
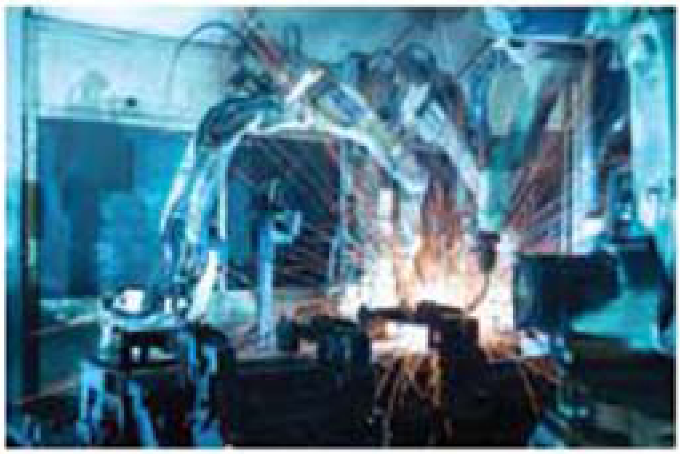


INDUSTRIAL ROBOTICS

KEITH DINWIDDIE

INDUSTRIAL ROBOTICS

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***Industrial Robotics,* First Edition**

Keith Dinwiddie

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Content Developer: Jenn Alverson

Product Assistant: Mara Ciacelli

Vice President, Strategic Marketing Services: Jennifer Ann Baker

Marketing Manager: Andrew Ouimet

Project Manager, Production Vendor Management: James Zayicek

Content Project Management: Lumina Datamatics, Inc.

Art Designer: Angela Sheehan

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Contents

Preface		vii
About the Author		ix
Dedication		x
Chapter 1	Safety	1
	Overview	2
	Robots Require Respect	3
	Danger Zones	3
	Guarding	6
	Safety Devices	8
	Electricity and You	11
	LOTO	14
	Handling Emergencies	15
	Review	19
	Key Terms	19
	Review Questions	20
Chapter 2	Introduction to Industrial Robotics	21
	Overview	22
	What Is an Industrial Robot?	22
	A History of Technology	23
	The Rise of the Industrial Robot	26
	Why Use a Robot?	35
	Review	38
	Key Terms	39
	Review Questions	39
Chapter 3	Components of the Robot	40
	Overview	41
	Power Supply	41
	Controller/Logic Function	48
	Teach Pendant/Interface	52
	Manipulator, Degrees of Freedom, and Axis Numbering	54
	Base Types	57
	Review	59
	Key Terms	60
	Review Questions	60
Chapter 4	Classification of Robots	61
	Overview	62
	How Are Robots Classified?	62
	Power Source	62

	Geometry of the Work Envelope	64
	Drive Systems: Classification and Operation	71
	ISO Classification	75
	Review	76
	Key Terms	77
	Review Questions	77
Chapter 5	End-of-Arm Tooling	78
	Overview	79
	What Is EOAT?	79
	Types of Tooling Available	79
	Multiple Tooling	93
	Positioning of EOAT	94
	Review	96
	Formulas	97
	Key Terms	97
	Review Questions	98
Chapter 6	Programming and File Management	99
	Overview	100
	Programming Language Evolution	100
	Planning	104
	Subroutines	111
	Writing the Program	112
	Testing and Verifying	119
	Normal Operation	121
	File Maintenance	122
	Review	124
	Key Terms	124
	Review Questions	124
Chapter 7	Automation Sensors	126
	Overview	127
	Limit Switches	127
	Proximity Switches	128
	Tactile and Impact Sensors	133
	Temperature Sensors	136
	Fluid Sensors	138
	Position Sensors	143
	Sound Sensors	145
	Connection to the Robot	147
	Sensor Selection Criteria	148
	Review	149
	Key Terms	150
	Review Questions	150

Chapter 8	Vision Systems	152
	Overview	153
	History of Vision Systems	153
	Components of a Vision System	156
	Image Analysis	159
	Lighting	161
	Review	167
	Key Terms	167
	Review Questions	168
Chapter 9	Integration and Networking	169
	Overview	170
	What Is a Network?	170
	Types of Networks	171
	Communication Protocols	177
	Integration	184
	Review	187
	Key Terms	187
	Review Questions	188
Chapter 10	Programmable Logic Controllers (PLCs) and Human-Machine Interfaces (HMIs)	189
	Overview	190
	What Is a PLC?	190
	A Brief History of PLCs	194
	Basic Components of the PLC	196
	Operation of the PLC	203
	Human–Machine Interfaces	209
	Review	213
	Key Terms	213
	Review Questions	214
Chapter 11	Maintenance and Troubleshooting	215
	Overview	216
	Preventive Maintenance	216
	Arc Flash	219
	Troubleshooting	221
	Crash Recovery	223
	Repair Tips	226
	Parts Swapping Versus Fixing the Problem	229
	Precautions before Running the Robot	230
	Review	231
	Key Terms	231
	Review Questions	231
Chapter 12	Justifying the Use of a Robot	233
	Overview	234
	Robot Versus Human Labor	234
	SWOT Analysis	235

	Return on Investment	237
	Precision and Quality	239
	Use of Consumables	240
	Hazardous Environments	241
	Review	242
	Key Terms	242
	Review Questions	243
Appendix A	Flow Charting Symbols	244
Appendix B	Recommended Tool List	245
Appendix C	Torque Conversion Formulas	246
Appendix D	Bolt Torque Chart: UNC/UNF Threads	247
Appendix E	Metric Bolt Torque Chart	248
Glossary		249
Index		263

Preface

This is my second textbook on robotics. Unlike my first book, which covered the basics of robotics in general, this book focuses on the industrial side of things. Inside, you, the reader, will find all the basic knowledge needed to start your exploration of the world of industrial robotics, written in a straightforward, conversational style that many find refreshing. The jargon used by industry is explained along the way and highlighted so you can find it as needed later on. In the pages of this book you will find tales from industry, hard-won knowledge presented in an easy-to-understand format, and meticulously researched historical facts. This book is the culmination of my many years learning about, working with, and teaching robotics. While many texts seem to be written for top-level engineers or industry experts, this book is designed for those who are new to robotics and eager to learn. It is my sincere hope that you enjoy reading this book as much as, if not more than, I did writing it!

As you dig into the text, you will find that Chapter 1 covers all the basic safety concerns that one might encounter in any technical environment. Here you benefit from my many years of teaching safety and first aid. In Chapter 2, you will learn what a robot is, how this technology evolved, and why we use them. The history behind robotics is longer and more intricate than you might imagine. Chapter 3 introduces the various parts of the robot and explains what each part does for the system. Notably, this chapter describes how to number the different axes of the robot for different configurations—coverage often missing in other books or addressed only for the arm type. Chapter 4 discusses how we group robots and describes the different work envelope geometries used by robots. This chapter ends with the ISO classifications utilized in many industries. Chapter 5 finishes up our exploration of the core robotic components with a look at the world of robotic tooling. Without proper tooling, most robots are fairly useless—so it is important to understand which options are available and what they are used for. As part of this chapter's coverage, we even consider ways to use multiple tools on one robot.

Chapter 6 explores the process of programming the robot and the basic steps that go into this process. This chapter gives the reader the knowledge base needed to create working programs for any robot, once they learn the specifics of the robot they are using. Chapter 7 examines the various sensors used in robotic work cells and other places in industry. Since the robot knows only what we tell it, it is crucial to understand the types of information that sensors can provide. Chapter 8 deals with robotic vision, an exciting addition to any robotic system that can help it see the world in a whole new light. Lighting is one of the primary concerns with any vision system, and you can find information on that topic in this chapter.

Chapter 9 presents an overview of networking and integration, which have become crucial skills in the modern factory. Gone are the days of dumb machines isolated and alone. Today, most (if not all) of the equipment in the plant is part of the plant's network and accessible from remote terminals. Chapter 10 covers the basics of programmable logic controllers (PLCs) and human–machine interfaces (HMIs). In this chapter, I share some hard-won knowledge about how the PLC works as well as how to think like a PLC. Most often, technicians have trouble with PLCs because of the way these devices' operation was explained to them. In Chapter 10, you will learn several crucial points that can prevent this kind of problem from happening to you!

Everything eventually breaks, and Chapter 11 provides tips on how to keep the robot running as well as how to fix it when something goes wrong. This chapter includes a section on arc flash, which is a major concern when engaging in any electrical work. It also has some tips for crash recovery, for those times when the robot runs into something it should not have. Chapter 12 finishes things off with a look at robots versus human labor and the return on investment from robots. When the topic of robotics comes up, it often leads to a discussion of whether robots will take all the jobs away from people. If you want to learn more about this debate, check out Chapter 12.

By the end of this book, you will have a deeper knowledge of robotics and will be set to explore the field deeper. There are many fields to go into once you have read this book and completed the course that introduced you to it. For those who want to program or design robots, several engineering fields might be appropriate career avenues. If you like getting your hands dirty and fixing broken things, a career as a repair technician could be a good fit. If you like to find solutions to production needs/problems, the integrator field—that is, the area where you find the right robot and get everything set up—may be your calling. No matter where your journey takes you, this text will provide a solid foundation so you can dig deeper in the field of your calling.

SUPPLEMENTS

Instructor Companion Site

Everything you need for your course in one place! This collection of book-specific lecture and class tools is available online via www.cengage.com/login. Access and download PowerPoint presentations, images, and an instructor's manual.

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MindTap is a personalized teaching experience with relevant assignments that guide students to analyze, apply, and improve thinking, allowing you to measure skills and outcomes with ease.

- *Personalized teaching*: MindTap becomes your own when you make available a learning path that is built from key student objectives. Control what students see and when they see it; match your syllabus exactly by hiding, rearranging, or adding your own content.
- *Guide students*: MindTap goes beyond the traditional "lift and shift" model by creating a unique learning path of relevant readings, multimedia, and activities that move students up the learning taxonomy from basic knowledge and comprehension to analysis and application.
- *Measure skills and outcomes*: Analytics and reports provide a snapshot of class progress, time on task, engagement, and completion rates.

ACKNOWLEDGMENTS

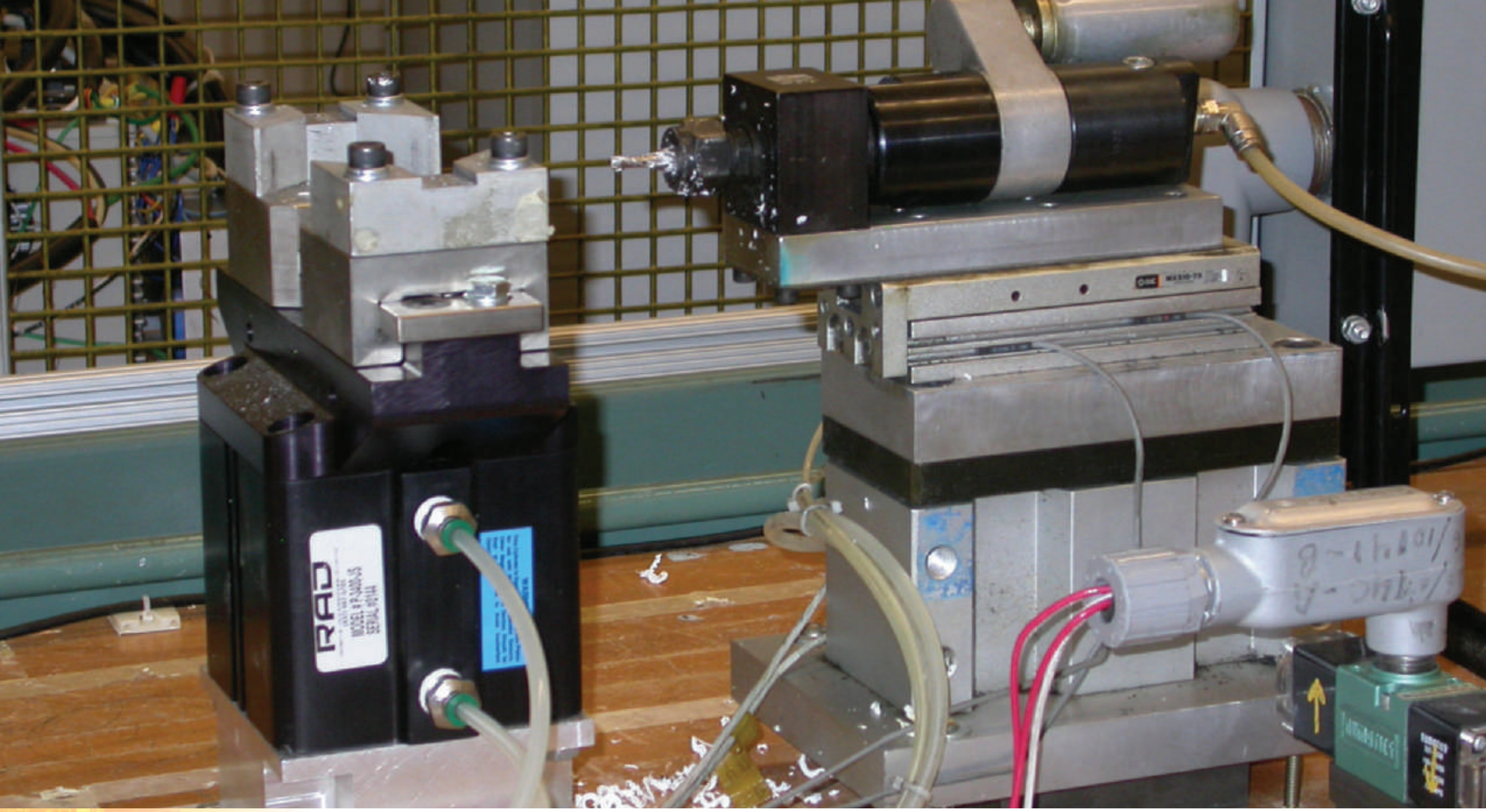
I would like to thank Katie McGuire from Cengage for giving me the chance to work on another textbook and Jennifer Alverson from Cengage for working with me throughout the project. Without their help and trust in me, you would not be enjoying this book. Special thanks go out to Jerry Guignon and Matthew Morris for helping with the ABB photos. Also, thank you to all the generous people from Yaskawa America and Panasonic-Miller, Kiel Vedrode from FANUC, and Kelly Fair from Schunk who helped me track down the images used in the text—this book would not be the same without these great images. And thank you, the reader, for taking the time to explore my book.

About the Author

Keith Dinwiddie has been teaching at Ozarks Technical Community College, based in Springfield, Missouri, for 10 years full time and 12 years total as of the writing of this book. In the past, Keith has worked as a maintenance technician in industry; he also did a stint in the army working on the Huey helicopter. Keith has loved all things robotic from a very young age and has had the chance to work with Panasonic, FANUC, Mitsubishi, and UR3 industrial robots as well as NAO, WowWee, and hobby robotic systems. Keith is a FANUC C.E.R.T (Certified Education Robotic Training) instructor for handling pro and vision, which means he can give his students a certificate that carries the same weight as going to the FANUC classes. This is Keith's second textbook but he has also authored various articles for Balluff or AZO.

DEDICATION

This book is dedicated to my loving wife, Lucia Dinwiddie. Thank you for becoming a book widow once more, and for all the support you have given me through the writing process. It is appreciated more than you know!



CHAPTER 1

Safety

WHAT YOU WILL LEARN

- How to work safely with robots
- The three conditions that will stop a robot
- The three zones around a robot
- How to ensure the safety of people in the danger zone
- Operation of several common safety sensors
- The dangers of electricity
- How to lock out or tag out equipment
- How to deal with emergencies
- Some basic first-aid procedures

OVERVIEW

Industrial robots are incredible technological marvels that have the ability to move heavy materials, perform machining functions, fuse metals, deposit various substances, and move much faster than humans. The same functions that make a robot valuable are also the biggest dangers of working with a robot. From the person who works around a robot, to those responsible for its maintenance, to the creators of robots—safety needs to be a primary concern at all times. To help you survive working with and around industrial robots, we will cover the following topics in this chapter:

- Robots require respect
- Danger zones
- Guarding
- Safety devices
- Electricity and you
- LOTO
- Handling emergencies

FOOD FOR THOUGHT

1-1

The following story comes from one of my students and is a great example of just how dangerous it can be to work around a robot without the proper safety precautions. In truth, my student is very lucky to be alive today.

The company where this event happened produces large lead-acid batteries. It utilizes robots to move the batteries from one station to the next as different operations are performed. In the cage where the accident happened, there were three different stations where the robot would pick up the battery and move it to another process. The robot had been stopped and my student was inside the **work envelope**—that is, the area that the robot could reach. The student was performing some routine cleaning operations, while another employee outside the protective cage was engaged in similar activities.

While my student was busy inside the work envelope, an engineer for the company came up and started to do something with the robot controller. While my student never fully understood what the engineer was trying to do, he did find out painfully what the engineer had done. One minute he was working; the next minute he was lying on the ground trying to figure out what happened. Somehow the engineer had started the robot with my student inside the cage and it had knocked my student down.

As he laid there trying to figure out what had happened, my student heard someone holler, "Don't get up, it's coming back!" A moment later he saw the robot sweep over his head at full speed, going about its normal programmed duties. Someone finally stopped the robot. After being trapped on the floor for what seemed like an eternity, my student was able to move once more. As he started to get up and take stock of his injuries, he realized that his head was only inches away from anchor bolts left in the floor from a previous machine that had been moved, and the severity of what had just happened started to sink in.

My student was lucky to walk away from this event with only some bumps and bruises. If he had been standing where the robot picked up the batteries instead of just in its movement path, the robot could have easily clamped down on him and thrown him around the work envelope. Considering that the parts the robot moved weighed as much as 150 pounds, it is very reasonable to think the robot could have picked up my student. If he had landed a few inches over, his head would have likely hit the bolts sticking up, which could have been fatal. If he had fallen onto some of the other equipment instead of hitting the floor and getting out of the robot's path, he could have been crushed. The possible ways he could have been severely injured or killed go on and on.

This incident raises some big questions—namely, what went wrong and what could my student have done to prevent this incident? First, one should never enter the work envelope of a robot without access to an emergency stop. Indeed, it is for this very reason that industrial robots have an E-stop on the teach pendant. It is also why OSHA requires you to have the teach pendant with you at all times while inside the reach of the robot. Second, no one should try to make alterations to the robot or controller while people are in harm's way. This is just asking for trouble—and in this case, trouble was found. Third, when working with industrial robots, we must always be aware of what is going on around us. The moment the engineer walked up and started to mess with the controller, my student should have exited the work envelope of the robot and waited until the engineer was finished. Of course, he also should have had the teach pendant with him so he could have hit the E-stop should the need arise, as it did in this case. We can also fault the engineer for working with the system while someone was inside the work envelope. Even those people who have tons of experience with robots can accidently hit the wrong button or switch from time to time.

ROBOTS REQUIRE RESPECT

Fatalities involving robotic systems are rare, but they do happen. The **Occupational Safety and Health Association (OSHA)** cites 27 fatalities involving robots from 1984 to 2013, an average of less than one death per year, but these are the numbers for just the United States. In 2015, two fatalities brought robotic safety to the forefront of concern—one in India, where a worker was impaled by a welding robot, and another in Germany at Volkswagen, where a worker was grabbed and crushed against a steel plate. In 2016, a young woman in Alabama was crushed inside a robotic station while trying to clear a fault. These deaths serve as a tragic reminder that industrial robots still have the ability to kill in spite of the safety equipment and regulations in use today.

When it comes to safety, you will often hear about the three Rs of robotics: *Robots Require Respect*. If safety equipment and regulations were enough, injuries and fatalities involving robots would be a thing of the past. Unfortunately, that is not the case. Some of the cases of injury or death involving robots trace back to faulty equipment, and others are the result of improper training, but many have a direct correlation to complacency. When we work with robots day after day, we become accustomed to their methodical nature and forget the inherent dangers of their functionality. When people stop respecting the robot as a powerful piece of equipment, they often start to take risks that could literally cost life or limb.

A robot performs its actions via programming, direct control, or some combination of the two. That is it. Robots do not have feelings, they do not have moods, they do not have intuitive thought, they do not think as we do, and they do not have their own agenda. While it is true we are working on artificial intelligence (AI) programs and have given robots the ability to deal with complex situations in which there may not be a clear-cut right answer, these machines are still performing only as programmed. Because of this functionality, there are only three conditions that stop a robot:

- *The program/driven action is finished.* The program or direct control is used to control robots. Thus, once the robot has run its program or we have stopped sending action signals, the robot simply stops and waits for the next command. A sensor or other system may initiate the next command/program, which explains why robots sometimes seem to start unexpectedly, but this is the robot working under program control.
- *There is an alarm condition.* Almost all modern robotic systems have some sort of alarm system. In many cases, this system monitors such things as safety sensors, **E-stops** (emergency stops), load on the motors, vision systems, and other available devices that give the robot information about the world around it or its internal systems. The alarm function stops the robot in an effort to prevent or minimize harm to people, other equipment, and/or the robot.
- *Some type of mechanical failure occurs.* Robots are mechanical systems, and like any other machine they are susceptible to breakdown. Motors fail, bolts break, air hoses rupture, wiring shorts out, and connections work loose, just to name a few of the potential failures. Anything of this nature can cause a robot to stop. In a worst-case scenario, the robot would keep operating, but perform its tasks erratically or unpredictably.

If you have the misfortune to be in the robot's path when it starts up either automatically or via your direct control, there is no amount of pleading, no bribe you can offer, and no reasoning with the system to halt its operation—nothing but one of the three conditions mentioned previously will stop the robot. If you do not respect the robot, then you, too, might learn this hard lesson.

DANGER ZONES

At this point, you may be wondering if it is ever safe to work around a robot. The answer is an absolute yes. Every day we use thousands of robots safely and effectively in many facets of the modern world. One of the first things we do to create this safe working condition is to determine the various zones around a robot. Each zone has a risk level and requires a certain level of awareness based on that risk. For our purposes, we will focus on three major zones: the safe zone, the cautionary zone, and the danger zone (Figure 1-1).

Safe Zone

The **safe zone** is where a person can pass near the robot without having to worry about making contact with the system. This area is outside of the reach of the robotic system as well as beyond the area the robot can affect. The distance from the robot to the safe zone depends on the type of robot, the maximum force of the system, and the actions performed by the robot. The more powerful the robotic system, the farther away you will need to be to remain in the safe zone. An example can help shed some light on what a safe zone truly is.

Suppose a group of new hires are on a tour of the plant to get an overview of where everything is and which

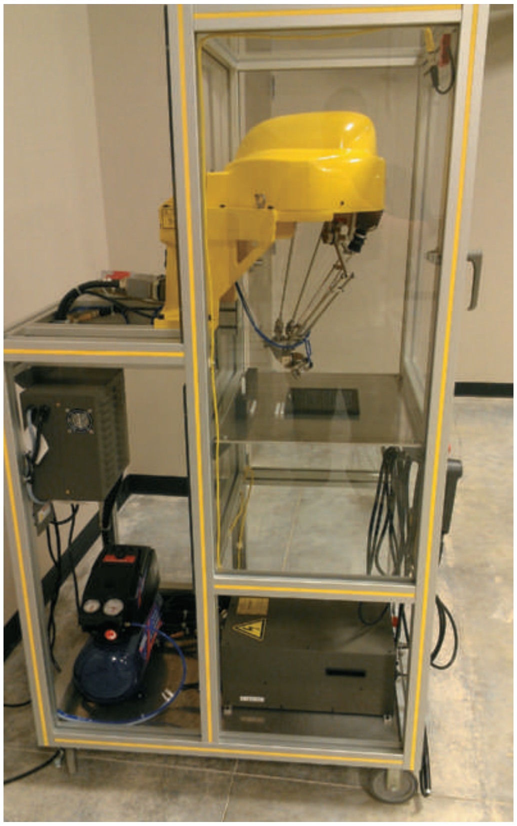


FIGURE 1-1 This is one of the trainers my students use. This system has a completely encapsulating cage that creates two zones: a danger zone inside the Plexiglas and a safe zone outside the safety glass as long as the door remains closed. If the door opens, it creates a cautionary zone directly in front of the robot. In the upper-right corner above the door handle, notice the red door switch: It senses when the door is open and keeps the robot from running in automatic mode in that situation.

dangers are associated with the various departments. The group walks through a production area where several robots are moving parts and performing welding operations. For many of the new employees, this is their first look at an industrial robot in action, but they can watch it safely because they stay in the taped-off pedestrian traffic path. This path is routed so that people are safe from a majority of the hazards of the area. In this safe zone, anyone could walk through the area without needing to know anything specific about the robot to remain safe.

Cautionary Zone

The **cautionary zone** is the area where one is close to the robot, but still outside of the work envelope or reach of the system. While the robot cannot reach you in this area, there could be danger during operation from things such as chips, sparks, thrown parts, high-pressure leaks, crashes, overspray, or flash from welding. Since this is often the area from which operators perform their tasks, they must understand the potential hazards involved to work safely. Because of the need for understanding of the system, this is not an area for just anyone.

A good example of this area is the operator station for an industrial robot that performs a **pick and place operation**—that is, picking up items from one area and placing them in another. Often this type of system will pick up a raw part from a conveyor or container, remove a finished part from a machine, place the raw part into the machine for processing, deposit the finished part on a conveyor or something similar, and then wait to start the process all over again. The operator is usually responsible for such tasks as loading raw parts onto the conveyor, checking the dimensions and quality of the finished parts, making corrections to the process as needed, and any other tasks needed to complete this portion of the production process. The requirements of this job often place the operator in close proximity to not only the robot but also other production equipment. Workers spend millions of hours in these areas each year without injury or incident, though accidents do happen on occasion. Because of this potential for accidents, workers in the cautionary zone need to be aware of all the dangers and know how to handle any situations that might arise. Because this is the normal space for the operator, the cautionary zone will contain stop buttons, emergency stops (E-stops), the controller for the robot, operator interfaces such as the teach pendant, and other ways to stop or control the system as needed.

Danger Zone

The **danger zone** is the area the robot can reach or the work envelope; it is where all the robotic action takes place. The various axes of the robot and the design of the system define the work envelope, so you need to be familiar with the robot to enter the danger zone. Each robot has its own danger zone, and you must exercise extreme caution in this area because it has the highest potential for injury or death. When in the danger zone you have to watch out for the robot, any tooling used by the robot, and any place where the robot could trap you against something solid, known as a **pinch point**.

In industrial settings, we have to mitigate the hazards associated with the danger zone in some way, so that when people enter this area the system either slows to a safe velocity with extra sensitivity for impacts or stops automatic operation. A popular method to achieve this kind of protection is to place metallic fencing around the robot, creating a cage that keeps people out of the danger zone while providing one or two entrances for necessary repair, cleanup, tool changes,

FIGURE 1-2 The teach pendant for the FANUC trainer. Note the big red E-stop on the upper-right corner of the teach pendant as well as the E-stop on the controller directly below the teach pendant.

or other normal job requirements. These entrances have sensors in place such that when they are opened, the robot stops automatic operations or in some other way renders itself safe for humans to be near it.

When we put ourselves in the danger zone, we should always have some way to stop or shut down the robot. If you enter the danger zone with no way of stopping the robot, you are asking for trouble—like the student in the Food for Thought box. In industry, an OSHA requirement states that anyone entering danger zone must take the teach pendant along. The **teach pendant** is a handheld device, usually attached to a fairly long cord, that allows people to edit or create programs and control various operations of the robot (Figure 1-2). It also contains an E-stop should the need for it arise.

Let us return to our industrial pick and place robot to explore the three zones in greater detail. This robot works with several machines and moves parts around in a defined area enclosed by a metal mesh cage. The operator has a workstation where he or she monitors operations, checks parts, and makes adjustments as needed. There is a clearly marked main isle near where the operator works, but it is 15 feet away from the process. The isle can be used by anyone and is considered a safe path for people—that is, a safe zone. The operator station is in the cautionary zone, as there is some potential for injury, but this area is safe for people to be as long as they have the proper training and safety equipment. Anywhere inside the cage is in the danger zone, exposed to all the dangers of the system and where access to an E-stop for the system is an OSHA requirement (Figure 1-3). To meet the E-stop requirement, anyone entering the danger zone should bring the teach pendant and have the ability to control the robot and prevent bad things from happening in the first place (Figure 1-4).

As another example, consider a robot that is responsible for dipping molten aluminum from a large cauldron and then pouring it into a feed tube for an injection molding machine. When I saw this actual robot in operation, the taped-off walkway used for my tour would be the safe zone. An operator for this

FOOD FOR THOUGHT

1-2

The Occupational Safety and Health Administration (OSHA) was officially formed in 1971 due to an act signed into law by President Richard Nixon on December 29, 1970. OSHA's sole mission is to assure a safe and healthful workplace for every working person. It does so by inspecting worksites and factories to ensure they are following the guidelines that OSHA has written or mandated by reference. Many of the rules OSHA enforces are derived from sources such as the National Electrical Code (NEC) or rules established by the National Fire Protection Association (NFPA).

OSHA enforces these rules by going to factories and work sites to conduct inspections, in which its personnel look for violations or things that do not conform to the rules. Companies are fined for violations and then given a set amount of time to fix the problem or face steeper fines and penalties. OSHA averages approximately 40,000 to 50,000 of these inspections each year, many of which occur in response to written complaints from workers.

If you would like to know more about OSHA or how to report safety violations, check out www.OSHA.gov.

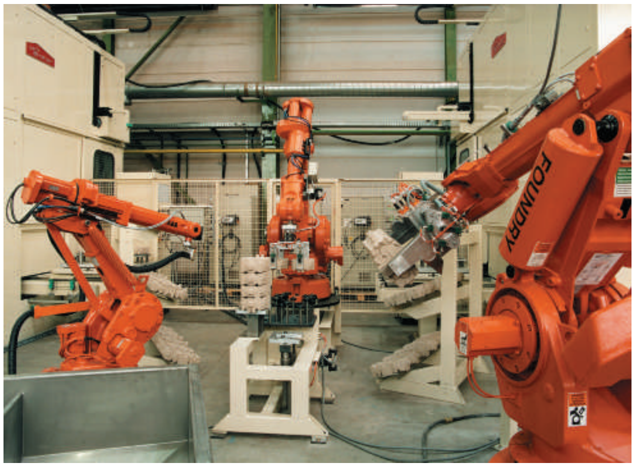


Image courtesy of ABB Inc.

FIGURE 1-3 These three robots are handling parts inside a caged area. Notice how much floor space is considered in the danger zone, as denoted by the white metal cage behind the robots.

Courtesy of Miller-Welding Automation

FIGURE 1-4 Here you can see a couple of operators in the danger zone working on the program with teach pendant in hand.

machine monitored the process as well as dealt with the finished pieces. He worked in the cautionary zone, but had to take some extra care as this robot worked with molten metal. From my safe observation spot, one of the things that caught my attention was the amount of aluminum that had spilled between where the robot collected it and where the robot filled the machine. One expects drips and spills at the collection and fill points, but not so much as to create a path of spilled aluminum lining the way between the two. In addition, aluminum could be observed *outside* the reach of the robot. Thus, the danger zone in this case extended past the reach of the robot to the area where the liquid aluminum splashes could reach.

These examples emphasize that each robotic system is unique and, therefore, requires individual assessment of both the risks it poses and the locations of the boundary zones. Remember, the more powerful the system and the more dangerous its function, the greater the potential for injury or death. Failing to respect the requirements of the cautionary zone or the danger zone is a quick way to experience the horror of being at the nonexistent mercy of a robot.

GUARDING

In our discussion of the danger zones, we briefly mentioned means of guarding robotic systems. **Guards**, for our purposes, are devices designed to protect us from the dangers of a system. The two types we will explore here are guards installed directly on the equipment and guards placed a set distance from the device. No matter the placement, a guard's main purpose is to keep people safe; only rarely do they improve the operation of the equipment. In fact, there are many situations where guarding limits the operation of the equipment and/or makes it more difficult to work with.

When it comes to questions about robotic safety systems such as "What are the min/max perimeter guard dimensions for a robot?" or "How is it possible for the Baxter robot to run without a cage?", ANSI/RIA R15.06-2012 provides the answers. This safety standard for robotics was developed by the **Robotic Industries Association (RIA)**, which has been working to further the use of robotic technology in United States for years; it was also adopted by the **American National Standards Institute (ANSI)**, which administers and coordinates private-sector voluntary standardization systems. This revision is an update to the 1999 standard and took full effect on January 1, 2015. While not referenced by OSHA and thus not legally binding, it is considered the proper way to make sure that workers and those around robots are properly protected. Any organization using this standard correctly to guard its robots would have a firm legal leg to stand on should anything go wrong.

The guarding that protects people from moving parts such as chains, pulleys, belts, or gears is mounted directly on the robot and is a part of the system (Figure 1-5). The manufacturer or designer of the robot supplies this guarding, which usually forms the outer structure of the robot. Often this guarding is made of a sturdy plastic or light metal that allows for its removal during repairs and when preventive maintenance is required. Depending on how the guarding fits together, it may be necessary to move the robot into specific positions to remove certain pieces of guarding. If you are having trouble removing a piece

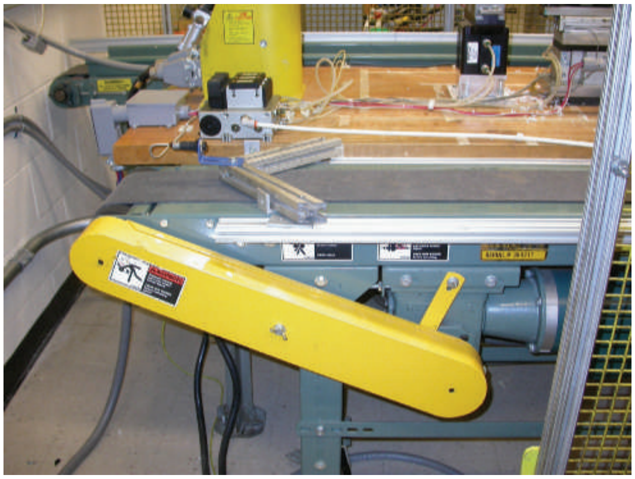


FIGURE 1-5 A guard to protect operators from the belt or chain underneath.

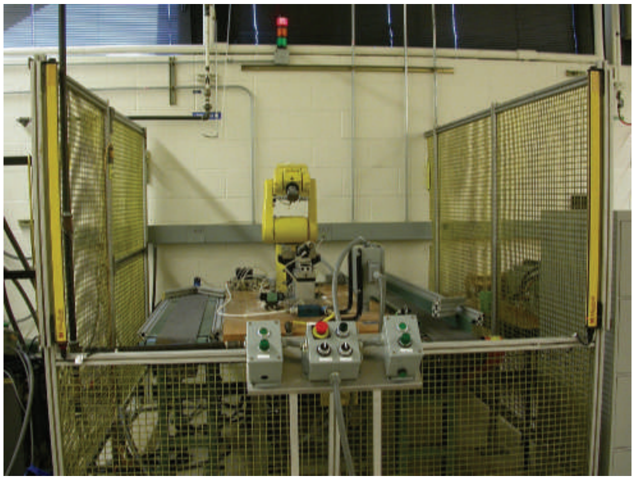


FIGURE 1-7 This small work cell is protected by metal mesh, the yellow fence, and two light curtains at the front opening.

of guarding, look for hidden screws or other pieces of guarding that may be holding it in place. Trying to force a piece of guarding off is a good way to break the guarding and possibly damage parts underneath. Always repair or replace damaged guarding to ensure proper operation of the system and the safety of those who work around it.

Guarding that encloses the work area of a robot, as mentioned earlier, can be made of various materials, with expanded metal or metal mesh being favorites. **Expanded metal guarding** is metal that is perforated and stretched to create diamond-shaped holes with 0.25-inch pieces of metal around it (Figure 1-6). **Metal mesh** consists of thick wire welded and/or woven together to create a strong barrier that is easy to see through (Figure 1-7). Metal mesh may be welded into metallic frames, usually angle iron pieces, that make up the panels of the robot cage. This creates a robust guarding system that is easy to see through, but strong enough to resist thrown parts, robot impacts, and people falling into or leaning on it. Add a few sensing devices (a topic covered later in this

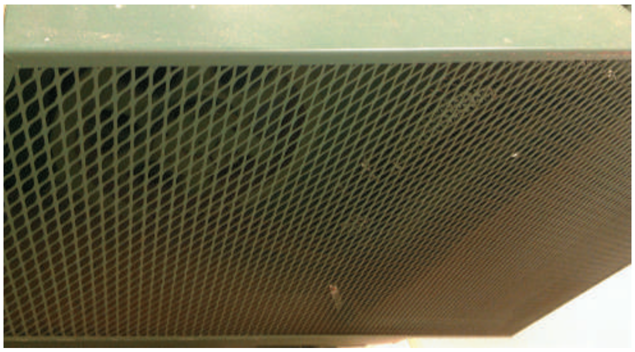


FIGURE 1-6 An example of expanded metal guarding rotating parts.

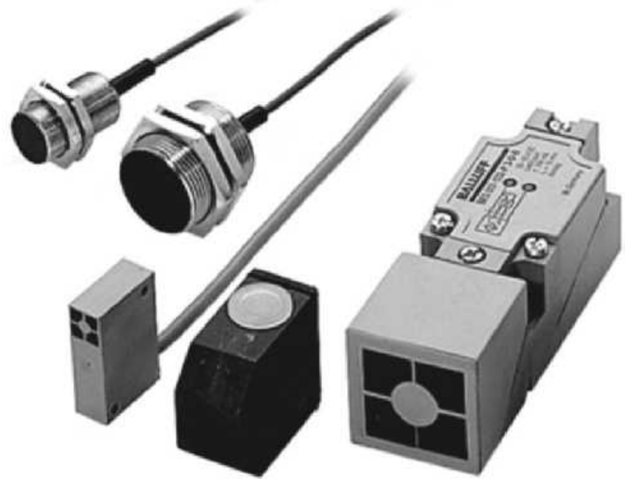
chapter), and you have an OSHA-approved system to ensure the safety of workers in the cautionary zone.

Metal cages are not the only way we can guard the work area of the robot. Another guarding option that is gaining popularity is a camera-based system mounted on the ceiling above the robot that detects when people pass into the danger zone, triggering the robot to respond accordingly. These systems often have a projector that defines the monitored area with clearly visible white lines, so operators can see the danger zone. With this camera-based system, it is easy to adjust the danger zone and increase the area protected as needed, while avoiding the costs and down time associated with moving and fabricating metal cages. The tradeoff is that this system does nothing to stop flying parts or anything physically entering the danger zone.

The Baxter robot, which debuted in 2012, performs danger zone guarding by using a 360° camera system in its head that detects when humans are in the danger zone (Figure 1-8). When it senses someone within range, the robot slows to what is considered a safe movement speed by the RIA, OSHA, and **International Standards Organization** (**ISO**); an organization that creates standards for any industry in the world to use), while also monitoring the sensitive collision detection system that will stop all movement of the robot if an impact is detected. This combination of safety features allows Baxter to work outside of the cage that restricts so many robots. Rethink Robots, which created Baxter, also created a more traditional style of robotic arm that uses the same technology. It is not alone in the charge to free robots, as Universal Robots put the cage-free UR5 into production at a Volkswagen plant

Courtesy of Rethink Robotics

FIGURE 1-8 Baxter operates in an industrial setting without any cage around it. This kind of machine is leading the charge to free the industrial robot from confinement.



Courtesy of Balluff, Inc.

FIGURE 1-9 Examples of various proximity switches.

in 2013. While the cage-free robot has not taken over industry as of yet, the longer these systems run without incident, the better the chances for adoption and evolution of this technology.

We have not covered every form of guarding available by any stretch of the imagination, but you should have a good idea of what guarding is and why we use it. Advancements in safety technology have given us options far beyond the traditional cage, even though the cage remains the most popular choice of today, especially in areas where the cage acts as a physical barrier to any parts that might go flying or similar dangers. As the newer technology proves its worth, more robots will likely be freed from the cage in cases where this barrier exists solely to prevent contact with humans.

SAFETY DEVICES

So far, we have looked at the broad picture of robot safety, ways to work with robots in general, and the threat levels associated with various areas around the robot. This discussion is just the tip of the iceberg, as the modern robot uses a multitude of sensors and devices to ensure human safety. Without these devices, many of the tasks we perform with and around robots would have a greatly increased risk of injury or death. This section introduces some of the devices used to help ensure the robot remains a benefit in the workplace and avoids the detriment of increased danger to workers.

Proximity switches are devices that are widely used to ensure the safety of those who work around robots as well as to direct robot operation (Figure 1-9). A **proximity switch** is a device that generates an electromagnetic field and senses the presence of various materials based on changes in this field (instead of physical contact). Such switches are used to sense parts, determine machinery position, and track items on conveyors, among many other applications. When it comes to safety, we tend to use the proximity switch to ensure something is in a specific position before an operation takes place—for example, to ensure parts are in position, monitor the entrance to robot danger zones, verify the machine door is open before loading or is closed before the process starts, prevent the robot from rotating too far in a given direction, and verify that the robot's tooling is in the correct configuration or position before an action occurs (Figure 1-10). In short, the proximity switch is a great tool for answering simple yes/no-type questions related to safety or operation.

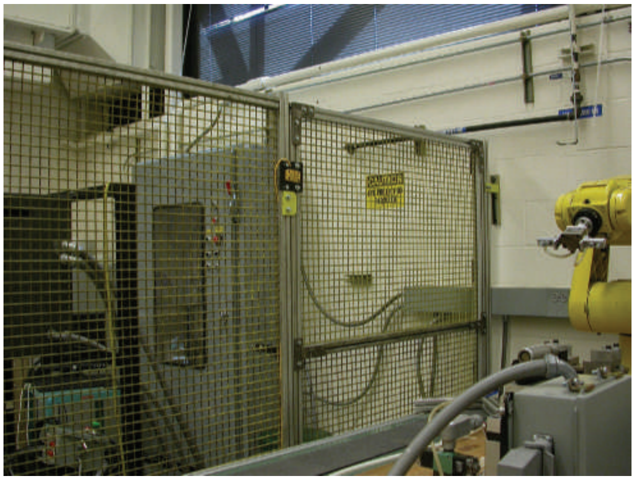


FIGURE 1-10 This proximity switch is guarding the door to the robot's cage. It consists of the two yellow pieces on the black metal near the top of the cage and over the light-yellow piece.

FIGURE 1-11 A limit switch.

A close relative of the proximity switch is the limit switch (Figure 1-11). The **limit switch** senses the presence or absence of a material by contact with a movable element attached to the end of the unit. Limit switches are used in much the same way as proximity switches, but the main difference between the two is that the limit switch actually makes contact with whatever it monitors. Because this device makes physical contact instead of depending on a sensing field, we can extend the range of a limit switch by simply extending the actuator mechanism. The physical contact aspect of the limit switch helps it overcome dirty environments and gives it a larger sensing distance compared to most proximity switches. The downside is that the limit switch experiences more wear due to the physical contact and requires more maintenance than a properly selected and mounted proximity switch.

Many times, we use proximity and limit switches as safety interlocks. A **safety interlock** is a system in which all the safety switches must be closed or "made" for the equipment to run automatically. If at any point during the operation of the equipment these switches open or lose connection, the system automatically drops into a manual or alarmed condition, with many systems doing both. Safety interlocks are often used to guard the doors of the robot cage: Whenever an entrance is opened, the robot automatically enters a safe mode and stops all automatic operation. If the system includes easy-to-remove covers, we can use the same trick to make sure they are in place before the robot runs in automatic mode. The downside to using interlocks on cage entrances is that someone could potentially open the door, step in, close the door, and then use the teach pendant to reset any alarms and put the robot back in automatic mode. To prevent this situation, we can use **presence sensors**—sensors that detect when a person is inside an area. The camera system used by the Baxter robot, pressure mats, and light curtains are examples of presence sensors that we can tie into the safety interlock system to add another layer of protection and prevent automatic operation of the robot with people nearby.

A **pressure sensor** detects the presence or absence of a set level of force. For safety purposes, these devices are placed in mats that can detect the weight of the operator and respond accordingly. They also contain safety circuitry that can detect when the pressure mat is malfunctioning, thereby preventing the dangerous situation in which someone is on the mat yet the system thinks everything is clear. In some cases, pressure mats are used to verify the operator is standing in a specific location, but more typically they are used to make sure everyone is clear of a danger zone. Small pressure sensors have also been used to cover robot grippers or other tooling so the robot can gather information on force exerted as well as information about the shape of the part.

A relatively new development in presence sensing for robots is robotic "skin." The skin in this instance is a covering of the robot that allows the system to sense people or objects and respond accordingly. Bosch unveiled its first version of this technology in 2014 on the APAS robot, which was covered in leather with embedded tactile sensors to detect impact. The 2017 version of this robot uses a capacitive system to detect humans and stop before any contact occurs. As of the writing of this text, Bosch was the main company working on this technology. As it works the bugs out, however, other companies may add this type of protection to their robots.

Many robots can tell when a motor has encountered something unexpected by sensing the increased power drawn. As a motor encounters resistance, it naturally starts to use more energy in an attempt to overcome this force, thereby increasing the amount of amperage used. When this happens, the part of the robot that drives the motor recognizes the additional power draw and shuts down the robot while