Robotics

2. Instrumentation and Control in Robotics

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In this part of the article, the robot that was introduced in Part 1[1] is expanded, by imparting to it some intelligence – explaining how the robot functioning is controlled. A brief description of the measurements involved is also discussed.

Introduction

Basically, the developments in two other related subjects, instrumentation and control engineering played a major role in aiding the rapid development of the field of robotics. By instrumentation, we mean the various sensing devices called the *sensors*; and by control, we mean the achievement of the final goal effectively, while maintaining the stability of the robot.

Instrumentation

Every animal has five basic senses – vision, hearing, smell, touch and taste. And we as human beings with an extra power of thinking have tried to develop devices that can detect/analyze the above (except smell and taste, perhaps). We have also developed devices to detect various other parameters like temperature, pressure, density, level, etc. These when integrated into a robot boost its capabilities. Obviously, the sensors that are used in a robot depend on the application and the environment in which the robot is to work.

One of the most important sensors is the 'eye' or the vision sensor. It can be a simple camera that can follow the path of an object, as in the case of a robot that catches a ball based on the signals from two cameras that track the motion of the ball. We have been able to impart 'insect vision' (found in insects like bees and houseflies) to the robots but have been unsuccessful with 'human vision'. Insects have many small eyes (ommatidia)

[1] Part 1. Components and Subsystems, *Resonance*, Vol.4, No.12, p.76–82, 1999.

arranged on the surface of a sphere providing them with a mosaic view known as the 'compound eye vision'. This has been emulated in robots by using pixelated arrays of visible light and infrared detectors. The mosaic image thus obtained is further processed leading to the compound eye vision of the robot.[4]. To overcome the lack of 'proper vision', many other sensors have been designed. Consider the following example.

One of the simplest binary touch sensors is made using whiskers, which close or open a switch when they touch an object.

In the case of a welding robot found in the automobile carrier line, the robot has to keep the welding rod (tip of the rod) at a constant distance from the surface being welded. The simplest way to do this (without an eye) is to fix an origin and move the end of the rod (fixed to the robot arm) along a fixed set of points. As the reader would have guessed, this system has a problem; one cannot be sure that the welding rod is at the right position (it will follow the same route even if there is no welding rod at all!). So, one would like to have a device that would detect whether the welding rod is at the right position. This device would be a *position sensor*.

Another important sensor is the touch sensor. This is required for two basic purposes – presence detection (*binary touch*) and characterisation. One of the simplest binary touch sensors is made using whiskers, which close or open a switch when they touch an object (they may use pressure to do the same). Another way of detecting an object is by using *proximity sensors*, which detect the presence of the object without touching it. In this, the sensor uses either reflected light, echoed sound or electromagnetic induction to detect an object. The development of characterisation sensors is much more sophisticated.

The human finger aided by the brain is the ideal goal for a touch sensor, as it can sense many characteristics, like shape, temperature, force, velocity, wetness, surface texture, vibrations and viscosity. One practical force sensor uses a pad of pins (like the head of a dot-matrix printer). When force is applied to the pad by an object, a *force image* of the outline of the object pressing against it is traced, which is used to detect the shape.

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The robot to protect itself is provided with sensors that can monitor 'its environment' and 'itself'. The robot has temperature sensors and pressure sensors to detect the heat that it is exposed to and react appropriately. Underwater robots may have pH sensors in addition to the above.

The other measurements that are to be made are velocity, angular velocity and acceleration of the various joints/links, force/torque on the links/wrist, cartesian/angular position of the end effector, inclination of object, magnetic and electric fields, etc.

The sensors described above fall into either *external sensors* or *internal sensors*. An external sensor measures the environmental parameters and the robot parameters with respect to an external reference; and an internal sensor measures the robot parameters relative to its internal reference frame.

Though it will be easy to say which sensors are required, to design them and position them properly are herculean tasks. Design of the sensors for the robot has to take care of the following criteria:

- Size and weight
- Accuracy and precision
- Durability – protection against external effects
- Interchangeability – must be easily replaceable and hence must also conform to established standards
- Speed of operation

The positions of the sensors depend on the environment and the robot construction.

Control

All the above detectors and sensors are used only to measure a particular parameter and aid its *control*. So, control was very obvious all along, although the reader might not have realised it. A controller may be considered as a 'music director' conducting the various artists to present the audience with a pleasant score. Consider the case of the welding robot used in the automobile carrier line. Previously, the robot followed a fixed path called the *open loop system*. If the data from a position sensor is used to move the robot arm such that the actual position is maintained at the required value, *a closed loop system*, where a part of the output is fed back as input is obtained. The feed back is mostly negative.

Just as the feed back controller, feed forward controllers do exist. In feed forward controllers, the controller anticipates the error and gives an appropriate output (Consider walking down the stairs with the eyes closed). For further details on the open and closed loop systems, see [3].

The various control parameters required in the welding robot are:

- Current co-ordinates of the robot arm (each and every mechanical link/elbow) with respect to some global reference point.
- Current co-ordinates of the tip of the welding rod from the robot arm.
- Current co-ordinates of the surface being welded; with this data, it is possible to find the direction and to calculate the distance by which the arm of the robot (and hence the tip of the welding rod) is to move.
- The required position of the welding rod (this is what one is to achieve).
- Allowable speed and acceleration of the robot arm.
- Temperature of the weld.
- Environmental parameters – temperature, pressure, etc.
- The time available for welding.

Before actually controlling any variable, one has to design a controller for the same using all these specifications. The first step in this is to 'model' the given system. A model can be considered as a representation of a system, generally using

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mathematical equations. It can be either a continuous time model or a discrete time model and can be done using *transfer function/state space* and can be *linear/non-linear*. A complete explanation of the above terms can be found in Part 3 of [3]. A typical mathematical model for a robot is a second order nonlinear differential equation. More details on the same can be found in [2] and [5].

In the case of a robot, the various actuators and motors have to be modelled. The major advantage of modelling is that we are able to predict (to a large extent) the way the system would behave for various inputs without actually experimenting. Also one could simulate the results for various inputs and various initial conditions.

The next step in the design of a controller is to study the system behaviour (analysis) and thus decide upon a controller that will bring the output of the system to the appropriate value as per the specifications. Here again, one could first derive a mathematical model (for the controller) that will produce the desired results and then synthesize a physical device representing the same.

Generally speaking, the robot controllers are always *over damped* (see *Box* 3) although the ideal case will be a *critically damped* system. Take the example of the welding robot. If the system was *under-damped*, then the robot might try to force the rod into the surface to be welded, thus breaking the rod. If the system were *over damped*, then the robot movement becomes very sluggish. Hence most controllers are designed to give a near critically damped response.

The simplest form of a controller is the proportional controller (potentiometer/amplifier), whose transfer function is simply a constant (output and input are in direct proportion). Unfortunately, a proportional controller does not always do the job. Hence we are forced to use other controllers like the derivative or integral along with it. More complex designs would involve controllers with transfer functions with both the numerator and

Box 3.

Transfer function of a general second order system is

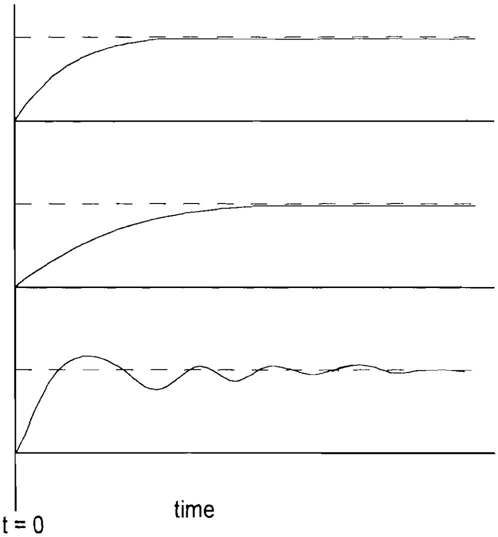
$$\frac{\omega_n^2}{s^2+2\xi\omega_n+\omega_n^2}$$

the system behaviour for various damping are shown aside

critically damped $\xi = 1$

over damped $\xi > 1$

under damped $\xi < 1$



denominator involving the Laplace operators; i.e., transfer functions involving poles and zeros (Refer Part 2 of [3]).

Control under Dynamic Conditions

As mentioned earlier, the speed of operation is very important in the design of a controller. When riding a motor cycle, one might have observed that at lower speeds (or when idling), the vibrations of the chassis are more than when riding at a higher speed. Also, when riding very fast, one would find it difficult to control due to sudden changes in the inertial loads. The same is the case with a robot. Hence it is essential to maintain the speed of motion of the robot at an optimum value; the design of the robot controller is based on this optimum value. Also, the inertial parameters of the robot may vary with the load upon which it operates. (An object moving robot might have to handle objects of different weights, sizes and mass distributions). Hence it is also essential to design controllers for an optimum load.

As mentioned earlier, the speed of operation is very important in the design of a controller.

A popular approach is the nonlinearity cancellation technique, in which the controller is designed so that it cancels out any nonlinearity in the system. This technique is referred to as the computed torque method or feedback linearization. Hence, the resultant system is linear and for this the controller is easier to design.

Software

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Software, in addition to acting as a binding thread for the various robot subsystems, plays an important role in control. Physical devices like amplifiers, integrators, differentiators, etc., can be replaced with equivalent programs, which are more reliable and produce better results.

Further, several processes (control loops) can be handled by a single processor very effectively. Now, with the advent of embedded chips, it is possible to program even in *high level languages* directly. A recent film, *Lost in Space*, starred Big Blue, a robot running on a Java embedded chip!

The advent of software controllers led to the development of the so-called intelligent controllers, viz., *fuzzy logic, neural networks, genetic algorithms*, etc. In a fuzzy logic controller, the controller uses a set of rules (called the *rule base* or *knowledge base*) to compute the output for a particular input. In neural network controller, the controller is first *trained* using one particular set of inputs and corresponding outputs. Thus, if the system input lies within the trained set of data, the controller gives the appropriate output. If the input is outside the training set, unfortunately, the result may be unpredictable. It has, however, the advantage of faster parallel processing. Readers can find further references to the above in [6], [7] and [8]. Fuzzy controllers from an industrial viewpoint are discussed in [11].

In a neural network controller, the controller is first *trained* using one particular set of inputs and corresponding outputs.

Concluding Remarks

Robots are fast replacing humans in places where humans behave like robots. One good example is the automated car driving developed by the Robotics Institute at the Carnegie Mellon University (www.ri.cmu.edu). In this project, a computer driven car was developed, reducing human drudgery and more impor-

Box 4. A Few Related Web Sites

www.robotwars.com	www.activrobots.com
www.solarbotics.com	www.mondo-tronics.com
www.robots.com	www.barrett.com
www.maths.usyd.edu.au:8000/jimr/pe/peregrinator.html –	www.telescope.org/rti/index.html
www.ee.rochester.edu:8000/users/weisberg/mouse.html	www.pbs.rog/wgbh/nova/robots
http://chaoskids.com/ROBOTS/robots.html	http://telerobot.mech.uwa.edu/au/
http://info.webcrawler.com/mak/projects/robots/robots.html	http://home.clara.net/roboter/

tantly providing safety using *collision avoidance strategies*. (An automated helicopter was also developed, which could follow a figure, say of a man, provided it is stored in it already!)

The day one expects androids to replace humans is far off. Mimicking human brain and the human system as a whole are as

Box 5. Robotics in India

Robotics, in India, is offered as a course in PG programmes in Mechanical Engineering in many universities (including IISc and IITs). The emphasis is on the mechanics of robots. Artificial intelligence and computer vision are generally offered in the Computer Science departments. The control aspects are usually at the PhD level in Electrical Engineering departments. At REC, Tiruchirapalli, a comprehensive course on robot dynamics, instrumentation and control is offered at the senior UG level in the Department of Instrumentation and Control Engineering. Efforts are currently being put to start a ME in Robotic Engineering from the year 2000. This would be the first PG program in India giving a degree exclusively in robotics.

The Department of Mechanical Engineering, IIT Bombay conducts Yantriki, a Robotics competition once every year. Now open to all colleges, it promises to be a ground for providing students an experience in innovation and development of robots right from scratch. This year, the game is Sumo Wrestling. More information on this can be seen at www.iitb.ernet.in/~yantriki.

The Defense Research and Development Organisation (DRDO) has set up a lab called CAIR in 1986 to conduct basic and applied research in the field of Artificial Intelligence, Robotics and Automation with emphasis on defense requirements. The Institute for Robotics and Intelligent Systems (IRIS) is a non profit society registered under the Karnataka Societies Act, under the Department of Defense Research and Development. The aims of IRIS are to popularize the technologies developed in CAIR for the benefit of society at large, including the Indian industry. BARC has already started using robots and has a Division of Remote Handling and Robotics. Public sector units like HMT and ECIL have R and D wings in Robotics and Automation.

Box 6. How can Robotic Spacecraft become Independent?

One of NASA's goals is to design exploratory spacecraft that do not need constant monitoring and control from Earth. Till now every single action by the spacecraft has been dictated by commands sent from the ground.

A new software system called Remote Agent literally runs the whole spacecraft, making situational decisions and carrying them out without consulting with Earth, even fixing problems all by itself. This saves money and time, and makes it possible to run more missions.

The first in-space tests of Remote Agent are now taking place aboard the Deep Space 1 craft as it flies past asteroids and comets. The spacecraft makes its own decisions about the course to take, basing them on camera views of the target and the rest of the Solar System.

More about Remote Agent: http://rax.arc.nasa.gov/saving.html
How it is being used by Deep Space 1: http://nmp.jpl.nasa.gov/ds1/tech/autora.html
Another Cool Fact about the Deep Space 1 mission: http://www.cool-fact.com/archive/1998/12/08.html
Excerpts from: The Learning Kingdom's Cool Fact of the Day for August 6, 1999
(http://www.LearningKingdom.com)

yet (fortunately!) out of reach of current technology. Our knowledge of the brain is far too scanty for the development of such technology, our knowledge may only be compared to that of a draftsman who is capable of copying without understanding. This again is an overstatement. Man has not yet been able to imitate smelling, the art of perfect vision or voice recognition! With the web boom, one sees a new class of robots called *soft robots* (the above discussion holds good for *hard robots*). A soft robot is an intelligent program that helps humans at work. A good example would be an intelligent web search engine, which searches the web for *only* what the user needs, for example, search for robots available for sale (and not those being researched) and downloads *only* the relevant information onto the hard disk, without affecting other processes running on the same system (the web search runs as a background process). It could also make purchases over the web for the user! Some more intelligence might be incorporated into it to make it search only during lean time when the cost is low. It could also perform periodic updates of the data already stored in the hard disk. These soft robots are also called *intelligent agents*. Readers may refer to [9] and [10] for details.

Robots that can be sent down the drainpipes to check for any leaks have been developed recently by an aerospace corporation. In this sewage pipe inspection system, two robot units are connected together and tethered to a support truck using long cables. Air pressure is applied between the two robot units and thus checked for any leaks. The air pressure, electrical energy and the control signals are all provided by the cables. Hence it becomes essential to control the cable tension very carefully in addition to preventing entanglements, failing which the robots could get stuck in the pipe. The initial approach to control this was by using conventional control. Finally, the solution to the control of the robot was implemented using fuzzy logic with about 200 rules for each robot unit. The fuzzy solution took only 10% of the time the conventional not so successful solution had taken.

Yet another development in the field of *hard robots* was the development of a *worm robot* by NASA. This highly mobile robot is activated by sets of spring-opposed shape-memory-alloy wires. Researchers believe that robots when fitted with micro-sensors could collect data from inaccessible locations and also search for survivors in a disaster stricken area (especially at earthquake hit places). Further information on this is available in [12].

Leonardo da Vinci possibly designed and built the first articulated anthropomorphic robot, called Leonardo's robot knight, between 1495 and 1497. The reader may think of this sentence as a misplaced one but this is purposely put here. For, to quote Mark Elling Rosheim [13], "Leonardo's powerful approach of linking kinesiology and anatomy, and translating them into kinematics and structure is a model for future lines of research". Robotics is still in its infancy. Robots have already been sent into unexplored areas in outer space, in the deep seas and on remote lands. Research is going on all around the world to further improve this branch of engineering science. Let us hope that this endeavour to help mankind succeeds.

Box 7. Unmanned Robotic Parachute

The US Army has developed a new robot guide that guides a parachute to a specific location with a high accuracy. The robot, named *Orion*, runs a program that maneuvers a parachute by pulling the appropriate strings of the parachute with enough force and in appropriate direction, depending on the wind speed and direction to reach its preset destination. It is guided by the GPS system. What more? Upon landing, Orion initiates a self-destruction procedure! It doesn't actually destroy itself – it destroys the program stored within it, leaving no trace of the path it traced even if it ends in the wrong hands. One immediate and potential use for this is in air dropping food packets in the war-prone areas, so that the food packets are not lost and land at the right destination. With this new advantage, the food packets can be dropped at a place far off from their actual destination and hence avoid any risk of the 'air plane being shot down'.

Courtesy:
Discovery Channel
(www.discovery.com)

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Suggested Reading

[1] Phillip John McKerrow, *Introduction to Robotics*, Addison-Wesley, 1991.

[2] Mark W Spong and M Vidyasagar, *Robot Dynamics and Control*, John Wiley, 1989.

[3] A Ramakalyan and J R Vengateswaran, Systems and Control Engineering, Parts 1, 2 and 3, *Resonance*, Vol. 4, Nos 1, 3 and 5, 1999.

[4] Vikram Dhar, Imaging Sensors: Artificial and Natural, *Resonance*, Vol. 4, No. 2, 1999.

[5] E Jean-Jacques, Slotine and Weiping Li, *Applied Nonlinear Control*, Prentice-Hall, 1991.

[6] Satish Kumar, Uncertainty in the Real World, *Resonance*, Vol. 4, No. 2, 1999.

[7] Satish Kumar, Managing Uncertainty in the Real World, *Resonance*, Vol. 4, No. 4, 1999.

[8] J R Roal and Sunilkumar S Mankame, Artificial Neural Networks, *Resonance*, Vol. 1, No. 2, 1996.

[9] Joe Kozma, Intelligent Agents, *IEEE Potentials*, April/May 1998.

[10] T B Rajashekar, Web Search Engines, *Resonance*, November 1998.

[11] Constantin von Altrock, Fuzzy logic merges with bang-bang, PID, *In Tech**, May 1999

[12] Technology Transfer – Biomorphic, robotic worm explorers tunnel ahead, *In Tech**, April 1999.

[13] Mark E Rosheim, In the Footsteps of Leonardo, *IEEE Robotics and Automation Magazine*, June 1997.

* InTech – *The International Journal for Measurement and Control* is an Instrument Society of America (ISA) publication.

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The most beautiful experience we can have is the mysterious. It is the fundamental emotion that stands at the cradle of true art and true science.

Albert Einstein