Using Augmented Reality to Develop a Robotics Safety System

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ABSTRACT

This paper discusses using augment reality to develop a safety system for high payload robots. For several decades, significant improvement of robotics technology has enabled a wider application of robotics and automation. For simple processes that involve many repetitions, complete hard automation provides an appropriate solution. However, for those processes that require different assemblies and positioning, hard automation leaves much to be desired. Due to the complexity of tasks, humans are still needed in many areas. Human operators need protection while working in the vicinity of a high payload robotic system. The standard practice is to use physical barriers to prohibit human operators from getting into the working envelope of the robotic system during operation, and this method eliminates the advantages of having a robotic system in many potential application areas. This paper reports the development of a safety system that allows human operators to work closely with the robots in a safe and cost-effective manner. The paper demonstrates the use of a robotic system through virtual techniques and provides means of training and implementing of such systems for robotic users. This multi-layer augmented reality-based safety system provides the concept of a fail-proof and safe working environment to protect humans, working objects, and the robotic system itself. Due to the prevailing economic climate in which companies are hesitant to spend resources on major hardware prototypes, extensive experimentation and hands-on training, and as such, augmented reality tools are perfect for the rapid and cost effective development and testing of this system for various high capacity and sensitive payloads. In addition to low cost, the DRSS (Dynamic Robotics Safety System) uses real-time simulation and augmented reality tools that allows the team to complete the design and perform lab tests successfully within a very short time.

ABOUT THE AUTHORS

Paul. Huang has over 29 years of experience in academia, aerospace and defense related tasks and programs. Dr. Huang has published over 60 technical papers in electronics, sensor systems, robotics, software, control systems, fire control, signal, and image processing. He also co-authored two book in applied mathematics. He has worked on various shipboard weapon systems those include many Guided Missile Launching systems and various gun systems. . He has been responsible for the planning and construction of several electronics and software system integration facilities. He was credit for the system integration of the first all-digital combat vehicle system – the Bradley Fighting Vehicle (BFV) A3 System. The process he developed, namely the SES^{TM} (Simulation-Emulation-Stimulation) Process, has been named as the "Best Practice" in 1996 by INCOSE (International Council for Systems Engineering). He holds several patents in sensory systems, software, and robotics systems. He has served as consultant for several industries in the areas of sensor systems, control systems, ordnance systems (from major caliber guns to small arms), and system integration.

Chris Holmes received Bachelor's of Science degree in Electrical Engineering from George Mason University in 1993, Chris Holmes has been growing his engineering experience in modeling and simulation, software development, rapid virtual prototyping, and control. Chris has worked on various flight simulators and military systems that include the F/A-18 Weapons Tactics Trainer, the V-22 flight simulator, Bradley Fighting Vehicle A3, DDG1000, FCS NLOS-C/NLOS-M. He also has experience as a software test engineer for cardiac pacemakers and a GPS ground station. He is the main developer of the Generic Visualization System (GVS) which can display the results of multiple digital simulations in one realistic 3D virtual environment.

Omar Khan has 14 years of experience in systems engineering, including, engineering development, mission analysis, modeling and simulation and augmented and virtual prototyping. His recent emphasis has been on the analysis of weapons systems, new product integration and business development. Mr. Khan's technical academic background includes a BS and an MS in Electrical engineering. He has also received an MBA from the University of Minnesota.

Steven French is the Manager -Technology Development, BAE Systems, USCS. Mr. French leads an engineering staff responsible for advanced weapon development. His team has produced automated weapon handling systems to include early design/development of FCS self-propelled howitzers, 120mm mortars and electrothermal chemical guns. His group is currently supporting development of directed energy weapons with particular emphasis on integration of pulsed power systems. He is a graduate of the University of Minnesota with a BS in Metallurgical and Materials Engineering, and has an MBA from University of St. Thomas.

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INTRODUCTION

Since the advent of robotics technology, robotic use has increased in many working areas that require flexible setup, repetitive actions, exposure to dangerous environments, or other tasks that are difficult for humans to perform. The introduction of robotic systems removes human operators from many less desirable tasks. However, the power, the speed, and the possibility of mechanical malfunction also prohibit a wider application of these useful tools. To safeguard human operators working in the vicinity of various high payload robotic systems, the standard practice is to use physical barriers to separate human operators from working robotic systems. Special warning devices\systems, in addition to humans monitoring those working robotic systems, prevent accidental intrusion of humans into the robotic working envelopes—the zones in which the robot arms and end effectors (hands or grippers) of those robots can reach. Even with those safety precautions, occasionally humans got hurt due to either machine malfunction or human error. Those safety practices are basically designed to protect humans and only a few safety practices protect the working parts/components or the robotic system. In reality, contrary to popular belief, the largest number of robot accidents does not involve collisions between personnel and the robot. The self-starting of ancillary equipment, the opening and closing of fixtures, and the unexpected indexing or transfer of fixtures and tools constitute the larger category of accident cause (Feingold, 2008).

Many tasks require certain delicate manual work that machines cannot perform such as the moving, repositioning, and lifting of heavy objects that are beyond the human's ability to perform. The standard practice is to use various fixtures, hoist, and other heavy payload moving devices to perform the tasks, and a significant amount of time is spent fastening, releasing, and other preparation tasks. A large crew of workers is needed to accomplish the task along with special fixtures and lifting devices.

The introduction of a heavy payload robotic system can potentially relieve humans of the tedious and labor-intensive material handling tasks. A substantial amount of time could be saved by eliminating the fastening and preparation of moving, repositioning, and lifting items by using the flexible and versatile robotic arms and end effectors. Many of the special fixtures can also be eliminated from the working environment to create a more compact and clean working cell. It also reduces the manpower requirements so that a smaller crew would handle more tasks. However, the most difficult hurdle is to apply robotic systems into those areas and still be able to guarantee the safety of human operators working closely with the robotic systems.

Industry has been deprived from a wider use of these versatile, flexible, and powerful tools because of the technology's inability to protect human operators within the working envelope of heavy payload robotic systems. This paper investigates the problems, searches for a possible break-through, identifies related technical issues about the human/machine, and derives a possible solution. Safety is critical when putting humans into the robotic working envelope.

BACKGROUND

The introduction of robotic systems has revolutionized the manufacturing processes. Robotic systems remove human operators from dangerous and tedious tasks, and possibly create many other new opportunities for their use. When compared with hard automation, robotics provides the flexibility of performing complicated functions and allows resetting the working cells in shorter time for different and/or difficult tasks. It fits better for a wider range of usages that require constant changing of fixtures for different operations. Within the same configuration, the versatility of robotic systems allows an operator to perform many different functions using the same mechanism without stopping and resetting. However, robotic systems can also cause substantial damage to the working components, the robotic system itself, and/or injury to any human within the reach of the arms/end effectors as a result of human error or mechanical failure.

The common safety practice used today for working robotic systems is to prohibit human operators within the robotics working envelope during operation. Various physical barriers and warning systems have been used to prevent human intruding into the working envelope of the robotics systems (STD 01-12-002-Pub 8-1.3, ANSI/RIA R15.06-1999, AMSI/RIA/ISO 10218-12007). When a human follows those safety rules, no injury has occurred. However, when a human purposely ignores those safety rules or absent-mindedly gets into the robotics working envelopes, injuries, even deaths have occurred.

Recent studies in Sweden and Japan indicate that many robot accidents do not occur under normal operating conditions but rather during programming, adjustment, testing, cleaning, inspection, and repair period. Unfortunately, to perform those tasks, the robotics power has to be on. During these operations, the operator, programmer, or maintenance personal may temporarily be within the robot work envelope while the robotics power is on (STD 01-12-002-Pub 8-1.3, AMSI/RIA/ISO 10218-120070).

Any moving mechanism can cause damage within its reach due to either mechanical failure or human error. Other than a few (Feingold, 2008), most of the robotics safety systems only concentrate on the protection of humans (ANSI/RIA/ISO 10218-12007, Kulic D., Croft E., 2006, Graham J., 1996). Those safety systems, in general, cannot not protect the working components. It is not uncommon that when the sensor system of the robotics arm failed or misaligned, the robotic system caused substantial damage.

The damage caused by any mechanism is due to the collision of the mechanism with an object. We should be able to eliminate the collision of objects completely, by detecting an incoming impact of mechanisms in the working envelope. To achieve this objective and the capability to detect the possibility of an incoming collision within the working envelope, the robotics safety system needs to react appropriately in stopping the impact before it happens.

To stop the motion of the robotics arm and end effector, the robot controller sends out the command to a set of brakes of the drives (motors) moving the robotic system. From the time that the controller sends out the command signals to the time that the mechanisms' motion stops (freezes) completely, the robotics arm and end effector have already traveled further. A safety system should take into consideration this extra distance that the robotics traveled during this reaction time interval.

The drives for the movement of mechanisms can be generally categorized as electric, hydraulic, pneumatic, or engine generated. In extreme situations, those drives may experience a problem commonly called "motor runaway". That phenomenon can be caused by an internal defect, valves (hydraulic and pneumatic) stickiness, or other reasons. When the controller detects "runaway", the motion sensor will detect the abnormal phenomena, send commands to the brakes, and stop the motion of the robot. From the time that runaway starts to the time that brakes stop the motion completely, the robot would also travel a certain distance. To prevent the collision of the robotic system with any object, these factors should be thoroughly considered.

APPROACH

A possible solution to protect humans within the working envelope of the robotic system is to detect the humans and to monitor their activity at all times. When a human is within the vicinity of the working robot's reach, the safety system will send out a warning signal to alert the human. When the human reaches motor runaway and braking-stop distance, the safety system will set all brakes, freeze the motion of the robotics system, and sound an audible alarm. Similar principles can be used to protect components and the robot mechanism.

The robotics safety system most likely should be an add-on to the existing robotic systems. The safety system needs to be able to protect humans within the robotic working envelope all the times. To achieve the near 100% reliability and availability, multi-level redundancy is a must. This safety system will depend heavily on sensory technology and precision computation to achieve accurate results in a timely manner for monitoring and acting needs.

Other than working components and fixtures within the robotic working envelope, both the human and the robotic mechanism move constantly and the general geometries within the reach of the robot morph constantly. To prevent the collision of constantly moving and morphing objects is difficult, but possible. A better design of the safety system can simplify the detection, tracking, and computation. Also, in the working environment for heavy machinery, the electromagnetic interference and electromagnetic pulse (EMI/EMP), noises, ambient light, cramped working cell, and other factors may limit the appropriate performance usage of many sensory systems. All of those factors should be listed as design considerations of the robotics safety system. In this paper, we present the design of such a robotic safety system. Due to its capability to handle the safeguard functions dynamically, we have called the system the Dynamic Robotics Safety System (DRSS).

Imaginary Multiple Air Bubbles

This paper discusses using the robot arm of a gantry robot to illustrate the design and function of the DRSS (**Figure 1**). Due to the high cost of hardware and the safety concern, a new technology—Augmented Reality (AR) —has been used for this development. The augmented reality allows the creation of "virtual objects", which exist only in design, to mix with real objects and people in either real or virtual environment. The robotics safety system discussed in this paper uses a set of imaginary multiple air bubbles to wrap the robot arm/end effector, the protected objects, and the human operators during the operation of the robotics system. Basically, these air bubbles exist only mathematically (**Figures 2 and 3**). In general, we use two air bubbles to wrap each section of the robot arms. For small sections such as end effector digits and to simplify the computation, we grouped those into a single entity and used only two air bubbles for the whole group. In Figures 2 and 3, we used different colors to show the inner and outer air bubbles.

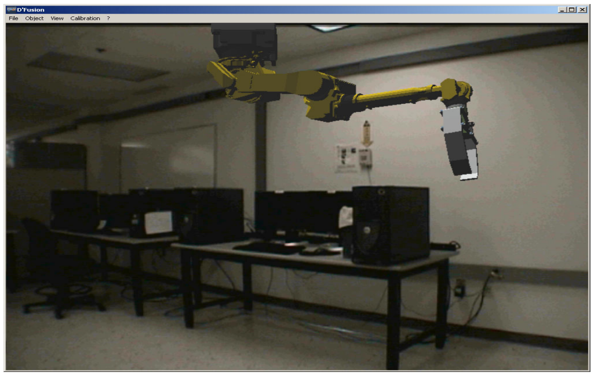

Figure 1. The DRSS uses the virtual prototype of a gantry robot arm and augmented reality to demonstrate the functions of the safety system.

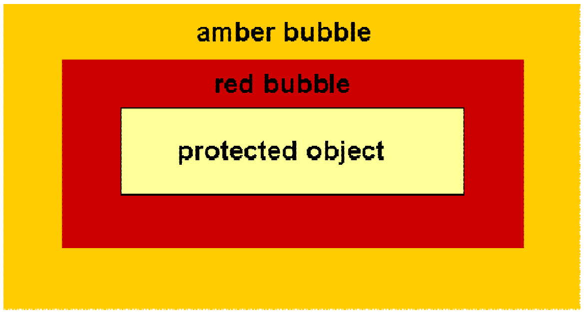

Figure 2. The simple cross-section view shows the concept of using two imaginary bubbles to wrap around the protected object. The amber bubble indicates caution; the red bubble indicates danger.

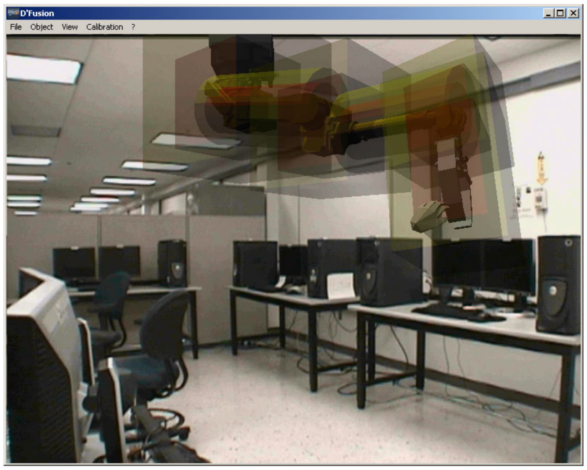

Figure 3. The DRSS uses a set of imaginary air bubbles to perform the safety functions.

The reason we used two air bubbles for the same section of the robotic arm is to set the situation in three stages for the safety system. In normal stage, the human is completely out of those air bubbles so there is nothing to worry about. When the human "touches" the outer (amber stage [caution]) air bubble, there is a safety concern. The human should be warned and proceed to get out of the potentially dangerous situation. If the human ignores the amber warning and proceeds into the danger, that person will "touch" the inner (red stage [danger]) air bubble. In this situation, the robot controller takes immediate action by sounding the alarm and setting all brakes to prevent an imminent disaster.

The amber air bubble warns of a potential collision. The thickness of the amber air bubble provides the response time for the human to react. The thickness of the red air bubble provides the cushion for the brakes to stop the movement of the robot arm before the collision caused by the motion or the runaway of the drives.

The thicknesses of the air bubbles (the distances from the object to the outer boundary or inner bubbles to outer bubbles) are determined dynamically by the speed and characteristics of the drives. The faster the speed and the longer breaking time, the thicker the air bubble. Also, for a fully extended robot arm, the "magnification" of the drives near the base would increase the speed at the end. This phenomena also results in a thicker air bubble at the end section of the robot arm/end effector.

Human Tracking and Protection

Most accidents that happen in working environment are caused by human actions either due to carelessness or without thinking. A complete safety system provides safety under all possible scenarios. Boredom, physical fatigue, or by taking a shortcut, the human can violate the safety rules unintentionally. The safety system should also take these into consideration and provide a safe solution.

During operation, there are people who are authorized to be within the working environment and others who are not authorized. Any unauthorized personnel are identified, warned, and escorted out of the working area, immediately. The safety system should recognize who is and who is not allowed to be present in the working environment. A proposed tracking method includes sensors that detect, identify, and track humans within the working cell.

Sensory Systems, Data Association, and Robustness

In the working cell, the fixtures, working components, people, drives, ambient light, temperature, humidity, and other factors create significant challenges to the performance of various sensory devices. For example, a vision sensor's (fixed mounted or mobile unit) view could be blocked sometime during the operation. A set of different sensory systems that complement each other should monitor and safeguard the operation within the working environment at all times.

Due to the closeness of humans to the robotic arm/end effector, precision is absolutely essential. The performance of common proximity sensors cannot achieve the accuracy required; hence, proximity sensors were not used as the primary sensory system for DRSS. Common proximity sensors may be used for other secondary safeguard applications.

Since the working cell requires many different sensors to cover the entire area under various conditions, this poses a significant challenge to analyze and apply the datum collected by those sensory systems. The overlap of sensory coverage creates another level of complexity for the safety system—to identify, track, and associate those objects individually. All of those datum and information should be used by the automated safety system while a simple scenario view will be available for human operator use.

The more complex the system, the more the system may encounter component failure. The multi-sensory safety system may experience component failure during operation. The safety system design needs to avoid a single point failure that may cause the failure of the complete safety system.

SYSTEM DESCRIPTION

In this section, we present the design of the DRSS using a simulated heavy payload gantry robotic system to demonstrate how the DRSS works. In this setting, humans are required to perform delicate manual work on those components while using the gantry robot arm is moving and repositioning the heavy loads. Since the reach of the gantry robot covers the entire working environment and it is inefficient to remove and introduce humans from and into the working cell constantly, a complete safe system needs to safeguard the humans and the working components at all times. From our tests, this DRSS might be the answer for a complete safety system, allowing humans to work safely within the robotic working envelope.

Overview

The DRSS consists of three major components: the System Controller, the Sensor Subsystem, and the Warning Subsystem (Figure 4).

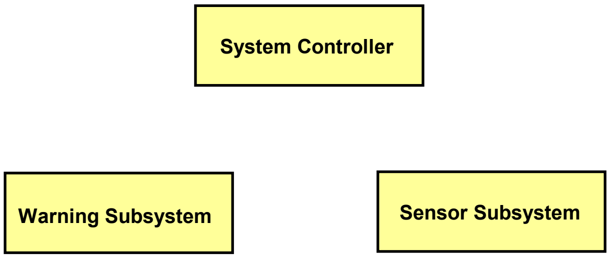

Figure 4. The DRSS is a modular constructed add-on system that can be used on almost any robotics system.

The System Controller performs the overall control functions of the DRSS. Those functions include initialization of the system, communicating with the robotics controller and all subsystems, displaying the situation within the work environment, reporting the health situation of the system components, sending out the warning, and sending the command to the brakes of all the drives of the robot arm/end effector. It also performs all the computation algorithms and system tests.

The Sensor Subsystem provides the sensor control, monitor, and feedback to the System Controller. The Sensor Subsystem consists of a set of fixed cameras, rotary and linear position sensors, and magnetic trackers. Most of those are hard-wired except the magnetic trackers. During the DRSS tests, we used wireless trackers for tracking human positions and orientations. The communication for the wireless equipment has been tested while mounted directly on low to medium power drives. The EMI/EMP noise generated by the sudden starts and stops of the drives is negligible with no degradation of performance of the magnetic trackers. Vision systems, in addition to the detection of the configuration of the working cell, were used as redundant sensor to track humans. Without using complicated hardware and software to handle sophisticated algorithms, the vision system could not determine the "orientation" of a human compared with the well-defined data collected by the magnetic tracker. That was the major reason we used the wireless magnetic trackers. Other kinds of sensors might be used to add another layer of safety to the working cell and/or replace the magnetic tracker if it has better performance.

The warning system includes a set of colored lights, audible voice warnings, and an emergency siren. When the amber lights are on, the warning system sends an audible voice warning to human operators. This situation means that at least one human is within the potential danger zone. When the red lights and the siren are on, the warning system has detected immediate danger in the working cell. The system controller will send an emergency command to the robot controller to apply all the brakes on those drives to freeze the movement of the robot arm.

LAB TESTS

Due to the high cost, long lead time, and associated danger, the initial development of the DRSS used an innovative method to perform proof of concept, component tests, and system tests (Huang, Kar, Kennedy, Kato, 1996). A combination of software simulation models, standard lab equipment, surrogate components, and sensory systems were used for the development and tests of the DRSS. This method has been used successfully on several engineering projects/programs. When performed rigorously, the completion of the lab tests can move directly into system integration stage (Huang, Kar, Kennedy, Kato, 1996, Huang, Kar, Fandrich, 1997, DoD Directive 5000.59). One of the most important components needed for this development is the robot arm/end effector of the gantry robotics system. Since this item is still under development, we used a new and interesting technology to create the surrogate gantry robot arm called "Augmented Reality" (AR). The AR can blend simulation with "real" objects and perform seamlessly to provide a perfect viewing environment for the development of the DRSS. This AR-created robotics system model can be viewed conveniently and allows humans to "walking around" it. This model exists in the developing lab and allows the DRSS developers to work on it without any real danger.

In one of the setups, we used a lab workstation as the DRSS System Controller. We created the gantry robotic arm as shown in Figure 1. We created the multiple-layer of air bubbles around the robotic arm, the simulated objects, and real objects. For the human operators, we used both "real" human and simulated mannequins for this work.

All the objects in the working space (real or virtual) for tests were wrapped by two layers of imaginary air bubbles. For each human operator, we used three trackers to define the shapes of the body, left arm, and right arm of the person. To simplify computation, we used only a set of three to five solid sections to represent a human (Figure 5). For fully extended arm/hand, we used only one section. For a bent arm/hand, we used two sections to represent it. The head-mounted sensor provides not only location but also the orientation of the person. When the tracked person makes a move, the System Controller tracks the sensor data and determines where the person is and predicts in which direction this person is moving. This data, in addition to the speed of the robotic arm/end effector, are used to determine the "thickness" of the air bubbles around the robotic components.

Figure 5. We used from three to five sections to define the space occupied by a person.

When the person touches the outer air bubble of the robot arm, the shinning amber light sends the audible caution signal (Figure 6).

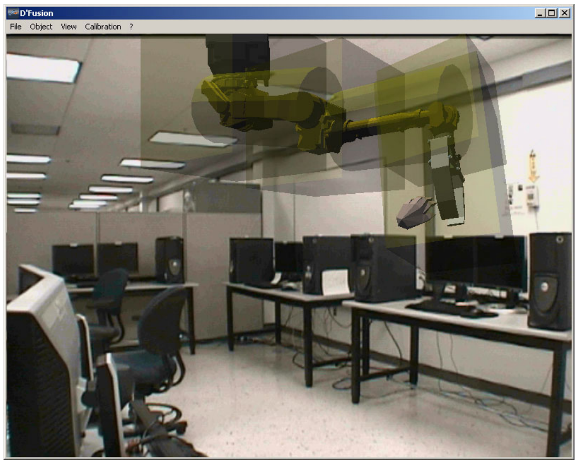

Figure 6. Using special goggles, the human operators can see the amber light, which indicates caution.

The intrusion of the inner bubble immediately turns on the red light, starts the siren, and sets all robot drive brakes to freeze the motion of the robot arm (Figure 7).

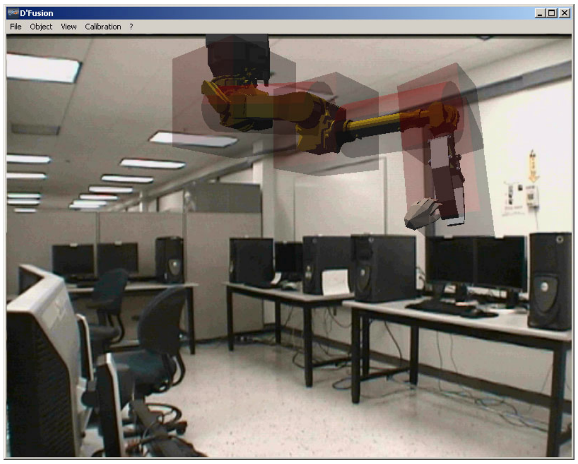

Figure 7. When the red light (danger) is on, the DRSS controller starts the sirens and sets the brakes to all robot drives. The human operators can see the red light when using special goggles.

DISCUSSION

From the development of the lab demonstrated DRSS, discussions with personnel who were responsible for the robotics maintenance and calibration, and the information gathered from several Flexible Manufacturing Systems (FMS), the developers have learned the following lessons:

Tracking Sensor for Human Operator

To track a human, the magnetic tracker provided satisfactory results for proving concept and testing. However, to ask a worker to wear an extra device, no matter how small it is, is an extra burden. For many people who are familiar with the operation process might conveniently forget to use it.

Devices that do not require humans to wear objects are preferred. We have tried to use a vision system, but with only limited success. Since a human moves in and out the working environment, the "hand over" from one camera to another involves a significant algorithm effort to handle. In a clustered working environment, the lost track adds another layer of complexity. Unless there is a significant advancement in data association, using vision for tracking may work only in simple working environments.

Most likely, the workers in the working cell are required to wear safety helmets and/or safety goggles. The trackers can be attached to or even embedded in those safety equipments. This easily solves the problem of a human forgetting to use trackers in the working environment. Other tracking devices, such as Digital Angel or RFID (radio frequency identification), cannot provide the necessary accuracy at this time. Future development tracking devices may result in smaller and more precise trackers for the safety system.

The use of vision for tracking unauthorized intruders, however, is very efficient and easy. The vision tracker needs to generate a binary result: either an intruder or no intruder.

Working Components

For the objects directly handled by the robot end effector, there is no air bubble to wrap around objects as they cannot be protected by the DRSS. The miscalculation and drive runaway would damage those. This is an unavoidable risk.

For the other objects and fixtures within the robotic working envelope, the DRSS uses only a simple geometry to enclose it. Using this approach, a complicated shape will be engulfed by using a simple, easy-to-compute shape. The DRSS will prevent the collision between the arm/end effector and the simple geometry. When the robot gets too close to those shapes, the safety system would set the brakes to freeze the movement of the robot. An alarm also warns the robot's human operator.

Air Bubbles

The creation of the outer air bubbles is to provide an early warning to the operators that a potential collision might happen. After the human operators see the amber light is on, they have a chance to react and prevent an accident. Although those air bubbles are visible in the real-time display of the system controller during operation, the air bubbles are invisible to those people unless they wear special goggles that overlay the air bubbles on the vision system. During the development of the DRSS, since the developers used a virtual gantry robot arm, the system tester had to be able to "see" the robot arm. A commercial off-the-shelf heads-up display (HUD) allows the human to "see" the robot arm and perform all the tests. This very HUD device was also the platform for mounting the magnetic tracker. In the future, this HUD device can be replaced by special safety goggles. The available air bubbles overlay in the safety goggles of workers is just a "nice to have" feature and is not essential for the safety system.

Legal and Regulations

To allow human to be present within the working envelope of high payload robotics system, legal questions/issues need to be addressed. Present OSHA and other regulations do not have a standard for humans working in the vicinity of robot but the guidelines (Feingold, 2008, STD 01-12-002-Pub 8-1.3 Guidelines for Robotics Safety), in general, prohibit human presence within the reach of any sizable robot arm. The legal and regulation-related issues, although are out the scopes of this paper, cannot be ignored for the successful implementation of a robotic safety system that allows human to work in the vicinity of the robot.

Pathfoward

The whole idea of DRSS was based on the search for a solution that allows humans to work in the vicinity of heavy payload robotic systems safely. When working closely with a robotic system, human operators can handle delicate tasks while the robotics system performs moving, repositioning, and other functions. The only way to achieve this goal is to develop a robotic safety system that can protect humans, completely.

It is impossible to design a system that will never fail, but it is achievable to design a system that will gracefully send warnings and prevent an accident. The ability for degraded performance instead of catastrophic failure is a must for any safety system. The DRSS uses multiple redundancies in monitoring and a staged process to handle potential risk conditions. The DRSS takes into consideration the unpredictable and sudden movement caused by faulty robotic drives.

To lower the cost and to speed up development, many lab surrogate components and simulation models replaced prototypes in component and system tests after the simulation, to prove the basic concept. The use of the hybrid tests that utilizes a collection of simulation models, lab equipment, and surrogate components not only lowers the cost for development, but also provides a safe environment that prevents potential accidents. Any hidden issue or problem identified during testing can be fixed and an improved version can be quickly tested.

We anticipate in the near future the special demands will create an urgent need to implement heavy payload robotic systems into human labor-intensive applications. Those areas include, but are not limited to mining, explosive ordnance handling, and certain manufacturing applications. To proactively create the technology and know-how, we will conduct more rigorous hardware and stress tests for the DRSS.

CONCLUSION

We have discussed the development of a safety system that allows human operators to work in the vicinity of heavy payload robotics systems. To allow human presence in the working envelope of a heavy payload robotic system involves more than technical concerns; legal and regulatory compliance rules will also play a significant role. Careful consideration of these compliance issues are required and are beyond the scope of this paper.

In addition to the potential collision with heavy machinery, the overall robotics working environment provides a less than desired condition for most sensory systems. In this environment, any false alarm can cost substantial delay, loss of productivity, and financial loss. The safety system, in addition to protecting humans, must have a very low or no false alarm rate. All of these add difficulty in the design of the safety system.

We discussed the DRSS design that uses a modular design to accommodate new technology and update component swap at ease. Instead of conventional modeling and simulation (M&S), we used a hybrid method to take advantage of M&S for the development and testing the DRSS. In future work, more surrogate components will be replaced. Eventually, prototype hardware will be needed for complete testing.

As the number of experienced personnel decreases, industries will be looking at automation for a solution. In special applications, such as ordnance assembly, the reduction of human operators is a must. Those needs will push for wider use of FMS (Flexible Manufacturing System), yet humans are still indispensable for many tasks. Those tasks will drive the urgent need to allow humans to work with robotic systems in the same working space. When need exceeds a certain threshold, those issues such as legal concern and safety rules will be updated to accommodate the new technology.

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