# Intelligent Robot Trends and Predictions for the New Millennium

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**ABSTRACT**

An intelligent robot is a remarkably useful combination of a manipulator, sensors and controls. The current use of these machines in outer space, medicine, hazardous materials, defense applications and industry is being pursued with vigor but little funding. In factory automation such robotics machines can improve productivity, increase product quality and improve competitiveness. The computer and the robot have both been developed during recent times. The intelligent robot combines both technologies and requires a thorough understanding and knowledge of mechatronics. In honor of the new millennium, this paper will present a discussion of futuristic trends and predictions. However, in keeping with technical tradition, a new technique for "Follow the Leader" will also be presented in the hope of it becoming a new, useful and non-obvious technique.

Today's robotic machines are faster, cheaper, more repeatable, more reliable and safer. The knowledge base of inverse kinematic and dynamic solutions and intelligent controls is increasing. More attention is being given by industry to robots, vision and motion controls. New areas of usage are emerging for service robots, remote manipulators and automated guided vehicles. Economically, the robotics industry now has more than a billion-dollar market in the U.S. and is growing. Feasibility studies show decreasing costs for robots and unaudited healthy rates of return for a variety of robotic applications. However, the road from inspiration to successful application can be long and difficult, often taking decades to achieve a new product. A greater emphasis on mechatronics is needed in our universities. Certainly, more cooperation between government, industry and universities is needed to speed the development of intelligent robots that will benefit industry and society.

## 1. INTRODUCTION

From the dawn of written history of our civilization (about 4000 BC), one can see a pattern. When humans work in teams focussed to solve common problems, they generally solved them. By necessity or choice, they encouraged or permitted others to perform specialized jobs, performing feats that could not be done by everyone. The result of this *direction of specialists* was that the societies (which at first were city-states) benefited in terms of safety, wealth and power. Engineers, mathematicians, doctors and artists were among the specialists that were builders of the great kingdom of Egypt about 3000 BC. Now 6000 years later, many benefits have accumulated but many problems remain to be solved.

Early writing using a picture language and wedge-shaped markings on clay, cuneiforms, was developed by the Sumerians and picture writing on paper, hieroglyphics, was developed on papyrus by the Egyptians.[1] This *curious interest in pictures and their content* has evolved into the *science of imaging* which today is still growing and improving the quality of human life.

On the eve of the new millennium, it is appropriate to think of the current common problems which this powerful and historically proven, technology of imaging science, has impacted. This study has led us to the consideration of intelligent robots that could have significant impact in the future. Perhaps this will permit us as stated by Patch Adams: "to look past the problems into the solutions."

Only 1000 years ago the average life expectancy was about 30 years. Men might live to 47, women to 44 but infant mortality rate was about 40%.[2] The most obvious beneficial effect today is that men might live to 80, women to 100 and the mortality rate for children is far less.

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We live in a truly amazing, high technology world. The state of the art has a host of known problems with known solutions. The World Wide Web is making a tremendous amount of information available to everyone. Computers can now even be obtained free. However, from reading the newspaper, I believe the following pressing current problems are known but not solved. I have divided them into two topical issues: social and physical.

**SOCIAL**

Peace. World peace is still not within our grasp. Defense is absolutely essential in order to survive.
Hunger. People are still starving. Food is not distributed to everyone.
Disease. AIDS and other diseases are for the most part unchecked.
Injuries: People kill people. Machines kill people.
Human resources. People are not used effectively. Over 1 million people are in jail in the US.
Prejudice. Intolerance of humans by humans causes many problems.
Jobs: A healthy economy is very important.
Morality. Humans are not naturally good.
Population. The world population is still increasing.

**PHYSICAL**

Climate. The weather is not controlled and can be devastating.
Environment. Our world is being threatened by our technology.
Energy. Energy is a scarce resource. Oil and coal will run out.
Other natural resources. Everything we need is limited.
Life on earth. Extinction of species, even the human species, is conceivable. We are not totally safe.

These problems are known but the solutions seem to be unknown. Solutions that require changing human nature are difficult indeed. Each new generation must again be taught to play nicely together and share and educated in the wealth of technological information that is our heritage.

Different classes of problems that are quite difficult to solve are the ones that are unknown. Unknown diseases, events from outer space, what will happen when we really understand the human brain are a few possibilities. Perhaps our greatest danger comes from the unknown.

## Users and Developers

There are needs for improvements in every field of human endeavor. Some of the improvements can be made through the use of intelligent robots. Most notable are situations which are dangerous for humans such as in outer space, under sea, under ground, as well as on the ground such as in a war zone or a left over mine field, in a volcano or earthquake or in man made situations such as in heavy traffic. In these situations it may not be possible to cost justify the robot in terms of a return on investment. However, saving lives or exploring the world and universe, are worthy goals. In other situations such as mass production where tasks must be performed repetitively perhaps millions of times per year, one can compare human and machine labor both technically and economically. In these situations, a cost justification can be developed to show that an investment in automation will, in fact, produce as good or better return on the capital investment than a standard saving method. Industries that recognize and use these advanced technologies will produce the highest quality goods at the lowest cost, capture the market for their products and lead the world.

## Money and Time

It is well known that economic advances require two components: capital investment and technical innovation. Advances in intelligent robots also require these components. Many real and perceived intelligent robots have been identified; however, only a few have actually been reduced to practice because one of the two required components was missing. One thesis is that technical innovation in intelligent robots is currently too difficult to be easily mastered by technologists. That is, in many cases we know what to do, but not how to do it in an easy, cost effective, state of the art, engineering manner. Another way to state this thesis is as a hypothesis: of 100 engineering or scientific readers of this paper, perhaps only one is capable of designing and constructing an intelligent robot in their working life time of 30 years. If this hypothesis were correct, then 30 brilliant engineers would need to work one year to develop one intelligent robot. Funding for projects of this magnitude are rare.

The remainder of this paper is organized as follows. In Section 2, some background in artificial intelligence and intelligent robots will be presented. In Section 3, some topics of mechatronics will be reviewed. In Section 4, an example of a new algorithm for a "Follow the Leader" intelligent system will be described. In Section 5, economic aspects will be presented. Finally, conclusions and predictions will be given in Section 6.

## 2. INTELLIGENT ROBOTS

Intelligent robots are an ideal, a vision. All one has to do to see the intelligent robot model is to look in a mirror. Ideally, all intelligent robots move dexterously, smoothly, precisely, using multiple degrees of coordinated motion and do something like a human but that a human now doesn't have to do. They have sensors that permit them to adapt to environmental changes. They learn from the environment or from humans without making mistakes. They mimic expert human responses. They perform automatically, tirelessly, accurately. They can diagnose their own problems and repair themselves. They can reproduce, not biologically but by robots making robots. They can be used in industry for a variety of applications. A good intelligent robot solution to an important problem can start an industry and spin off a totally new technology. For example, imagine a robot that can fill your car with gas, mow your lawn, a car that can drive you to work in heavy traffic, a machine that repairs itself when it breaks down, a physician assistant for microsurgery that reconnects 40,000 axons from a severed nerve.

Intelligent robots are also a reality. Many are used today. Many more prototypes have been built. Typical applications are: high speed spot welding robots, precise seam welding robots, spray painting robots moving around the contours of an automobile body, robots palletizing variable size parcels, robots loading and unloading machines.

The components of an intelligent robot are a manipulator, sensors and controls. However, it is the architecture or the combination of these components, the paradigms programmed into the controller, the foresight and genius of the system designers, the practicality of the prototype builders, the professionalism and attention to quality of the manufacturing engineers and technicians, that makes the machine intelligent.

Just where is the intelligence in an intelligent robot? It is in the controller just as the intelligence of a human is in the neural connections of the brain. However, it is only possible to see this intelligence through some action just as it would not be possible to see intelligence in a comatose human. Where does the intelligence come from? The control program and architecture provide for real time responses to a variety of situations. If these responses are intelligent, then the robot appears intelligent.

When are intelligent robots needed? When a task is repetitive such as making a million parts per year, automation is needed. The most suitable automation may be an intelligent robot. Also, when a task is hazardous for humans, automation is needed. The best solution may be an intelligent remote manipulator. Finally, when an industry needs to be internationally competitive in cost and quality, automation is needed. Again the intelligent robot may play a significant part in the solution.

What are the benefits from using intelligent robots? Robots can do many tasks now. However, the tasks that cannot be easily done today are often characterized by a variable knowledge of the environment. Location, size, orientation, shape of the workpiece as well as of the robot must be known accurately to perform a task. Obstacles in the motion path, unusual events, breakage of tools, also create environmental uncertainty. Greater use of sensors and more intelligence should lead to a reduction of this uncertainty and because the machines can work 24 hours a day, should also lead to higher productivity. More intelligence could also lead to faster, easier setups and reduced cycle times. More intelligence should also lead to faster diagnosis of problems and better maintenance for the systems. Finally, there is the fact that to remain internationally competitive, the best technology usage is required. Waste of human or material resources is too expensive for industry and for society.

Since this paper is about factory automation, which may not be obviously considered high technology, let us begin with a few definitions. Intelligence is the most outstanding human characteristic; however, it is still not totally understood and therefore has many varying definitions, implied meanings, and levels of sophistication. Human intelligence is defined in Webster's dictionary[3] several ways. Consider the two following.

1. The capacity to acquire and apply knowledge. This capacity may lead to the ability to learn or understand or to deal with new or trying situations.
2. The faculty of thought and reason. This faculty may lead to the ability to apply knowledge to manipulate one's environment.

Studies in Artificial Intelligence (AI) attempt to implement the first definition of learning or understanding usually with a mathematical or computer algorithm. Research in Machine Intelligence (MI) is directed toward designing new, useful, adaptive machines. Some of the goals of AI are:

- Finding new methods for extracting useful information from the environment using sensors.
- Developing methods for building, updating, mining and retaining information from a knowledge base.
- Inventing algorithms for utilizing information stored in a knowledge base to make intelligent decisions.
- Finding improved methods for translating user needs into a workable software system.
- Developing reusable software components that can expand toward an ultimate software system.

Why all the emphasis on computers and AI if we are talking about mechanical robots? Genetic engineering aside, it is only with computer control that we have any possibility of building an intelligent robot. Any comparison of the complexities of a human arm and a manipulator arm show how little we still know about arms. The best prosthetics today are poor substitutes for the originals. Also, designing a robot requires the use of many computer tools such as symbolic computation of non-linear inverse kinematic and dynamic equations, simulation of control characteristics, simulation of manipulator motions and interactions, path planning, obstacle avoidance, self diagnosis, self repair, etc.

Robot intelligence implies doing something in the real world and is often taken as the ability of a robot to adapt to changes in its environment, and possibly to learn from these adaptations. Intelligence is a difficult characteristic to guarantee in either humans or machines and is not mentioned in either the industry or standard definition. Intelligence cannot be easily measured. Only in science fiction does one try to defend a robot gone awry as lacking intelligence. In our world, the designers, manufacturers and users must answer and often pay dearly for design mistakes and manufacturing flaws.

The Robotics Industries Association (RIA) [4] definition of an industrial robot is: “a reprogrammable multifunctional machine designed to manipulate materials, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks.”

The definition according to the International Standard ISO 8373:1994(E/F) for a manipulating industrial robot is: “An automatically controlled, reprogrammable multi-purpose manipulator programmable in three or more axes, which may be either fixed to place or mobile for use in industrial automation applications.

A trend[3] is: “a general inclination or tendency; a direction of movement, a course, a move in a specified direction.” A factory is: “a place where goods are manufactured, a plant.” Automation is: “automatic operation or control of a process or system or of equipment; the techniques and equipment used to bring about automatic operation or control; the condition of being automatically controlled or operated.”

## 3. MECHATRONICS

Mechatronics is a methodology used for the optimal design of electromechanical products[5]. The Mechatronics system is multi-disciplinary, embodying four fundamental disciplines: electrical, mechanical, computer science and information technology. The mechatronics design methodology is based on a concurrent, instead of sequential, approach to design, and the use of the latest computer tools, resulting in products designed right the first time. Mechatronics covers: modeling and simulation of physical systems; sensors and transducers, actuating devices, hardware components for Mechatronics; signals, systems and controls; real- time interfacing; advanced applications and case studies.

### NEW ROBOT MANIPULATOR DESIGNS

In 1985, the four common types of robot manipulators were the Cartesian, cylindrical, spherical and vertically articulated or anthropomorphic designs. Then the horizontally articulated or Selective Compliant Articulated Robot for Assembly (SCARA) was introduced. In 1995, a totally different design, a tricept, Stewart platform was displayed at the Robot and Vision Exhibition by Comeau. It was advertised as being as flexible as a robot, as precise as a machine tool and strong as a press. It seemed ideal for press fitting bearings and other tasks requiring thousands of pounds rather than tens or hundreds of pounds of force. Nearly all industrial manipulator arms can be classified into one of six categories: Cartesian, cylindrical, spherical, vertically articulated, horizontally articulated (SCARA) or Steward platform types. New designs are still possible.

## FASTER

Rotational speeds of robot manipulator links of 240 degrees/second are typical. For a 1-meter joint length, this would produce linear speeds of 4 meters/second. The overall cycle time is usually more important than individual link speeds. In a great variety of applications, robots are easily made as fast or faster than humans.

## SMALLER

> "Many manufacturing applications have emerged that can't be successfully performed without robots. In the electronics industry, miniaturization is driving the demand for robots. 'The trend toward further miniaturization of products like pagers, cellular phones, and two-way radios makes it virtually impossible for humans to repeatedly place, weld or solder components accurately,' according to Jim Hager, Site Manager, Motorola Manufacturing Systems, Boynton Beach, Florida. 'Good robotic systems can handle these tasks and help Motorola achieve Six Sigma quality."[6]

Micromechanical manipulators, molecular robotics, nanorobotics are names applied to the emerging field to produce new materials and devices at a nanometer scale, perhaps by direct interaction with atomic structures[7].

## REPEATABLE

The repeatability of an industrial robot refers to its ability to return to a previously taught point in space with a certain precision. Typical repeatability is on the order of + or – 0.1 mm (+ or **-** 0.004 inch). Accuracy is the ability to go to a target point in space and generally can be achieved with a calibration setup. The trend is to make the robot as repeatable as required by the application.

## SAFER

Both industrial robots and automated guided vehicles are potentially dangerous since they move. Industrial robots in the U.S. have killed people. Safety requires administrative controls, engineering controls and training. Administrative controls such as restricted use of the equipment to qualified personnel, proper maintenance and management insistence on safe operation, is vitally important. Engineering controls such as protective fences with safety interlocks on entrances, pressure sensitive mats and light curtains, all properly installed and maintained are also more commonly used than a decade ago. Training is also important and should not be overlooked especially when a company is downsizing. Safety is not something that can be relaxed. However, more safety features and self **-**diagnostics can be built into the robots and work cells. Also, the use of simulations to discover interferences and potential collisions is a step in the direction of safe application.

## EASIER

Using an industrial robot is easy but putting it into an intelligent workcell requires much more than the robot. Important accessories such as grippers, process tooling, safety devices, programmable logic controllers, simulation programs, etc. are needed to make robots easier to use. As an example, Adept has published the Adept MV Partner Catalog[8]. This book provides a listing of sources of third party components that have been certified to be compatible with Adept's MV controller based products. System integrators can readily incorporate these products into their designs by utilizing the product specifications, technical notes and expert resource contacts to reduce engineering time and risk.

### OPEN ARCHITECTURE CONTROLS

The control system is the set of logic and power functions which allows the automatic monitoring and control of the mechanical structure and permits it to communicate with the other equipment and users in the environment. Open architecture control refers to software designs that can use or be used with products from a variety of manufacturers. The move toward open architecture controls is relatively recent but follows the trend in computers that caused a tremendous explosion in usage.

### THEORETICAL KNOWLEDGE BASE

#### Inverse Kinematic Solutions

Most industrial robots are operated in position control mode as contrasted with velocity or force control. To move the motors to position a robot manipulator in space, an inverse kinematic solution is needed. The inverse kinematic solution must be discovered for each new manipulator design. Developing forward kinematic equations and solving them symbolically provides a mathematical result that can be used by anyone, forever.

**Inverse Dynamic Solutions and Experimental Designs**

Even though industrial robots are position control devices, the path between position points can be extremely important, for example, in seam welding. Since any moving system is described by a dynamic differential equation according to Newton's Second Law, the dynamic solution must also be determined in the design of a robot. This dynamic solution should be used in the design of the control system. It may not be obvious that a control system as simple as that of a robot manipulator cannot be theoretically proven to be stable. However, the dynamic system is non-linear and subject to noise from various sources. Criteria for practical stability rather than optimal stability are used today. A variety of motion control solutions have been developed but a greater understanding of non-linear systems is needed.

**Integrated Robots with Vision and Sensors**

For the industrial robot to be intelligent and adapt to changes in its environments such as part location, orientation, size, shape, sensors are needed. Vision is the most powerful sensor for humans and machine vision also adds adaptability to industrial robots which makes them intelligent. Many robot manufacturers now offer integrated vision and robotic systems.

**Simulators and Code Generators**

In the design of a robot work cell, a three dimensional simulation permits one to observe interference, avoid collisions and determine feasibility of an operation. In some modern simulation software, once a series of motions are selected, the robot code generator program can translate the motions into robot programming language automatically and download this program to the robot. This is a major simplification and improvement.

## AUTOMATIC GUIDED VEHICLES

Automatically guided vehicles are becoming more feasible in factory automation. An excellent compilation of information on air, ground and undersea-unmanned vehicles was recently published.[9] The development of practical and useful unmanned autonomous vehicles continues to present a challenge to researchers and system developers. Educators are also using these challenges. Building a mobile robot is an excellent way to teach robotics. It's challenging and fun.

## SERVICE ROBOTS

The service robot area is also growing. The International Service Robot Association is an individual and corporate member organization devoted to the application of robot technology to human services such as health care, education, security, space, and undersea exploration and related non-manufacturing areas. Examples of service robots include hospital food delivery robots, sentry robots, robot lawn mowers, robot vacuum cleaners, inspection robots, etc.

## ROBOTS, VISION and MOTION CONTROL

The combination of robots and vision with the motion control is a trend toward understanding all the components of the intelligent robot, the manipulator, the sensors and the controls. If engineers can understand all the elements, i.e. Mechatronics, then some exciting new products and applications will be forthcoming.

# 4. SELECTED EXAMPLE – FOLLOW THE LEADER

An interesting problem in truck or tank convoys gives rise to a problem called “Follow the Leader.” A similar problem in the air is called “Lead – Pursuit.” A lead vehicle, perhaps driven by a human, can follow any arbitrary path. The following vehicle, perhaps a robot, must follow this vehicle at a given distance either by tracking either a target on the vehicle or the entire vehicle. In this example, we describe the use of a unique vision sensor, the omnidirectional vision system and the techniques required for following the leader and controlling a mobile robot.

The leader vehicle is shown in Figure 1 and consists of a ride lawn mower with a white and black target about the size and location of a read license plate.


Figure 1. Leader vehicle and target. This vehicle was used for the Follow the Leader contest at the 7th International Ground Robotics Competition that was held on June 7, 1999 at Oakland University. The 8th IGRC is planned for July 7, 2000 at Disney World. Further information can be found at the WWW site: http://users.erols.com/auvsicc/.

Dynamic, omnidirectional vision guidance was used[10]. The actual system is shown in Figure 2 and consists of an omnidirectional vision system mounted on the Bearcat II mobile robot. The real time video information is fed to an Iscan image tracker. Either the entire vehicle or the target can be selected for tracking. Also, either dark or light blobs may be tracked. The measured position of the target, in terms of azimuth angle and following distance may be compared to the

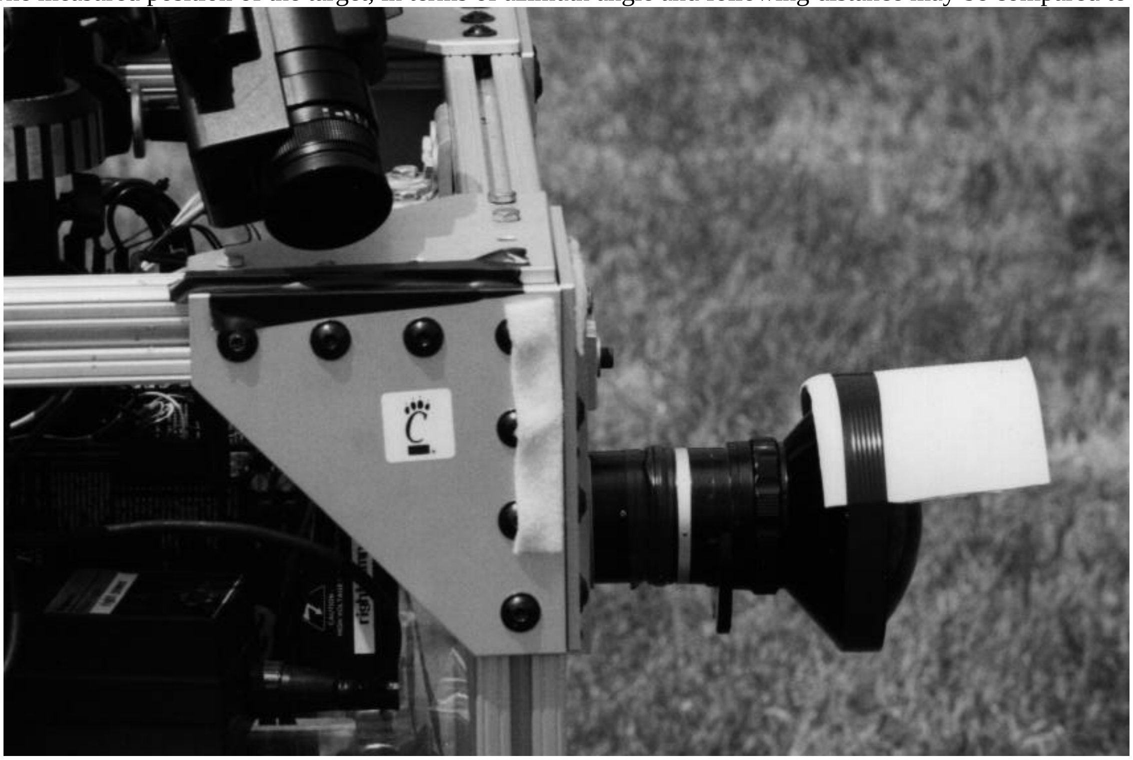

Figure 2. Wide-angle lens mounted on Bearcat II mobile robot.

desired angle and distance and commands sent to the robot to change the steering angle and velocity to implement path correction.

The vertically mounted fisheye lens and camera is shown in Figure 2. In this orientation, one may describe a global coordinate system with an origin at the lens center of the camera, with the x-axis across the track, the y-axis down the track and the z-axis pointing up. The orientation of the robot requires three angles: a roll angle, θ, (rotation about the y-axis), a pitch angle, ϕ, (rotation about x-axis) and a yaw angle, γ, (rotation about the z-axis). A spherical coordinate system is natural for the imaging geometry. Two pointing angles, an azimuth angle, θ, (rotation about the y-axis) and an elevation angle, β, (rotation about x-axis) and a radial distance, R, then describe a point in physical space as (R, α, β).

The view in the circular fisheye image can be described with respect to its center ($x_c$ ,$y_c$ ), in cylindrical coordinates with a radius, r, and an azimuth angle, θ, to describe a point in image space as (r, θ). A sample image is shown in Figure 3.

Two properties of the wide-angle lens may be used in a tracking algorithm. One is that the azimuth angle to an object point is invariant to both elevation and object distance. Next is the linear relationship between the between the radius to an image point and the elevation angle, β.

The calibration procedure[11] consists of measuring the location of the image center ($x_c$,$y_c$ ), and determining one constant of the lens, C1. If these values are known then for each new point ($x_i$,$y_i$) from the tracker, one may compute

$$r_i = \mathrm{sqrt}(\ (x_i-x_c)^2+ (y_i-y_c)^2\ ) \qquad [1]$$

$$\theta_i = \mathrm{atan}(\ (y_i-y_c)/\ (x_i-x_c)\ ) \qquad [2]$$

Figure 3. Sample fisheye image.

At this point there are two choices. One is to use the calibration values and compute the elevation angle and projected radius, then compute the 3D distance using equations [3-5]. If the height, H of the lens is known, then one may compute:

$$\beta_i = C_1 r_i \qquad [3]$$

$$R_{XYi} = H \tan(\beta_i) \qquad [4]$$

$$R_i = \text{sqrt}( R_{XYi}^2 + H^2) \qquad [5]$$

Then with the radius, azimuth and elevations angles known, one may compute the three dimensional position of the target.

$$x = R \sin(\beta) \cos(\theta) \qquad [6]$$

$$y = R \sin(\beta) \sin(\theta) \qquad [7]$$

$$z = R \cos(\beta) \qquad [8]$$

A new algorithm is under development by Mundhenk that does not require the height to be known. This new algorithm is being studied but appears promising. Early experimental results are shown in Figure 4.

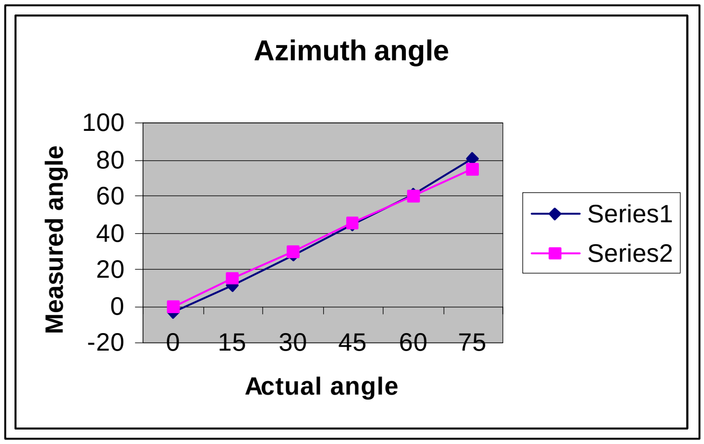


Figure 4. Experimental measurement of the robot tracking algorithm.

An alternative method to measure the range is also available. A sonar system mounted on a rotating motor may be directed to the azimuth angle of the target and the elevation angle assumed to be small. Then the sonar range is used for the distance measurement. The sonar control system is described in [12] in more detail.

The advantage of this omnidirectional vision method is that since the lens has an extremely large field of view; it should be able to follow the target dynamically even though the target moves on a very tortuous path. And if total target tracking is used, the leader vehicle could even turn 180 degree without the system-losing track. This helps prevent the following robot from becoming lost. There are many other situations that could occur in this game, such as the leader turning and colliding with the follower. In such cases more sophisticated AI techniques would be needed to change the game from follow the leader to escape from the leader. Also, other wide-angle mappings such as described in [13] could be studied.

## 5. ECONOMIC ASPECTS – BILLION DOLLAR MARKET

Recent reports regarding the use of industrial robots are encouraging as shown in the following quotations from Donald Vincent, Executive Vice President of the Robot Industries Association[14]:

> "The North American robotics industry sold more robot in the first quarter of 1999 than in any quarter since the industry began collecting statistics in 1983. A total of 4,732 robots valued at $362.8 million were sold, which is an increase of 67% in units and 24% in value over the first quarter in 1998."
>
> "RIA estimates that some 92,000 robots are now at work in American factories and that the automotive industry accounts for at least 50% of all robot orders, with electronics, food and beverage, pharmaceutical, consumer goods, aerospace and appliance accounting for the majority of the other sales."
>
> "This is just a fraction of the potential market, since thousands of companies that could benefit from robots, particularly small and medium-sized companies, haven't purchased even one robot yet."

### AGE of REALISM in ROBOTICS

New technologies go through a pattern of usage starting from zero, then increasing perhaps too far, then coming down then, then reversing and going steadily upward until the reach a downward turn at the end of their useful period. When a technology is first introduced, we may expect more than it can deliver. This period has been called the Age of Overexpectation. Following is a period of disillusionment in which less is expected than the technology can actually deliver. This period is called the Time of Nightmare. Finally, reality sets in and we learn to expect only what the technology can deliver -- the Age of Realism. The industrial robot has now reached this age of realism. The U.S. has a solid base of nearly 92,000 successful installations.[13] Broadening the robot definition to include automated guided vehicles, remote manipulators which must be supervised by a human as well as totally programmable robots, and a growing interest in personal and service robots has strengthened the technology base even more.

Robotics has today developed into a solid discipline that incorporates background, knowledge and creativity of mechanical, electrical, industrial and computer engineering and other engineering and scientific fields. However, there are still many challenges, unsolved problems, and needed inventions.

### CHEAPER

Cost is a difficult concept to pin down since there are a great variety of industrial robots and an even greater variety of applications. To provide an estimate, the following data from the RIA records for the first quarter of 1999 of shipments and new orders indicates that $362.8 million in new orders of 4732 robots gives an average cost of $76,864. Another estimate was observed in the results of robotics application feasibility studies for a variety of applications done by the engineering robotics students for 1997. In these studies, each student selected his/her application. Then they examine the characteristics of the application and determine the requirements for a robotic solution. They then select three candidate commercial robots, design a work cell with one or two robots, and perform a cycle time analysis and an economic justification. The average robot cost from 14 different applications was $69,141. The average internal rate of return on these robotic investments was 98%.

The internal rate of return may be interpreted as the return on the investment in automation. The reciprocal of the internal rate of return is the payback period or the time in which the investment will be recovered. After the payback period the automation equipment is producing wealth. Interestingly, in almost all industrial applications with sufficient production, a robot installation is nearly always feasible. The question is whether the rate of return is sufficient. An internal rate of return of 50% or a payback period of two years is often suggested for industrial applications. This is not the case for all robotic applications. For example, robots in most space, undersea, environmental, defense and service applications are not yet proven technology and cannot be easily cost justified using the internal rate of return concept. This is not to say these are poor investments, but rather like education and research, vitally important activities that will pay off in a longer term.

### MORE NUMEROUS

The growth of the robotics field in the U.S. is indicated in several ways. In 1982 the RIA indicated that 6300 industrial robots were in use in the United States with 2453 used for welding, 1060 for machine loading and unloading, 875 in casting, 1300 in material handling, 490 in painting and finishing, and the remaining 122 for assembly and other areas. According to the RIA more than 92,000 robots were at work in U.S. factories[14] in 1999.

The number of robots in use tells one important part of the story; however, another important aspect for the U.S. is the technology base of trained engineers and technicians who are familiar with industrial robots. A search of the World Wide Web resulted in more than 3,500 robotics references. The number of people is increasing who have interests and training in the cross disciplines of mechanical, electrical, computer and industrial engineering, “mechatronics.” These manufacturing engineers and technicians no longer look at a task or a machine and see only the operating machine but also appreciate that the concurrence of all components and the consensus of all the humans involved are required for a successful product. Whether this concept is called total quality, consensus management, or customer awareness, it has been an important lesson to learn.

### STILL BEHIND JAPAN

Even though the US market is healthy and growing, there is the fact that the US is still significantly behind Japan in the use of industrial robots, automated guided vehicles and mechatronics. The Mazak Corporation is a good example of a worldwide leader in advanced manufacturing technology. The company president, Teruyuki Yamazaki has stated[15] “The greatest secret in promoting marketing activities efficiently is to get a grasp of exactly what the market requires and to develop and offer to the market those products which will sell even when there is a recession.” Robots can play a significant role in improving productivity, quality, and flexibility and time to market. The 1998 RIA estimate was that the Japanese had more robots in use than the entire rest of the world put together[3].

## 6. CONCLUSIONS and PREDICTIONS

Intelligent robots for industry make sense technically, economically and socially. Robotic devices that increase the level of flexibility of industrial automation can directly lead to improved productivity. The feasibility of a successful implementation is high. Also, such automation is a good investment. Repetitive jobs which a robot can do, such as applying sealant to rear windows of an automobile at the rate of a million per year, or stacking boxes at the rate of 360 per hour, are unfit for humans since repetitive motions by humans lead to cumulative trauma disorders.

It appears that most advances in intelligent robots have been “bottom up” applied research. One application at a time is being solved. Furthermore, this advance is being funded directly by industry. The limitation of this bottom up approach is that only low risk technology will be developed. If industry limits research to current products, where will new products come from?

There is also a need for "top down", high risk, research and development. New ideas need to be tried. Theoretical research that can be used by everyone and may never be seen from the bottom up use of existing technology, needs to be funded by the government. A new robot could not or should not be built until the inverse kinematic and dynamic solutions are known. Theoretical advances are needed in intelligent control theory that would at least enable us to say that robots are stable and controllable and safe before millions of these devices are put out in society. Sensor integration can be attempted in a research environment much easier that in an actual application.

Experimental robotic projects need to be encouraged in engineering schools so that our engineering students learn the fundamental principles of mechatronics in school, rather that on the job. Doesn't it make sense for our universities and colleges to have the latest and greatest engineering software and hardware tools so that the graduates can take this knowledge directly to industry?

The intelligent industrial robot is not a panacea; however, the goal of building an intelligent robot is a worthy one and leads to continual improvement. A robotic solution may be the best technically, economically and socially. However, the road from inspiration to successful application is still long and difficult, often taking decades to achieve a new product. Our students need Greater understanding of mechatronics. More cooperation between government, industry and universities is also needed to speed the development of intelligent robots that will benefit both industry and society.

## SAFE PREDICTIONS

Robots play golf, weld, spray paint, assemble, handle materials, load and unload machines, sheer sheep, mow lawns, cut trees, pick oranges, solve Rubik's cube, play checkers, play black jack, play board games, fill cars with gas, make milk shakes, package hamburgers, deliver food to patients in hospitals, brain surgery. All these have been done by prototype systems at least. Some have made it to market. Others are on the way.

## FUTURISTIC PREDICTIONS

As stated 15 years ago [16]: "The ultimate goal of the use of robots always should be to help, not hurt us. This calls for thoughtful planning, intelligent policies, and foresighted decisions on the parts of leaders in field that will use robots, from factory owners to medical researchers. We are approaching a new era in our continuing industrial evolution. It can mean freedom from all mindless work, freedom to develop our uniquely human abilities to their fullest extent, and freedom to explore the frontiers that we could never physically explore ourselves. Continued sensitivity, however, to the effects of technology on all people is of paramount importance for the wisest and happiest implementation of this new technology."

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