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Applications and Automation

Volume 1

RICHARD C. DORF

INTERNATIONAL ENCYCLOPEDIA OF ROBOTICS: APPLICATIONS AND AUTOMATION

VOLUME 1

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FOREWORD

Looking Ahead

In 1939, when I was 19 years old, I began to write a series of science fiction stories about robots. At the time, the word *robot* had been in existence for only 18 years; Karel Capek's play, *R.U.R.,* in which the word had been coined, having been performed for the first time in Europe in 1921. The concept, however, that of machines that could perform tasks with the apparent "intelligence" of human beings, had been in existence for thousands of years.

Through all those years, however, robots in myth, legend, and literature had been designed only to point a moral. Generally, they were treated as examples of overweening pride on the part of the human designer; an effort to accomplish something that was reserved to God alone. And, inevitably, this overweening pride was overtaken by Nemesis (as it always is in morality tales), so that the designer was destroyed, usually by that which he had created.

I grew tired of these myriad-told tales, and decided I would tell of robots that were carefully designed to perform certain tasks, but with *safeguards built in;* robots that might conceivably be dangerous, as any machine might be, but no more so.

In telling these tales, I worked out, perforce, certain rules of conduct that guided the robots; rules that I dealt with in a more and more refined manner over the next 44 years (my most recent robot novel, *The Robots of Dawn,* was published in October 1983). These rules were first put into words in a story called "Runaround," which appeared in the March 1942, issue of *Astounding Science Fiction.*

In that issue, on page 100, one of my characters says, "Now, look, let's start with the three fundamental Rules of Robotics . . ." and he proceeds to recite them. (In later stories, I took to referring to them as "the Three Laws of Robotics" and other people generally say "Asimov's Three Laws of Robotics.")

I am carefully specific about this point because that line on that page in that story was, as far as I know, the very first time and place that the word *robotics* had ever appeared in print.

I did not deliberately make up the word. Since *physics* and most of its subdivisions routinely have the "-ics" suffix, I assumed that "robotics" was the proper scientific term for the systematic study of robots, of their construction, maintenance, and behavior, and that it was used as such. It was only decades later that I became aware of the fact that the word was in no dictionary, general or scientific, and that I had coined it.

Possibly every person has a chance at good fortune in his life, but there can't be very many people who have had the incredible luck to live to see their fantasies begin to turn into reality.

I think sadly, for instance, of a good friend of mine who did not. He was Willy Ley who, for all his adult life was wedded to rocketry and to the dream of reaching the moon; who in his early twenties helped found rocket research in Germany; who, year after year wrote popular books on the subject; who, in 1969, was preparing to witness the launch of the first rocket intended to land on the moon; and who then died six weeks before that launch took place.

Such a tragedy did not overtake me. I lived to see the transistor invented, and solid-state devices undergo rapid development until the microchip became a reality. I lived to see Joseph Engelberger (with his interest sparked by my stories, actually) found Unimation, Inc., and then keep it going, with determination and foresight, until it actually constructed and installed industrial robots and grew enormously profitable. His devices were not quite the humanoid robots of my stories, but in many respects they were far more sophisticated than anything I had ever been equipped to imagine. Nor is there any doubt that the development of robots more like mine, with the capacities to see and to talk, for instance, are very far off.

I lived to see my Three Laws of Robotics taken seriously and routinely referred to in articles on robotics, written by real roboticists, as in a couple of cases in this volume. I lived to see them referred to familiarly, even in the popular press, and identified with my name, so that I can see I have secured for myself (all unknowingly, I must admit) a secure footnote in the history of science.

I even lived to see myself regarded with a certain amount of esteem by legitmate people in the field of robotics, as a kind of grandfather of them all, even though, in actual fact, I am merely a chemist by training and a science-fiction writer by choice—and know virtually nothing about the nuts and bolts of robotics; or of computers, for that matter.

But even after I thought I had grown accustomed to all of this, and had ceased marveling over this amazing turn of the wheel of fortune, and was certain that there was nothing left in this situation that had the capacity to surprise me, I found I was wrong. Let me explain . . .

In 1950 nine of my stories of robots were put together into a volume entitled *I, Robot* (the volume, as it happens, that was to inspire Mr. Engelberger).

On the page before the table of contents, there are inscribed, in lonely splendor *The Three Laws of Robotics:*

1. *A robot may not injure a human being, or, through inaction, allow a human being to come to harm.*
2. *A robot may obey the orders given it by human being except where such orders would conflict with the First Law.*
3. *A robot must protect its own existence as long as such protection does not conflict with First or Second Law.*

Never, until it actually happened, did I ever believe that I would really live to see robots, really live to see my three laws quoted everywhere.

Nor did it ever occur to me that I would live to see a vast three-volume *International Encyclopedia of Robotics* in which there would be enormous quantities of data and to which I would write the foreword (one that has already appeared in essence in the *Handbook of Industrial Robotics,* edited by Shimon Y. Nof).

It takes no great imagination to see that the *Encyclopedia* will increase in length and detail from edition to edition.

I see the world, and the human outposts on other worlds and in space, filled with cousin-intelligences of two entirely different types. I see silicon-intelligence (robots) that can manipulate numbers with incredible speed and precision and that can perform operations tirelessly and with perfect reproducibility; and I see carbon-intelligence (human beings) that can apply intuition, insight, and imagination to the solution of problems on the basis of what would seem insufficient data to a robot. I see the former building the foundations of a new, and unimaginably better society than any we have ever experienced; and I see the latter building the superstructure, with a creative fantasy we dare not picture now.

I see the two together advancing far more rapidly than either could alone. And though this, alas, I will not live to see, I am confident our children and grandchildren will, and that future editions of this *Encyclopedia* will detail the process.

ISAAC ASIMOV
New York, New York

PREFACE

Robotics and automation are critical ingredients in the world's efforts towards an improved standard of living for all. Automation, the automatic operation of processes, and robotics, which includes the manipulator, controller and associated devices, are all critical to effective operation of our plants, factories, and institutions. In this *Encyclopedia* we have taken both an encyclopedic and international view of this field of robotics. Thus, we include numerous articles written by international experts and have striven to include all the associated theoretical aspects of the field as well as most of the present and future applications of robots in the factory, office, and home.

The *International Encyclopedia of Robotics* defines the discipline and the practice of robotics by bringing together the core of knowledge and practice from the field and all closely related fields. The *Encyclopedia* is written primarily for the professional who seeks to understand and use robots and automation. The *Encyclopedia* has made significant contributions to the literature, not only because it brings many disciplines into one comprehensive reference, but also because it contains many articles that bring new or fresh insights.

The articles and the authors invited to write them were chosen with the cooperation of an editorial advisory board of distinguished authorities. The author of each article is a recognized research expert on the topic. Each article had a bibliography and extensive cross-references to other articles. The reader may start with almost any article and be led by cross-references to almost every other article in the *Encyclopedia.* There are more than 2000 tables and figures. Stressing readability, accuracy, and completeness of facts as well as overall usefulness of material, this great work brings you the result of years of labor and experience.

I became involved in the project to develop this *Encyclopedia* in the fall of 1984 when I was approached by Martin Grayson of John Wiley & Sons, Inc., and Professor Shimon Nof of Purdue University. Although I was warned by several people that this would involve a great effort, the opportunity to help create a definitive and comprehensive view of the field, authored by a wide variety of experts, each writing on his or her own area of expertise, and the promise of significant help from Wiley's Encyclopedia Department lured me onward. With the excellent assistance of Shimon Nof, the consulting editor, we put together an outstanding team of writers and reviewers. Michalina Bickford joined us as the managing editor and performed superbly.

Robotics is a relatively young field, and still has controversy about what it is and about what constitutes good and valuable research and application. Some researchers felt that an encyclopedia was premature. There was some controversy about the selection of articles. Nevertheless, I was extremely gratified with the number of people who were willing to take time from their already busy schedules to write and to review articles. Those involved constitute a significant percentage of all active practioners, from all the different companies and major research institutes and universities.

I am grateful to many people whose efforts have gone into making this *Encyclopedia:* Shimon Nof and Martin Grayson, who started it; the members of the editorial board, who defined it; Michalina Bickford, who managed it all; and the authors and reviewers, who created it.

Finally, my sincere appreciation goes to Joy, my wife who, as a humanist, has questioned and refined my views of the benefits and uses of robots, automation, and machines in the workplace and elsewhere.

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CONVERSION FACTORS, ABBREVIATIONS AND UNIT SYMBOLS

Selected SI Units (Adopted 1960)

Quantity	*Unit*	*Symbol*	*Acceptable equivalent*
BASE UNITS			
length	meter†	m	
mass‡	kilogram	kg	
time	second	s	
electric current	ampere	A	
thermodynamic temperature§	kelvin	K	
DERIVED UNITS AND OTHER ACCEPTABLE UNITS			
* absorbed dose	gray	Gy	J/kg
acceleration	meter per second squared	m/s^2	
* activity (of ionizing radiation source)	becquerel	Bq	l/s
area	square kilometer	km^2	
	square hectometer	hm^2	ha (hectare)
	square meter	m^2	
density, mass density	kilogram per cubic meter	kg/m^3	g/L; mg/cm^3
* electric potential, potential difference, electromotive force	volt	V	W/A
* electric resistance	ohm	Ω	V/A
* energy, work, quantity of heat	megajoule	MJ	
	kilojoule	kJ	
	joule	J	N·m
	electron volt^x	eV^x	
	kilowatt hour^x	kW·h^x	
* force	kilonewton	kN	
	newton	N	$kg·m/s^2$
* frequency	megahertz	MHz	
	hertz	Hz	l/s
heat capacity, entropy	joule per kelvin	J/K	
heat capacity (specific), specific entropy	joule per kilogram kelvin	J/(kg·K)	
heat transfer coefficient	watt per square meter kelvin	$W/(m^2·K)$	
linear density	kilogram per meter	kg/m	

magnetic field strength	ampere per meter	A/m	
moment of force, torque	newton meter	N·m	
momentum	kilogram meter per second	kg·m/s	
* power, heat flow rate,	kilowatt	kW	
radiant flux	watt	W	J/s
power density, heat flux density, irradiance	watt per square meter	W/m^2	
* pressure, stress	megapascal	MPa	
	kilopascal	kPa	
	pascal	Pa	
sound level	decibel	dB	
specific energy	joule per kilogram	J/kg	
specific volume	cubic meter per kilogram	m^3/kg	
surface tension	newton per meter	N/m	
thermal conductivity	watt per meter kelvin	W/(m·K)	
velocity	meter per second	m/s	
	kilometer per hour	km/h	
viscosity, dynamic	pascal second	Pa·s	
	millipascal second	mPa·s	
volume	cubic meter	m^3	
	cubic decimeter	dm^3	L(liter)
	cubic centimeter	cm^3	mL

* The asterisk denotes those units having special names and symbols.
† The spellings "metre" and "litre" are preferred by ASTM; however "er-" is used in the Encyclopedia.
‡ "Weight" is the commonly used term for "mass."
§ Wide use is made of "Celsius temperature" (t) defined by

$$t = T - T_0$$

where T is the thermodynamic temperature, expressed in kelvins, and T_0 = 273.15 by definition. A temperature interval may be expressed in degrees Celsius as well as in kelvins.
ˣ This non-SI unit is recognized by the CIPM as having to be retained because of practical importance or use in specialized fields.

In addition, there are 16 prefixes used to indicate order of magnitude, as follows:

Multiplication factor	*Prefix*	*Symbol*	*Note*
10^{18}	exa	E	
10^{15}	peta	P	
10^{12}	tera	T	
10^{9}	giga	G	
10^{6}	mega	M	
10^{3}	kilo	k	
10^{2}	hecto	h[a]	
10	deka	da[a]	
10^{-1}	deci	d[a]	
10^{-2}	centi	c[a]	
10^{-3}	milli	m	
10^{-6}	micro	μ	
10^{-9}	nano	n	
10^{-12}	pico	p	
10^{-15}	femto	f	
10^{-18}	atto	a	

[a] Although hecto, deka, deci, and centi are SI prefixes, their use should be avoided except for SI unit-multiples for area and volume and nontechnical use of centimeter, as for body and clothing measurement.

Conversion Factors to SI Units

To convert from	*To*	*Multiply by*
acre	square meter (m^2)	4.047×10^3
angstrom	meter (m)	1.0×10^{-10}†
atmosphere	pascal (Pa)	1.013×10^5
bar	pascal (Pa)	1.0×10^5†
barn	square meter (m^2)	1.0×10^{-28}†
barrel (42 U.S. liquid gallons)	cubic meter (m^3)	0.1590
Btu (thermochemical)	joule (J)	1.054×10^3
bushel	cubic meter (m^3)	3.524×10^{-2}
calorie (thermochemical)	joule (J)	4.184†
centipoise	pascal second (Pa·s)	1.0×10^{-3}†
cfm (cubic foot per minute)	cubic meter per second (m^3/s)	4.72×10^{-4}
cubic inch	cubic meter (m^3)	1.639×10^{-5}
cubic foot	cubic meter (m^3)	2.832×10^{-2}
cubic yard	cubic meter (m)	0.7646
dram (apothecaries')	kilogram (kg)	3.888×10^{-3}
dram (avoirdupois)	kilogram (kg)	1.772×10^{-3}
dram (U.S. fluid)	cubic meter (m^3)	3.697×10^{-6}
dyne	newton (N)	1.0×10^{-5}†
dyne/cm	newton per meter (N/m)	1.0×10^{-3}†
fluid ounce (U.S.)	cubic meter (m^3)	2.957×10^{-5}
foot	meter (m)	0.3048†
gallon (U.S. dry)	cubic meter (m^3)	4.405×10^{-3}
gallon (U.S. liquid)	cubic meter (m^3)	3.785×10^{-3}
gallon per minute (gpm)	cubic meter per second (m^3/s)	6.308×10^{-5}
	cubic meter per hour (m^3/h)	0.2271
grain	kilogram (kg)	6.480×10^{-5}
horsepower (550 ft·lbf/s)	watt (W)	7.457×10^2
inch	meter (m)	2.54×10^{-2}†
inch of mercury (32°F)	pascal (Pa)	3.386×10^3
inch of water (39.2°F)	pascal (Pa)	2.491×10^2
kilogram-force	newton (N)	9.807
kilowatt hour	megajoule (MJ)	3.6†
liter (for fluids only)	cubic meter (m^3)	1.0×10^{-3}†
micron	meter (m)	1.0×10^{-6}†
mil	meter (m)	2.54×10^{-5}†
mile (statute)	meter (m)	1.609×10^3
mile per hour	meter per second (m/s)	0.4470
millimeter of mercury (0°C)	pascal (Pa)	1.333×10^2†
ounce (avoirdupois)	kilogram (kg)	2.835×10^{-2}
ounce (troy)	kilogram (kg)	3.110×10^{-2}
ounce (U.S. fluid)	cubic meter (m^3)	2.957×10^{-5}
ounce-force	newton (N)	0.2780
peck (U.S.)	cubic meter (m^3)	8.810×10^{-3}
pennyweight	kilogram (kg)	1.555×10^{-3}
pint (U.S. dry)	cubic meter (m^3)	5.506×10^{-4}
pint (U.S. liquid)	cubic meter (m^3)	4.732×10^{-4}
poise (absolute viscosity)	pascal second (Pa·s)	0.10†
pound (avoirdupois)	kilogram (kg)	0.4536
pound (troy)	kilogram (kg)	0.3732
pound-force	newton (N)	4.448
pound-force per square inch (psi)	pascal (Pa)	6.895×10^3
quart (U.S. dry)	cubic meter (m^3)	1.101×10^{-3}
quart (U.S. liquid)	cubic meter (m^3)	9.464×10^{-4}
quintal	kilogram (kg)	1.0×10^2†

rad	gray (Gy)	$1.0 \times 10^{-2\dagger}$
square inch	square meter (m^2)	6.452×10^{-4}
square foot	square meter (m^2)	9.290×10^{-2}
square mile	square meter (m^2)	2.590×10^{6}
square yard	square meter (m^2)	0.8361
ton (long, 2240 pounds)	kilogram (kg)	1.016×10^{3}
ton (metric)	kilogram (kg)	$1.0 \times 10^{3\dagger}$
ton (short, 2000 pounds)	kilogram (kg)	9.072×10^{2}
torr	pascal (Pa)	1.333×10^{2}
yard	meter (m)	$0.9144^{\dagger}$

† Exact.

ABBREVIATIONS AND ACRONYMS

A	ampere
AACW	active adaptive compliance wrist
ac	alternating current (*noun*)
a-c	alternating current (*adjective*)
ACI	automatic component insertion
AFR	Air Force Regulation
AGV	automated guided vehicle
AGVS	automated guided vehicle system
AI	artificial intelligence
AMR	autonomous mobile robot
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATC	automatic tool changes
ATE	automotive test equipment
avg	average
BCD	binary coded decimal
bpa	basic probability assignment
bps	bits per second
BWR	boiling water reactor
°C	degrees Celsius
ca	approximately (*circa*)
CAD	computer-aided design
CAE	computer-aided engineering
CAM	computer-aided manufacturing
CAPP	computer-aided production planning
CAT	computer-aided testing
CFR	Code of Federal Regulations
CIM	computer-integrated manufacturing
CL	control law
CMM	coordinate measuring machine
CMU	Carnegie Mellon University
CNC	computer numerical control
CPPP	computerized production process planning
CPU	central processing unit; control process unit
CRC	computer robot control
CRT	cathode ray tube
DAC	digital to analogue converter
dc	direct current (*noun*)
d-c	direct current (*adjective*)
DCF	discounted cash flow
DDM	direct drive motor
DMA	direct memory access
DNC	direct numerical control
DOD	Department of Defense (U.S.)
DOF	degree of freedom
DOT	Department of Transportation (U.S.)
DOM	design of maintenance
EEC	European Economic Community
eg	For example (*est gratia*)
EIA	Electronic Industries Association
EOD	explosive ordnance disposal
EPA	Environmental Protection Agency (U.S.)
est	estimated
ESU	emergency service unit
°F	degrees Fahrenheit
FAA	Federal Aviation Administration (U.S.)
FDM	frequency division multiplexing
FMC	flexible manufacturing cell
FMS	flexible manufacturing system
FOF	factory of the future
ft	foot
ft·lbf	foot-pound force (1.356 J)
FTAM	file, transfer, access, and management
g	gravitational acceleration
g	gram
gal	gallon (3.785 L in the U.S.)
GC	gas chromatography
GDB	global data base
gf	gram force (0.0098 N)
GNP	Gross National Product
GPS	general problem solver
gy	gray (10^{-2})
h	hour
hp	horsepower (746 W)
Hz	Hertz (cycles per second)
IC	integrated circuit
ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronic Engineers
I/O	integrated circuit

IQR	interquartile range
IRR	internal rate of return
IRS	Internal Revenue Service (U.S.)
ISO	International Organization for Standardization
IWP	intelligent work in process
J	Joule (energy)
JIT	Just-in-time
JPL	Jet Propulsion Laboratory
K	Kelvin
kgf	kilogram-force (9.086 N)
kJ	kilojoule
km	kilometer
kPa	kilopascal (0.145 psi)
L	liter (volume)
LAN	local area networks
lb	pound (mass) (453.6 g)
lbf	pound force (4.448 N)
LCD	liquid crystal display
LED	light-emitting diode
LTD	long term debt
LTP	local tracking problem
LVDT	linear variable differential transformer
m	meter
MAP	manufacturing automation protocol
MARR	minimum attractive rate of return
max	maximum
mg	milligram
MHS	material handling system
MICAPP	microcomputer-assisted process planning program
min	minute; minimum
MLS	master laboratory station
MMFS	manipulating message format standard
MMS	maintenance manipulator system
MP	microprocessor
ms	millisecond
MTBF	mean time between failures
MTTR	mean time to repair
N	Newton
na	not available
NBS	National Bureau of Standards
NC	numerically controlled
NRC	Nuclear Regulatory Commission (U.S.)
NYPD	New York City Police Department
OD	outer diameter
OI	operation interface
OLP	off-line program
OSHA	Occupational Safety and Health Administration (U.S.)
OTA	Office of Technology Assessment (U.S.)
Pa	Pascal (pressure)
PC	programmable controller; programmable logic controller; personal computer
PCM	pulse code modulation
psi	pound (force) per square inch (6.893 kPa)
psig	psi pressure gauge
PWA	printed wire assembly
PWM	pulse-width modulation
PWR	pressure water reactor
qv	which see (*quo vide*)
RAM	random access memory
RCC	remote center compliance
RCMC	resolved motion rate control
R&D	research and development
rf	radio frequency (*noun*)
r-f	radio frequency (*adjective*)
RGS	remote guidance system
rh	relative humidity
RIA	Robotics Institute of America
RLL	relay ladder language
RM	remote mobile investigator
ROI	return on investment
ROM	read only memory
RPS	robot programming system
RPV	remotely piloted vehicle
RTM	Robot time and motion
s	second
SAT	symmetric axis transform
SCA	sensor-controlled automation
SCARA	selective compliance-assembly robot arm
SIC	Standard Industrial Classification
SMC	surface mounted components
SMD	surface mount devices
SME	Society of Manufacturing Engineers
SOC	self organizing control
SRBP	synthetic resin bonded paper
SRI	Stanford Research Institute
SUNY	State University of New York
SUR	speech understanding research
SUS	speech understanding system
t	metric ton
T	temperature
TDL	task description language
TDM	time division multiplexing
TMI	Three Mile Island
TMV	technical maintenance vehicle
UIMS	user interface management system
uv	ultraviolet
UVS	unmanned vehicle system
WIP	work in progress
WM	working memory
V	volt
VLSI	very large scale integration
vs	versus
yr	year