Safety Considerations for Humanoid Robots

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Abstract. The issue of assuring the safe operation of humanoid robots may well be one of the greatest challenges facing humanoid robot researchers. It is almost a certainty that legal restrictions will prohibit the general deployment of humanoid robots until a high level of safety can be guaranteed. This paper discusses the key issues for safe operation of humanoid robots and identifies the key technical developments which will be necessary to achieve this goal in next-generation robots. It also presents an overview of approaches investigated for industrial robot safety and assesses how relevant these approaches are for humanoid robot safety.

1 Introduction

Assuring the safe operation of robot systems has always been an important consideration in the planning and implementation of industrial and service robot installations. Many of the industrial robot applications to date have involved fixed-base robot arms involved in material transfer and assembly operations. Safety for these robots has been achieved, to a large extent, by isolating them with cages and interlock devices. These systems essentially exclude humans from the robot's working envelope during normal operations. Specific limitations on robot speed and operating modes are specified for installation, programming and maintenance by national standards [1].

Automated guided vehicles (AGV's) add a bit of complication to the industrial robot safety picture in that they are not fixed and often operate in parts of the plant where humans are present. Their pathways are clearly marked, and they usually have visual (flashing lights) and auditory (beeps) indications of their activity. Most have a simple proximity sensor system, which will shut down the AVG if it encounters an obstacle. The ANSI standard for guided industrial vehicles specifies that emergency stop conditions should be activated due to loss of path reference or deviation from required trajectory by more than 15 cm, and specifies the inclusion of collision sensing device in the direction of travel [2].

Service robot installations add even more challenges in that, by definition, service robots are created to perform some service to aid humans. Thus humans and robots must interact in order for the service to be performed. The definition of a service robot is somewhat ambiguous, and may include such things as sentry robots, robots which deliver hospital trays, etc.,. As in the case of AGV's the mobility plus the human interaction prohibits the use of isolating barriers used so effectively in traditional industrial robot installations. Apparently there does not presently exist an accepted national safety standard for general-purpose service robots.

The humanoid robots of the future, which are the subject of this conference, pose much more imposing challenges for safety than either the industrial or service robots which are presently deployed. It is assumed that humanoid robots will have approximately the same size and at least the same strength as humans. A device of that size and strength clearly presents a safety threat to humans. It is also assumed that one of the chief reasons for creating a humanoid robot is to deliver service to humans, thus necessitating close interaction between the robot and the human. It is almost a certainty that such devices will fall under existing legal guidelines for consumer protection and for manufactures' liability for the safety of their products. Any manufacturer foolish enough to ignore safety considerations for this type of product will probably not remain in business for long!

It should be mentioned here that while there are some issues of a robot protecting its own physical integrity, the focus of this paper is on the protection of humans from actions of the robot. In the opinion of the author, we are still a long way away from worrying about trying to fully implement Asimov's Three Laws of Robotics [3]. The possible consequences of conflicts between the requirement of Law 1, which states that a robot will not injure a human or allow a human to be injured due to inaction, and the requirement of Law 2, which states that a robot will not allow itself to be injured, are still in the realm of science fiction.

The main purpose of this paper is to present an overview of some of the safety considerations which will come into play as the development of humanoid robots moves out of the laboratory and into commercialization. Section 2 presents an overview of the likely safety system requirements for humanoid robots. Section 3 gives a brief summary of some of the sensory modalities, which likely will be important for achieving safe operation, and section 4 discusses various options for processing safety decisions and integrating these decisions into the robot control architecture. Section 5 briefly presents some previous and current work by the author and others on industrial robot safety which is relevant to the issues of humanoid robot safety, and section 6 gives conclusions and some directions for future work in this area.

2. Requirements

In a field that is as new as humanoid robots, it is hard to construct a very definitive list of requirements and specifications. In the area of humanoid robot safety, it is, however, possible to make some reasonable inferences about what some of these requirements will be based upon legal and societal expectations for safety of mechanical devices.

The main requirement is for accurate and timely detection of possible safety hazards. This must be accomplished in a dynamically changing real-time environment, and thus, any off-line planning will be of only limited use for safety purposes. It should be noted that there is a bit of a probabilistic trade-off as to how good this detection can be. There will always be some probability that a situation that appears safe is actually unsafe (Type I error) and some probability that a situation that appears unsafe is actually safe (Type II error). Type I error potentially places a human in jeopardy of injury from the robot. By contrast, Type II error results in false alarms, and requires an unnecessary shutdown or avoidance maneuver on the part of the robot. Typically, the smaller that you make the Type I error probability, the higher the Type II probability becomes. Eventually, the frequency of false alarms becomes unacceptable, and makes it impossible for the robot to accomplish tasks. Thus some Type I error must be accepted in any humanoid robot system.

Timeliness of response in safety situations is also a relative concept. A suitable response time is a function of the mass of the robot and the velocity at which it is traveling. An envelope of safety can be calculated for the robot at any velocity indicating the safe-stopping distance for the robot. Typical mechanical stopping times are estimated to be in the range of fractional seconds to seconds. Acquisition and processing of sensory data can easily be accomplished in that time-frame, provided the sensory fusion and safety decision making algorithms are efficient.

The safety-related sensing units must be rugged, and either redundant or very reliable. The safety system, and the whole robot system, should operate in a fail-safe mode, so that a system failure results in a failure state that does not jeopardize any humans in the vicinity of the robot. An interesting example of this principle was a service robot manipulator system constructed in Japan, which used a pneumatically operated hollow rubber body that would transition to a high compliance state when a mechanical threshold was exceeded. [4]

Obviously, cost considerations must also come into play. The added cost of the safety system should be a relatively small fraction of the overall cost of the humanoid robot. Fortunately, as discussed below, many of the sensors that are needed for other robot functions can also provide information for the safety system. However, some sensors, such as laser range-finders, may be too expensive to include just for safety reasons on general purpose humanoid robots.

3 Sensory Modalities

This section provides an overview of sensory modalities that may be involved in assuring safe operation for humanoid robots. More detailed discussions of sensors for robots can be found in [5].

3.1 Vision

Computer vision systems have improved greatly in recent years, and at some time in the future will probably be the major sensory modality for humanoid robots, both for safety and for acquiring environmental information for completing robot tasks. However, it is the opinion of the author, that at the present time computer vision is still too slow and too limited to be the sole source of sensory information for robot safety. The author recognizes that some computer vision researchers may challenge this position.

Furthermore, the author thinks that it is unwise to defer research on other sensory modalities while waiting for computer vision to reach acceptable performance levels for robot safety. Even with excellent vision systems, other modalities can provide valuable information for making safety-related decisions, in cases including low ambient light situations, occluded scenes, etc.,. Thus it seems prudent to push for better vision systems, but also at the same time, to fully investigate the other sensory modes described in the following paragraphs.

3.2 Tactile

Tactile information is essential for successful completion of many humanoid robot tasks, and would be useful in certain safety situations involving the touching of humans by the robot. Tactile sensing systems are of somewhat less importance for the general safety situation of avoiding unplanned contact with humans. By the time tactile information is received, it is too late to prevent the contact and possible injury. Many AVG's have a safety bumper of a soft material, which detects and permits some impact before contact with solid surface of the vehicle is reached. Possibly some modification of this same strategy can be usefully employed for humanoid robots.

3.3 Auditory

Humans make effective use of auditory cues to avoid collisions, and so it seems possible that auditory sensing has some potential for robot safety, particularly when integrated with other sensory information. It is unlikely, however, that it would be a primary source for safety information in a humanoid robot.

3.4 Proximity

Proximity sensors (not including vision) are of key importance for safe operation of humanoid robots. Proximity sensors, especially ultrasound, are the main navigation and safety devices used in many of the current generation of mobile robots. Ultrasound transducers are inexpensive and rugged, but suffer from problems of beam-width, specular reflection, and secondary reflections, all of which can lead to either Type I or Type II safety errors. Laser-based range-finding systems avoid some of these problems. However, specular reflection is still a problem for mirror-smooth surfaces, and the laser ranging units tend to be somewhat bulky, temperature sensitive, and fragile. Also laser range-finders tend to be much more expensive than ultrasound range-finders. Additional proximity sensing technologies that might be applicable include: microwave presence sensing, capacitance-based presence sensing, and active infrared sensing.

3.5 Sensory Fusion

Regardless of the sensory modalities selected, a key challenge is to process and integrate the disparate information provided by the sensors into a safety decision. A variety of approaches including Bayesian statistics, Dempster-Shafer evidential reasoning, and neural networks have been proposed and investigated [6-9]. Sensory fusion still remains largely an open problem that requires additional research for the case of safety of humanoid robots.

4 Control Approaches

This section provides a brief overview of control options for the robot safety system. As discussed in the section on requirements (section 2), it is likely that the safety system will be an integral part of the overall control system of the humanoid robot. One reason is that, as stated before, it is almost certain that governmental regulations and product liability considerations will mandate that the humanoid robot not be able to operate unless it can do so (relatively) safely. The discussion in this section then primarily concerns those robot control components that deal with the initial processing of sensory data, the integration of the sensory data, and the initial identification of potential safety hazards. It is assumed that the actual avoidance maneuver or emergency halt would be processed by the main robot control system after it was alerted by the safety subsystem of the hazard. The following control architectures have been investigated by the author for industrial and service robot safety, and seem to offer some desirable features for the humanoid robot safety problem [11-15].

4.1 Conventional Control

Some ideas from conventional and optimal control have been applied to the safety control system. In particular, several researchers have investigated the use of potential function formulations with cost functions to penalize proximity to obstacles [10]. This is a very elegant approach for the case of off-line planning for robot movements in fixed environments, but seems less appropriate for operation in the type of dynamically changing environment which humanoid robots are likely to encounter.

4.2 Rule-based Control

An attractive alternative to conventional control for many industrial robot safety systems has been rule-based control. In many cases the sensors used produce binary outputs, or the outputs can be easily converted to binary through a thresholding operation. A set of simple rules can then be created, designating situations in which a safety hazard is possible. Evaluation of these rules can be very fast, yielding good real-time response to hazardous conditions. This approach was effective for many industrial applications but, like the conventional control approaches, seems less appropriate for humanoid robot safety control, in part, because of the extremely large number of input combinations which would have to be considered in the rule-base.

4.3 Fuzzy Logic Control

Fuzzy logic control is attractive for control of robot safety systems for a variety of reasons. They maintain some of the flavor of a rule-based system, while still providing approximate reasoning with modest computation. A fuzzy rule-based decision-making system can be implemented as the composition of the fuzzy input and the fuzzy rule base. Given the noise and imprecision inherent in many of the sensing systems it seems reasonable to take advantage of a fuzzy logic system to exploit this inherent lack of precision. One approach to fuzzy logic control of an industrial robot safety system is given in [11].

4.4 Neural Network Control

Artificial neural networks are attractive in many control applications because they provide the possibility of learning the parameters of the safety situation (robot and environment) and thus improve the performance of the safety system over time. In theory, this approach could also adapt to changes in the environment. This approach was shown to work well in learning a complicated nonlinear mapping of sensory data for an industrial robot application [13].

4.5 Hybrid Control Schemes

The author has a bias towards hybrid control systems for both the robot safety problem and the more general control problem for humanoid robots. Using the subsumption architecture [16] approach, it is quite feasible to use different control strategies for different functional levels of the humanoid robot. If humanoid robot control does, in fact, develop in this fashion, it will hardly be surprising since humans clearly use a variety of control mechanisms for different functions and tasks.

5 Preliminary Results

Several references have been made in the preceding sections to robot safety approaches used in industrial and service robots that might be relevant to humanoid robots. In general, research projects at the Intelligent Systems Laboratory at the University of Louisville, West Virginia University, Rensselaer Polytechnic Institute, and Tampere University have investigated a number of approaches for sensory-based industrial robot safety. Many of the sensory systems discussed in section III have been implemented and tested. All of these systems can be considered as attempts to give some degree of sentience to industrial robots - they attempt to make the robot aware of its environment, at least to a very limited degree. The robot system attempts to detect situations in which human intruders, or other obstacles, are within the safety envelope of the robot. The most sophisticated of these systems attempt to determine when an obstacle is in the path of the current robot trajectory. A good overview of these efforts can be found in [17].

6 Conclusions and Future Research Directions

This paper has attempted to provide an overview of the robot safety problem for future humanoid robots. Although many of the operational characteristics of humanoid robots are significantly different from those of current industrial robots, it appears, from this overview, that many of the sensing and control strategies which have been effective for advanced safety control of industrial robots have good potential for application to humanoid robots with some further research efforts.

If a Grand Challenge type effort was to begin tomorrow to attempt to construct a next-generation humanoid robot, here is a short list of the main research and development tasks which would have to be accomplished to assuring safe operation of the robot:

1. Creation of better proximity sensors (smaller and more reliable)
2. Creation of improved sensory fusion algorithms
3. Creation of a robust, hybrid safety control algorithm, possibly using a neural-fuzzy approach
4. Creation of improved computer vision systems

Humanoid robot research is in its infancy when viewed against the ambitious list of capabilities that we would like for a humanoid robot to possess. It is not surprising then that safety research for humanoid robots is in precisely the same situation. Hopefully the two will progress more or less together. Many of the capabilities of sensing, perception, decision-making and control that are required for effective operation of the humanoid robot are the same, or very similar, to capabilities that are required for safe operation of the robot. As previously stated, it is the opinion of the author that general purpose humanoid robots will be required to operate (relatively) safely in order to be distributed to the public.

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