliable as the measurement taken with a 2-bit sensor with known reliability.

![Figure 4.3: Multi-sensor array attached to the fuel tank measuring only one level, \( B < \text{level} < A \).](image)

Starting with an array of only one one-bit sensor the following equation could be used to calculate \( r \):

\[
p(B < \text{level} < A) = p(s_1 = 1) \tag{5.2}
\]
Where \( p(s_1 = 1) \) is the probability that sensor 1 measures the correct value when it shows that value, in other words, the reliability of measurement from sensor 1. The truth table for this sensor looks as follows:

<table>
<thead>
<tr>
<th>sensor 1</th>
<th>B &lt; level &lt; A</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>no</td>
</tr>
<tr>
<td>1</td>
<td>yes</td>
</tr>
</tbody>
</table>

The tank contains some fuel but it is not possible to determine how much when the sensor shows value of logical 1 and empty when it shows value of logical 0. Expanding on the equation 5.2

\[
p(B < \text{level} < A) = R = p(s_1 = 1) = r
\]

This is the trivial case where one sensor is replaced with another of the same reliability. Now let's examine a more interesting case of two one-bit sensors used to measure the same level on the same fuel tank.

\[
p(B < \text{level} < A) = p(s_1 = 1, s_2 = 1) + p(s_1 = 0, s_2 = 1) \quad \text{Equation 5.3}
\]

There are two ways to determine that the fuel level is between points A and B. One combination of measured values indicating that \( s_1 = 1 \) and \( s_2 = 1 \) meaning that the fuel level is above the level of sensor \( s_1 \) and \( s_2 \) and another combination indicating that \( s_1 = 0 \) and \( s_2 = 1 \) which again indicates that the fuel level is between points A and B. There are two different combinations of measurements that give the same result. Therefore, the
reliability of measurements with two sensors increased as shown in Equation 5.3. With 
addition of an extra sensor, \( s_2 \) the reliability of measurements increased as follows:

\[
p(B < \text{level} < A) = R = p(s_1 = 1, s_2 = 1) + p(s_1 = 0, s_2 = 1) = \\
= p(s_1 = 1 \mid s_2 = 1)p(s_2 = 1) + p(s_1 = 0 \mid s_2 = 1)p(s_2 = 1),
\]

or equivalently

\[
p(B < \text{level} < A) = R = p(s_1 = 1, s_2 = 1) + p(s_1 = 0, s_2 = 1) = \\
= p(s_2 = 1 \mid s_1 = 1)p(s_1 = 1) + p(s_2 = 1 \mid s_1 = 0)p(s_1 = 0)
\]

Equation 5.3 reduces to

\[
p(B < \text{level} < A) = R = p(s_1 = 1, s_2 = 1) + p(s_1 = 0, s_2 = 1) = \\
= p(s_1 = 1)p(s_2 = 1) + p(s_1 = 0)p(s_2 = 1) \\
= r_1r_2 + u_1r_2,
\]

where \( r_1 \) and \( r_2 \) stand for reliability of sensors \( s_1 \) and \( s_2 \) and measure the probability that 
these sensors measure value of logical one when they indicate so. \( u_1 \) stands for the 
probability that sensor one measures value of logical zero when it indicates so. Lets 
assume that \( r \) and \( u \) are the same.

From the previous equation and setting \( r = r_1 = u_1 = r_2 \),

\[
R = 2r^2
\]

\( r \) is calculated to be

\[
r = \sqrt{\frac{R}{2}}
\]
Comparing the case with one sensor and with two sensors, the ratio \( r(1)/r(2) \) is calculated to be

\[
\frac{r(1)}{r(2)} = \frac{R}{\sqrt{2}} = \sqrt{2} R
\]

From this expression it is not clear if \( r(1) \) is greater or smaller than \( r(2) \). In order to resolve this ambiguity, the solution space for the various values of \( R \) and number of sensors is obtained by solving the following general expression

\[
r = \#\text{sensors} \sqrt{\frac{R}{\#\text{sensors}}} = \sqrt{0.1}
\]

This expression is used to plot graph below for \( R = [0,1] \) and number of sensors ranging from 1 to 10.

![Figure 4.4: Solution space for \( R = [0,1] \) and \#sensors = [1,10]](image)

Figure 4.4: Solution space for \( R = [0,1] \) and \#sensors = [1,10]
Table 5.2: Percentage reliability change using single bit sensors

<table>
<thead>
<tr>
<th>Reliability of 2-bit sensor</th>
<th>% improvement in reliability achieved with 10 single bit sensors</th>
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<tr>
<td>0.1</td>
<td>631%</td>
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<tr>
<td>0.2</td>
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<td>0.3</td>
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<tr>
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</tr>
<tr>
<td>1.0</td>
<td>79%</td>
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</table>

Figure 5.4 shows the reliability on the y-axis and number of sensors on x-axis. Reliability is incremented from 0.1 to 1 with a 0.1 step size and given by the sensor manufacturer. Figure 5.4 shows that the best use of one-bit sensors is achieved for sensor reliabilities from 0.1 to 0.5 because the overall system reliability increases from the nominal reliability of the original 2-bit sensor. Interesting result is obtained for reliabilities in range [0.6, 1]:

- For $R = 0.6$ reliability of single bit sensory array increases for #sensors $\geq 4$.
- For $R = 0.7$ reliability of single bit sensory array increases for #sensors $\geq 6$.
- For $R = 0.8$ reliability of single bit sensory array never reaches $R$
- Nominal reliability could not be recovered for range $R = [0.8, 1]$ even after using ten single bit sensors.
Addition of extra sensors in this case could be justified only if more resolution is needed in the actual measurement. In other words, if measuring finer additional sub-levels is likely to be of greater importance than the reliability of measurement than using the single bit sensors would still be considered as a good practice. Another simulation with a maximum of 40 single bit sensors was run and results shown in Figure 5.5.

![Figure 4.5: Maximum of 40 sensors used to replace the higher resolution sensor.](image)

Note that the nominal reliabilities could eventually be reached at the expense of using large number of single bit sensors. A practical approach to using large number of single bit sensors would be to make sensor matrix such as one shown in Figure 5.6. This matrix would be easy to apply to the surface of interest and would contain N x M single bit sensors. Single matrix could be used for measuring a single fuel level.

![Figure 4.6: Matrix of single bit sensors](image)
4.4 Improving the Accuracy of Single bit Sensor Measurement

In order to compare reliability between higher resolution sensors and single bit sensors, it was assumed, for the purposes of analysis, that the single bit sensors had perfect or 100% reliability in their measurement. Low-cost, single bit sensors would probably have low reliability due to low cost of technology used to manufacture them. Low reliability of each single bit sensor would have an effect of lowering the overall reliability of measurements. To improve overall individual reliability a technique called sensory synthesis [2] could be applied. Sensory synthesis is equivalent to method a human would use in monitoring a manufacturing process.

When a human controls a manufacturing process he or she uses multiple senses to monitor that process. Similarly, one can consider a control approach where measurements of process variables are performed by several sensing devices. These devices feed their signals into process models. Each of these models contains mathematical expressions based on the physics of the process which relate the sensor signals to process state variable (see Figure 5.7a,b). The information provided by the process models should be synthesized in order to determine the best estimates for the state variables.

Figure 4.7 a: Process Monitoring Scheme Featuring Sensor Synthesis [2]
Synthesis of sensor information offers the following benefits:

- The process model can correct the differences in reliabilities that occur during a single process in different types of sensors. Knowing the process input parameters, or other parameters, the sensor synthesis could account for the appropriateness of various sensor measurements in various process conditions.

- Several sensors could be synthesized to provide better resolution of measurements.

### 4.5 Approach to Sensory Synthesis

Basic approach to the synthesis of multiple sensors is to synthesize the state variable estimates determined by the different sensors and corresponding processes models through a mechanism based on statistical criteria to estimate the best synthesized state variable estimate from the state variable estimates provided by the process models (see Figure 5.6).

A typical approach has been presented in [4] for obtaining statistical information about correlation between the state variables and their estimates provided by the process model through evaluation of process models, which are based on process physics. The
development of sensor synthesis started with military research trying to develop reliable target identification technique [5, 6, 9]. Sensor synthesis was also developed for use in robotics [6-8, 11].

One of the techniques for sensor synthesis is called Shafer-Dempster reasoning and is used for target identification in military applications [9, 10]. In this method, the degree of support for a final proposition is determined by the confidence for the truth of the logical antecedents of the final proposition. The degree of confidence assigned to each antecedent proposition reflects the degree to which the information is true as well as the reliability of the sensor that gives the information. In order to implement this method for sensory synthesis in process monitoring, multiple final propositions would have to be considered. Each of these final propositions would suggest that the estimated state variable is within a certain range. The information from each sensor would indicate that the state variable might be within one of the several ranges, and logical rules would have to be developed in order to determine the degree of support for each final proposition.

Other approaches for the synthesis of sensor information have been utilized in robotic applications [11]. These methods were used here because they are convenient and easy to implement compared to Shafer-Dempster approach. For these methods, the largest consensus group of sensors whose information is considered to be in agreement is first determined. In order to define the sensors in this group it is first determined for each sensor whether or not the information from each of the other sensors is supportive. Sensor i is said to be supported by sensor j if the confidence distance measure \( d_{ij} \) is less than a threshold value \( r_{ij} \). The confidence distance measure is defined as

\[
d_{ij} = 2A
\]

where

A is the area under the probability density curve \( P_i(x) \) between \( x_i \) and \( x_j \) (Figure 5.7). \( P_i(x) \) is the probability density function for the value of state \( x \) given that the state estimate provided by sensor i and its corresponding process model is \( x_i \).
In order to specify a value for $r_{ij}$ it is necessary to look at the previous reliability of the sensors. $r_{ij}$ can take any value from 0.0 to 1.0. If $r_{ij} = 0.0$ than sensor $j$ does not support sensor $i$. If $r_{ij} = 1.0$ than sensor $j$ completely supports sensor $i$. The largest group of sensors that is mutually supportive and/or supported by the other sensors is used to determine the synthesized estimate of the state variable.

![Figure 4.8: Definition of an area A used to determine if sensor j supports sensor i](image)

The assumption is that probability density function for each sensor $P_i(x)$ is considered to be Gaussian [11]. Variance of each distribution is considered to be equal to the variance of the sensor-based state estimates about the actual state.

The variance can be determined either through experiment or possibly through evaluating the process models, which convert the measured variables to estimates of the state variables based on an understanding of the process. The following are the methods for obtaining the synthesized estimate such that the following two expressions are maximized:

$$\sum_{i=1}^{l} P_i(\theta / x_i)$$

where
\( \theta = \) synthesized estimate

\( l = \) number of sensors considered to be in agreement

\( x_i = \) state variable estimates provided by each process model

\( P_i(\theta/x_i) = \) value of the probability density function at \( \theta \) given that the distribution is centered at \( x_i \) (Figure 5.7)

\[
\prod_{i=1}^{l} P(x_i / \theta)
\]

where

\( P(x_i/\theta) = \) value of the probability density function at \( x_i \) given that the distribution is centered at \( \theta \)

Maximizing the first expression, the total probability for the synthesized estimate is maximized. Maximizing the second expression, the synthesized estimate that best agrees with all of the state estimates is found. For both methods the indices are over the set of sensors considered to be in agreement. The first method does not have a closed form solution and must be solved by iteration. In this approach, one of the state estimates is taken as a first approximation to the synthesized estimate, \( \theta \). In the second expression, the synthesized estimate has a closed-form solution. Graphically, the definition of \( P_i(\theta/x_i) \) is shown on Figure 5.9.
Figure 4.9: Definition of $P_i(\theta|x_i)$ used to determine synthesized estimate for a state variable

If the process models do not reflect the process entirely, there is an error or a bias between the state estimates provided by the model and the actual state. If this bias is known, the corresponding state estimates can be corrected for the bias before synthesizing the estimate with other state estimates.

4.6 Chapter Summary

This chapter made a comparison between use of single-bit sensors vs. high-resolution sensors. Some of the most important advantages of single-bit sensors are lower cost, ease of installation and increased resolution. The common denominator for both single-bit and high-resolution sensors was the reliability of the measurement. The result of this chapter shows explicitly how many single-bit sensors are needed to replace the higher-resolution sensor achieving the same or better reliability. Here is the short summary of results:

- For $R = 0.6$ reliability of single bit sensory array increases for $\#sensors \geq 4$.
- For $R = 0.7$ reliability of single bit sensory array increases for $\#sensors \geq 6$. 
For $R = 0.8$ reliability of single bit sensory array never reaches $R$

Nominal reliability could not be recovered for range $R = [0.8, 1]$ even after using ten single bit sensors.

In order to improve an overall individual reliability of single-bit sensors, commonly used technique called sensory synthesis [2] could be applied. Sensory synthesis is equivalent to method a human would use in monitoring a manufacturing process. Synthesis of sensor information offers the following benefits:

- The process model can correct the differences in reliabilities that occur during a single process in different types of sensors. Knowing the process input parameters, or other parameters, the sensor synthesis could account for the appropriateness of various sensor measurements in various process conditions.

- Several sensors could be synthesized to provide better resolution of measurements.
5.1 Automatic inventory of soft drinks via World Wide Web

The new tag based technology was implemented to automate the soft drink inventory using the World Wide Web. Chapter 2 presented the mathematical model to be used in making decisions about ordering new supplies of soft drinks. It was shown how cost constraints affect the actual model. This chapter shows how to integrate the theoretical model into the World Wide Web and storing data and protocols in data base on the network of computers to be used in automation.

There are two unique components of the model integration: software and hardware. Software consists of Java-based application on top of the RS232 protocol that connects physical machinery with World Wide Web. Hardware is made of a force sensor, an A/D converter and interface between computer and the A/D converter. The future implementation would be based on the new tag-based technology. This would make tag usage ubiquitous and cost effective. Tags would be seen on items such as frozen dinners, automobile parts, home appliances, even coke cans. The author is aware of the privacy and security problems that can arise but the security issue depends on how well new standard will be adopted and regulated between government and businesses, as well as how much information should be encrypted in the tag itself. Privacy and security issues related to this technology are being addressed by the Distributed Intelligent Systems Center (DISC) at MIT, however their implementation is beyond the scope of this thesis.

The refrigerator that connects to the WWW was used for the experimental implementation. The motivation for using refrigerator as an example was in the simplicity of the device and the flexibility to store many different types of objects. Having such a mix, purchasing could be consolidated or done on product per product basis. Consolidated purchasing would require the analysis of the best time to make a new
order for the entire product mix, and not just a single product. It is the overall economics that would be most important in this case. On one hand, the delivery cost is lower because various products are delivered at the same time. On the other hand, not all the products in the product mix will be delivered on time or maybe even prematurely. In either case, there will be some penalty associated with the approach. Purchasing done on product per product basis has an advantage to always deliver a particular product when needed, therefore minimizing the storage costs and costs associated with results of customer dissatisfaction when products are late. On the bad side, the cost of delivery may be significant because there is always a single delivery associated with each of the products.

5.2 Experimental Setup

The experimental setup consisted of refrigerator, force sensor, A/D converter, computer, dedicated software and dedicated Internet link and is shown in Figure 5.1.

Figure 5.1: Experimental setup featuring the feedback loop
5.2.1 Software

Java [32] based software was designed to read data from the refrigerator and send out the request for the delivery to the soft-drink distributor. RS232 protocol was used to allow communication between the computer and A/D converter. The Java application connected C++ code with TCP/IP [31] interface. The interface allows for connection to the World Wide Web. The software implementation is shown on Figure 5.2.

![Software Diagram](image)

Figure 5.2: Software used for automated inventory management. Communication is both ways. This allows for controlling and observing a device simultaneously.

5.2.2 Hardware

The maintenance of automated inventory was using force sensor. This approach is very simple and works well for the demonstration purposes. In the future, instead of using a force sensor, tags could be used to count the inventory of soft drinks. Since this tag-based technology is still developing, and for the purposes of the application, the force sensor was used to obtain the information about the quantity of soft drinks in a refrigerator. The refrigerator used in the experiment had a force sensor to detect a change in the weight of soft drinks and therefore to estimate the amount of drink in the
refrigerator. The analog signal from the force sensor was converted to the digital signal and read off in the computer using an electronic interface. The computer was linked to the World Wide Web using dedicated Internet connection. The single force sensor was used to measure the quantity of beverages left in the refrigerator. If there were more than one type of drink in the refrigerator, than tags would have to be attached to them to determine their identity and also their quantity and the force sensor would not be required in that case.

Figure 5.3: Experimental setup for automatic inventory management system
Currently, the problem of inventory management requires a considerable amount of funds to be devoted to it. For example, something like 50% of the operating funds in heavy manufacturing are tied up in inventory which is why so much effort is being put into reducing this investment. One way to reduce the investment into inventory is to automate the tasks related to it. The tag-based technology from MIT offers a unique way to automate the inventory management. Savings that could be obtained using this technology depend on how much the cost of labor can be reduced and how big are the cost savings as a result of benefits of a standard way of information exchange.

A cost-effective model for automated inventory management is presented here. The model estimates the reorder point based on the several variables such as the inventory size, the demand rate and the probability that the inventory will not run out of stock. This model could be applied to all classes of resources including discrete and continuous objects. Special contribution on managing a continuous class of inventory is presented. Simple, single-bit sensors can replace expensive, high-resolution sensors to track continuous classes of inventory. Results of this thesis should be evaluated with regard to the real-world example in order to calculate the real cost benefit. Therefore, the cost analysis could show the real advantages or disadvantages of the model applied to a particular business situation. This benefit stems from the mathematical model used to automate the inventory management as well as for the use of single-bit sensors to replace the higher-resolution sensors.

In the future, the technology based on remote identification of objects is likely to become ubiquitous. Theoretically, every object ever manufactured could be “tagged” and therefore there is a potential of connecting that object to the World Wide Web. The tag is a unique identification for an object and the descriptive information about an object is deposited on the Web. The automated inventory management is an excellent example of the type of application to be used with new tag-based technology. This technology is likely to change the inventory management dramatically. All classes of inventory,
discrete and continuous could be tracked using tags and ubiquitous readers. The advantages of this approach are ease of locating objects, automation of information retrieval about objects, and standardized way to manipulate the information.

Future use of single bit sensors could be in the mechanical systems, primarily for maintenance purposes. Imagine a car that has miniature sensors inside its components that track and diagnose the condition of auto parts. A sensor could be combined with a tag to allow integration of the entire automobile system into the Web. A company that services cars could retrieve information about a status of the components in the car via the Web and suggest the repair to an automobile owner before the failure occurs. This preventive maintenance should not add excessive expense of implementation and should be cost effective. Cost effectiveness would show in preventing of a major failure that could start with failure of a single sub-component. If that sub-component could be diagnosed as being faulty beforehand, the cost of maintenance could go down because replacing the faulty component would preserve the rest of the system.

New tag-based technology presents tremendous opportunities for robotics research. Robots capable of finding objects in their working space which does not need expensive computer vision hardware and software could be developed. For example, imagine a task where robot has to pick up a can of soda, open it and pour it in a glass. A tag attached to a can would transmit an information to several readers. These readers determine object's location. Furthermore, readers could locate a web site with object's Object Description Language (ODL) file describing the information about object's geometry, weight, material properties and other information useful to a robot. Robot command inputs would come straight from the ODL file and there would be no need for complex and expensive object recognition software and hardware. Coke would simply "tell" a robot how to pick it up and where it is located instead of robot trying to figure all this out itself. Savings in hardware and software obtained with this approach would be significant. The tag-based technology would be relatively cheap once the infrastructure is in place.
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David L. Brock.

G. Chryssolouris, M. Domroese, P. Beaulieu
Presented at NAMRC, May

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Flanagan, David.
A.1 Poisson Distribution Function

**Table A3.1 Poisson Distribution Function**

\[ P(X \leq x) = F_X(x) = \sum_{k=0}^{\infty} \frac{\lambda^k}{k!} e^{-\lambda} \]

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A.2 Network Specifications

The communication protocol used in the server-client design is TCP/IP. TCP/IP stands for “Transport Control Protocol/Internet Protocol”. TCP and IP are really two different protocols, but together govern the basics of the Internet. TCP is all about ensuring that data is transmitted correctly between two computers. If any errors occur, these are detected and data is retransmitted. If data sent to a particular machine had to be divided into smaller pieces, called data packets, and sent separately, all of these packets are reassembled on the receiving end in the correct order. The Internet Protocol (IP) uses a four-byte value to identify computers over the Internet. This value is called the IP address. In addition to the IP addresses, there is one more piece of information that distinguishes where the data should go, which is the port number.

By convention, port numbers are divided into two groups. Port numbers below 1024 are reserved for well-known system uses such as Web protocols, email, ftp, and so on. The numbers above 1024 up to $2^{16} - 1$ are left to the user who can assign personal programs and services to these port numbers.

The combination of IP address and port number uniquely identifies a service on the machine. Such a combination is known as a socket. A socket identifies one end of a two-way communication. When a client requests a connection with a server on a particular port, the server identifies and keeps track of the socket it will use to talk to the client.

Even though the server is communicating over the same port with many clients, it uses these sockets to determine the destination and source of that communication. The figure A.1 illustrates this concept.

![Figure A.1: Server – Client Communication via Sockets](image-url)
The server listens for connections on a particular port; when it receives a connection, it obtains a socket to use for the communication and begins a dialog with the client at the other end of the socket. The client initiates the connection and communicates with the server via this socket as shown in figure A.2.

Figure A.2: Basic Interaction between a Client and a Server